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PGE - PRODUCT GENERATION ENGINEERING IN ENGINEERING EDUCATION: REAL-WORLD PROBLEMS FOR BEGINNERS IN STUDENT PROJECTS

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ABSTRACT
The academic education of engineering students aims at qualifying for engineering practice. Hence courses in mechanical and mechatronic design in the early stage of engineering education include often project works, where the students themselves design technical systems. The task description usually includes a first system structure, functional and other requirements and design constraints. Starting with this the students design a new system from scratch. However, real product development is PGE – Product Generation Engineering: a purposeful combination of new development activities and carrying over subsystems from already existing products. The product documentation of those existing products (CAD models, test reports etc.) and the analysis of this data are essential for design activities. Making engineering students fit for real-world problems requires such activities to be part of the project works described above. Therefore, those teaching concepts need to change. This transition is associated with several challenges. This contribution presents first approaches for bringing PGE to courses in the early stage of engineering education, particular to project works. Based on current research concepts for the conduction of PGE in project works in mechanical and mechatronic design courses are derived for the specific conditions in the early stage of engineering education. Subsequently the implementation of those concepts is described. Conclusively first experiences and evaluations from these implementations are presented.

Keywords: Early stage engineering education, mechanical design, mechatronic design, teaching concept

1 INTRODUCTION

The academic education of engineering students has to qualify future engineers for engineering practice. Key elements of engineering practice such as project work, team work or tools like CAD have been integrated into engineering courses at universities to meet this aim. Engineering education itself has become subject of specific research which is furthermore closely related with research on product development and engineering design itself. To keep engineering education up to date it is necessary to check results from engineering design research and their possible implications on engineering education regularly.

PGE – product generation engineering is a recently developed approach to describe fundamental phenomena of engineering design in a new way. According to PAHL AND BEITZ there are different categories of product development projects: new design, adjustment design and variant design. They are distinguished by the degree of novelty, uncertainty of boundary conditions and the opportunity to use known solution principles [1]. Similarly the DIN 6789-3:1990-09 differentiates between product change and new design [2]. By analysing those approaches and real development projects ALBERS developed the approach of PGE – Product Generation Engineering to describe real development projects more accurate [3]. PGE states that technical systems are always developed based on existing systems which serve as reference products. These reference products can be preceding product generations or competitors' products, for example. They predetermine the system structure and embodiment to a certain extent. Starting with reference products new product generations are developed by the combination of carryover variation of subsystems, including only adjustments at the subsystem’s boundary, and the new development of subsystems, starting either with variation of the embodiment or variation of the solution principle [3].

Current teaching concepts are based on the approach of PAHL AND BEITZ. This is understandable as this was the state of the art when those concepts were created. However, the new insights provided by the PGE approach demand an adjustment of those teaching concepts as well. Many courses in the early stage of study are project based learning [4, 5]: the students acquire knowledge that cannot be taught in the lecture [6]. DYM ET AL. describes that courses with project based learning are more expensive, but that they are relatively small compared to the cost of lost human talent in the engineering pipeline [5]. Project based learning improves retention, student satisfaction, diversity and student learning [5]. However, PGE is not implemented sufficiently in those projects. The students get references, for example principle sketches, but the quality of those references does not match reference products from development practice, e.g. technical drawings, test reports, fittings etc. As a consequence the students are not sufficiently enabled to synthesise new technical systems based on existing product documentations from preceding product generations and real technical systems. This is contrary to the aim of qualifying the students for real development activities [7]. Hence, the PGE approach should be implemented in engineering education from the very beginning.

The research question that arises is: *How can PGE be integrated into existing teaching concepts in the early stage of engineering education*?

2 RESEARCH METHOD

In current teaching courses for beginners there are no generation spanning approaches although this might be expected intuitively. As a consequence there are no experiences regarding the implementation of such formats in study courses. Thus, an explorative approach is chosen here as a research method, according to BLESSING AND CHAKRABARTI [8]. First, possible measures to encounter the **challenges for the implementation of PGE** into existing teaching concepts are analysed as a descriptive study. Subsequently a **teaching concept** is developed in a prescriptive study. This **concept** is finally **implemented** in two teaching projects.

The first teaching project is called “mechatronic systems and products” and is attended by 80 students. The course is offered in the 5th semester of the mechatronics and IT degree course and is assessed with 8 ECTS points. The teaching concept was evaluated in writing by the students (N=61) as part of the teaching evaluation and in a two-hour feedback interview (N=9). The second teaching project, “Mechanical Design III & IV” (MD III, MD IV), lasting one semester each, are usually located between the third and the sixth semester for students, depending on the course of study. The majority of the 450 – 500 participants studies either Mechanical Design or Mechatronics and IT. The course is rated with 13°ECTS points. The teaching concept was evaluated by observations of the lecturer during the semester and by direct feedback from participants and assisting students.

