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Engineering design education at German universities: potential for a common basis to create personalized e-learning content

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Abstract

E-learning materials require a high initial development effort but can then be used by a large number of students with little effort. It therefore seems reasonable to develop and use these across universities. Particularly in the field of Engineering Design Education, standardized principles through norms and guidelines lead to a high degree of transferability. For the development of such e-learning offers, however, the context of application must be identified. As a fundament for the development, this publication analyzes Engineering Design Education in Germany.

Keywords: engineering design, design education, digital learning

1. Introduction

Well-trained engineers are needed to meet the current challenges of mechanical engineering, e.g., the development of sustainable products and thus new or modified product concepts. A central starting point is Engineering Design Education in higher education at universities. Courses in Engineering Design Education are often attended by a large number of students. Therefore, lectures often take place in frontal format (Albers *et al.*, 2012). In addition to the lectures, self-study time is an important part of university education in Engineering Design (WiGeP e.V., 2018). However, students often have difficulties using their self-study time efficiently (Arnold 2015). These existing teaching formats cannot compensate for the initial heterogeneity of knowledge in the group of students (Kossack and Bender, 2022). To address this issue, we have proposed the use of an adaptive e-learning environment for personalized support in the self-study time for Engineering Design Education (Kossack *et al.*, 2022). The development of such e-learning resources requires a high initial development effort but can after successful implementation be used by a large number of students requiring no additional effort (Schönwald, 2007). Therefore, we propose to develop and use digital learning materials like adaptive e-learning environments across universities as open education resources. This is particularly useful for the field of Engineering Design Education, as many fundamentals are based on norms and standards and the provide a uniform basis for teaching content. To ensure that these e-learning materials can be used across universities and complement the concept of the existing courses at the different universities in a meaningful way, it is necessary to know how Engineering Design Education is taught. In Engineering Design Education, efforts are being made to standardize teaching, for example Scientific Society for Product Development (Wissenschaftliche Gesellschaft für Produktentwicklung WiGeP e.V., 2018) provides teaching guidelines for engineering education. However, the information available on existing teaching formats, e.g., Albers et al. (2012), is out of date, especially considering the pandemic, which has permanently changed university teaching in many areas (Dittler and Kreidl, 2023).

This paper therefore examines Engineering Design Education across German Universities to identify the potential of creating common e-learning content like adaptive e-learning environments to support students in their self-study time. The following research questions are addressed:

- RQ 1: To what extent is the same learning content at different universities addressed?
- RQ 2: To what extent does individual support with adaptive e-learning in the self-study time at different universities seem to be appropriate due to the existing Teaching and Learning activities? Specific questions here are to what extent frontal lectures and self-study times remain dominant, to what extent initial knowledge heterogeneity is considered in courses and whether teachers perceive existing knowledge heterogeneity as a challenge.
- RQ 3: To what extent do examination forms support the learning process and give students feedback on their performance?

In the second section, the essential basics of university didactics are explained (subsection 2.1) and previous findings on Engineering Design Education are detailed (subsection 2.2). In the third section, the method used to investigate the questions is explained. Courses relevant to the research questions are identified, the associated subject descriptions are analyzed, and lecturers are interviewed using a developed interview guideline. The fourth section presents the evaluation of the analysis of the curricula and subject descriptions of 26 German universities and the results of the interviews with 12 lecturers. The results are grouped into the components of Constructive Alignment, namely Indented Learning Outcomes (subsection 4.1), Teaching and Learning Activities (subsection 4.2) and Assessment Tasks (subsection 4.3), because many university courses are based on this didactic concept. The results are then critically discussed in the fifth section. Finally, the sixth section summarizes the results.

2. Theoretical background

Virtual learning opportunities become qualified educational resources by means of didactic integration (Arnold et al., 2018). Therefore, these virtual learning opportunities must be adapted to the learning objectives and examinations (Biggs and Tang, 2011) as well as to the context of application (Niegemann and Heidig, 2019). The didactic terms and principles required in the results section are presented in subsection 2.1. Subsection 2.2 explains findings regarding the questions and specify current existing problems.

2.1. Didactical terms and models

The outcome-based approach Constructive Alignment assigns teaching and assessment to Intended Learning Outcomes. (Biggs and Tang, 2011).

Intended Learning Outcomes are central in the system and explain what students are expected to achieve with which level of understanding and performance. Learning Outcomes can be formulated at different levels of detail, e.g., indicative learning objectives for entire degree programs, General Learning Objectives for individual courses or Refined Learning Objectives for individual subject units, such as a single lecture. (Pfäffli, 2015; Mayer and Hertnagel, 2009) In addition these Intended Learning Outcomes can be differentiated according to different areas of competence. Professional competence comprises knowledge and skills. It is the ability and willingness to work on tasks and problems independently, appropriately, and methodically and to assess the results. Depending on the verb used, Krathwohl classifies based on Blooms taxonomy Learning Outcomes into six main categories of cognitive dimensions: remember, understand, apply, analyze, evaluate, and create (Krathwohl, 2002). In addition to professional competences, methodological competences, i.e