3 CHALLENGES FOR THE IMPLEMENTATION OF PGE

The tasks, which are given to students in project works in early stages (Bachelor) of engineering education, are usually limited in their extent and level of detail due to a limited time frame of one or two semesters. The product development in the project works therefore usually terminates with systems which differ in their maturity level from real world systems. As a result the students might get a wrong impression of design activities. Hence, it is important for a project work to provide a reference product with an appropriate maturity level. If it is too simple, the simplification in comparison with development practice is too big and the design task does not match real world problems. If the reference product is too complex it is too difficult for the students to perform the development of the next generation due to their lack of knowledge. However, providing reference products from the beginning in general (compare figure 1) enables the students to handle complex systems similar to real world problems earlier.

Within the same time as before they can gain additional competence in using product documentations. They learn of the advantages which result for a development project, if already evaluated subsystems are used as a basis. The necessity to find new creative solutions for the new development of selected subsystems is maintained at the same time. The provided product documentation of reference products has to be suitable for the students. Their experience and their methodical and technical knowledge, which is required for the analysis and synthesis of technical systems, differs in some ways strongly from the knowledge of engineers with a completed degree. The students are not used to handling

detailed and extensive product documentations such as models and prototypes, for example. They have to understand not only the embodiment-function-relation of the reference product in detail but also the documentation of the reference product, e.g. the structure and part tree of a CAD model.
In reality product development is iterative. Physical-virtual prototypes ("development generations" in terms of PGE) are tested in simulations or on test benches. Further development is based on the results until the product is market-ready. If it is desired that the students terminate their development activities with a maturity level similar to real world problems the validation of development generations has to be part of the project work. However again, the students at this point lack some of the required knowledge and furthermore the organising institutes do not have the necessary resources.

4 TEACHING CONCEPT

The current teaching concepts have been established and are well evaluated by the students. The aim was therefore to investigate which elements of the existing concepts can be retained and where new elements are required due to the current knowledge of PGE. Subsequently the maintained elements are described first, followed by the description of new aspects. Relating to the objective, the development problems are clearly outlined in lectures in early studies. Due to the level of competence of the students projects with real tasks from an industry partner are hardly possible at that stage. In difference to the PGE in development practice, the development task does not have to be defined by the students - e. g. by market analysis, based on customer feedback, field observations and the like. This has didactic reasons and will be maintained. The criteria to verify the achievement of the development goal are different between courses in early study from real PGE. For example, the degree of maturity to be fulfilled or the implemented functional scope is different. At the end of real developments, suitability for serial production must be given or defined tests must be carried out. In contrast, in courses in early stages of study, the extent of the product documentation (drawing, calculation, etc.) to be prepared is specified as the target. The elaboration must satisfy elementary principles, e. g. for the design of machine elements, or fulfil specific functions, e. g. "stacking blocks". This is due to didactic and organisational constraints and is therefore maintained.
In courses on product development, in the early stage of engineering education, the focus is on the design of the embodiment of the products. In practice, design starts on the basis of reference products or their product documentation, i. e. on the basis of technical drawings, CAD models and test reports. As an essential new element of the teaching concepts – in addition to the actual task definition – a reference product including the associated product documentation is therefore provided to the students. The given development task must be fulfilled by the combination of carryover of subsystems and new development of other subsystems. Furthermore, considerable creativity is required for the design process. For example, in the development of new subsystems, but also in the adaptation of subsystems, or in the integration of subsystems. The carryover of subsystems and the partial reuse of already existing product documentation is not considered as "plagiarism" but is an intended effect, similar to real product development. The share of own creative work of the students can nonetheless be determined by comparison of their results with the given reference product. The task definition must be created in such a way that the analysis of the reference product will be the actual starting point of the development activity. These demands on the tasks are also a new part of the teaching concepts. The reference product and its product documentation are based on a selected work result of the previous student year. The advantages are as follows: a) based on experience, it can be expected that the complexity of the system is manageable within the project work; b) the used product documentation is the result of real development activities and therefore sufficiently close to real-world problems. This also includes the resulting challenges in the analysis of the systems.

5 IMPLEMENTATION OF THE CONCEPT

In the following, the specific implementation of PGE will be presented in two different courses in the early stage of engineering education.
The course *"mechatronic systems and products"* (MSuP) consists of lectures with integrated exercise phases and a student project. For the student project, which is managed by a stage-gate-process, the students are subdivided into teams. With this guided stage gate process most parts of the industrial product development process is covered. To solve the development task of the student project, the team has to develop, manufacture, validate and optimise a mechatronic system. Project goals are examined in milestone meetings. It is up to the students to decide how they reach these project goals.

The systems of all teams have to perform on a simulated market (competition) against each other. [9] Students can use a microcontroller, various actuators and sensors as well as fischertechnik parts to manufacture the mechatronic systems. Individual parts can be produced with a 2D laser cutter. This year, PGE - product generation engineering was integrated into the course concept for the first time. Students develop their systems based on the previous year's systems (compare figure 1). For this purpose, the students can transfer or adapt the selected subsystems. They also can design the subsystems themselves. The available reference systems are either mechanical or IT systems. In the case of mechanical reference systems, the CAD model and the video documentation of the validation are provided. Students can test the manufactured models once at the beginning of the semester. In the case of IT reference systems, students receive the Simulink model with the corresponding product documentation. Because the development task of the student project is modified slightly every year, the subsystems must also be adapted to changed requirements by the students. Next year, students will receive the reference systems further developed by this year's students for a modified task.

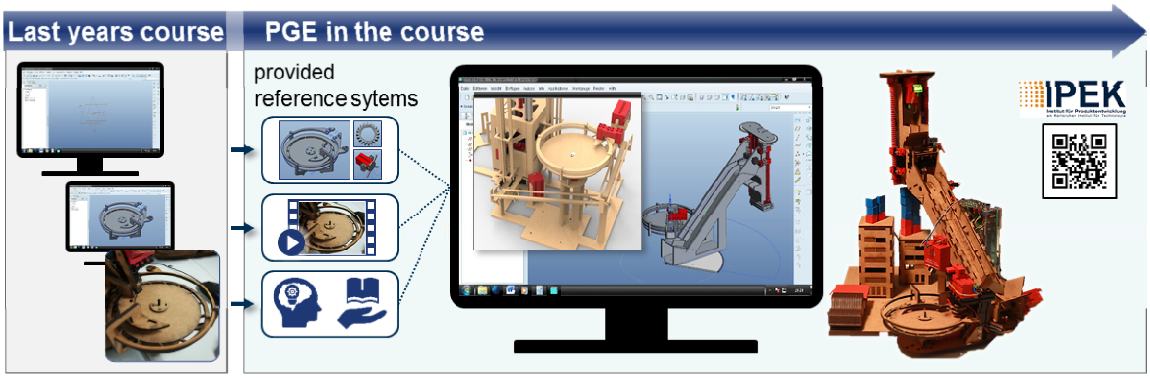

Figure 1. Implementation of PGE in the course concept: Left so far, right with PGE

The insights of the first run with PGE are:

- Testing the reference systems by the students themselves is much more important than expected. The CAD model and the test videos are not enough for the students to assess the suitability.
- The evaluation of the students whether they use a provided reference system or not is decided at the end of the stage "concept". At the beginning of this phase, the students work out the concept for their system. They do not know yet whether they can use one of the reference systems for their concept. After this phase, the concepts are tested in prototypes and a change of concept is too risky for the students. Reference systems are not used anymore.
- The students are not aware of the developmental advantage that results in using validated subsystems.
- The evaluation of the project work has shown that the integration of PGE is successful and the students wish for further reference systems. The question whether further reference systems should be provided was positively evaluated by the students on a scale of 1 (Yes) to 6 (No) with 1.87 (N=61).

The courses "*Mechanical Design III & IV*" (MD III, MD IV) focuses on mechanical systems. Unlike MSuP the developed systems are not manufactured in the end. The main project results which are evaluated are CAD models (only MD III), project plans, flow charts and code for calculations, principle sketches and technical drawings by hand. Up to now, students have got a new task and a new system every year. Whereby the task and the system were repeated every 3 years. To implement PGE one system was focussed on: a power train for a four by four agricultural tractor, consisting of all subsystems between the combustion engine and the wheels. For the development of the first product generation with using a reference product they received a CAD model of the manual gearbox from the last course which had also developed the power train. The given gear box (cf. Figure 2) had two speed ranges, and two gears and one reverse gear in each range. The new task was to add another gear in the high speed range only. This task fulfilled the aspired requirements: there were three foreseeable, nontrivial ways to solve the task. Each option included notable new development activities but at the same time allowed for the carryover of a certain share of the reference product. In a similar way, the students in the next semester will receive the further developed gearbox of this year's students and adapt the coupling to a changed task, for example.

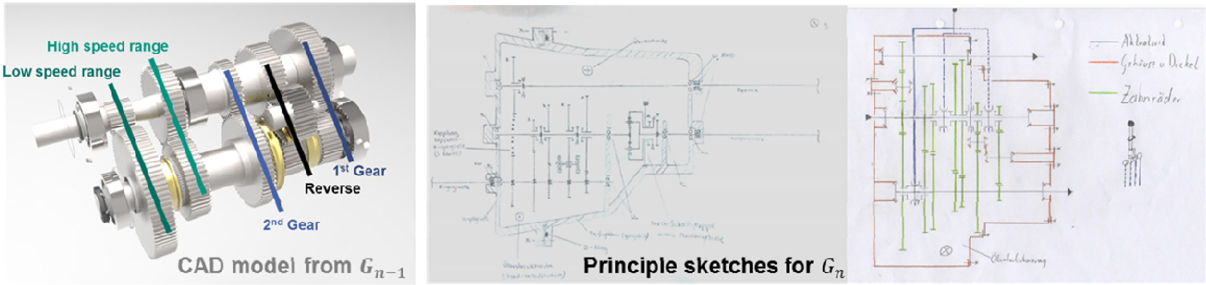

Figure 2. CAD model of the reference product (G_{n-1}) for the subsystem "manual gearbox" and different principle sketches in the development of the next product generation (G_n)

As a result it could be observed that most groups chose one of the foreseen solutions to solve the task. However, the students did not seem used to evaluating different possible solution alternatives by the share of new development or carryover respectively, although this is an important factor for expected development risks in companies. This indicates the need to strengthen this topic in the corresponding lectures. Using the given model of the reference product it could be observed, that the included knowledge in terms of for example bearing arrangements or gear wheel assemblies could be reused. However, reusing the model itself was sometimes more difficult, as the structure was not comprehensible in every aspect. More generally it became obvious, that the results, even if the demanded type was predetermined, e.g. a principle sketch, could vary in a broad range (cf. Figure 2). Here, different properties could be observed, which are linked to the reusability of the knowledge or its documentations, respectively. For example is the reuse of original MS Office files easy as they are editable, while for PDFs or even scanned handwritings only the knowledge is reusable but not parts of the documentation. For other characteristics of product documentation objects it is not yet that clear, which characteristics are important for the reuse of those object in the development of further product generations, e.g. what makes a principle sketch a "good" principle sketch, regarding its reuse?
Another rising question for the continuous implementation of PGE in MD III&IV is how development tasks such as the one described above can be derived systematically. A possible approach might be the use of methods which can also be used in development practice for the estimation of development risks in early stages of the development process [11] or methods for the assessment of the effects of changes of individual subsystems on other subsystems [12].

6 DISCUSSION AND OUTLOOK

It was surprising how much more complex the design of the task for the project will become. First of all, a technical system is required which will probably allow further development over several product generations. In the creation of the first task, first visions are already needed as how the products could be further developed in the future and where development potential exists. In addition, the fact that some parts of the task description and other documents cannot be reused due to the adjusted development task also results in a noticeable effort. The teacher becomes development manager who has to organise existing capacities for new tasks. In addition, the teacher must also estimate the amount of new development that can be realised within a year. This includes to anticipate possible alternative solutions for the given development task and to estimate their consequences – such as the variation effort that occurs in the various subsystems. A readjustment of the task is often not easily possible. At the same time, the authors were able to observe a higher level of motivation amongst the students. One reason for this is that the emerging vision was shared with them and it was clear that they were contributing a better starting point and more realistic task for their successors. This can also be seen in the subsystems which are becoming significantly more complex. The students confirmed that this gave them the feeling that they were designing practice-oriented. Another advantage is that students from higher semesters - who are tutors for the current year - are also the developers of previous generations of the product. They are therefore better acquainted with the system, which is the subject of the assignment, and are better able to supervise the students of the current year.
The authors see a great advantage in the fact that particular topics, which used to be only taught as extremely important in the lectures, but not needed by the students in the projects are now applied for the adjusted tasks. One example of this is the analytical competence. Although methods for the analysis of the embodiment-function relation had been taught previously, the students now recognised

much more clearly how important it is to understand the embodiment-function relations in realistic development projects. This is a consequence of the fact that the students were now given embodiment, which they had not designed themselves and had to analyse. Another example is the development in generations: The students have taken it for granted that reference products are already available and a development on the "white paper" is not usual. The third example is the need for good documentation. The students could experience clear differences, depending on how good their predecessors made their documentation For example, individual components contained clear justifications, e. g. for fits and tolerances. While other previous groups only documented the results and thus often triggered a new elaboration of the results.

Based on the evaluation of the courses and the students' feedback, the implementation of the teaching concept can be further adjusted in the following semester. The teaching concept offers the possibility to improve the research and development of methods of product development. The fact that the students develop complex real-world problems creates a unique research environment. Scientists can use the student development projects to test new methods and processes in realistic environments.

This creates a so-called LiveLab [10], which combines the advantages of laboratory and field studies. On the one hand, the boundary conditions can be adapted to the method-specific requirements. On the other hand, the purpose of the course is not simply to carry out methods. They have to generate a specific added value in the student project in order to be accepted. In this way, the students' feedback can be classified as similar to practice.

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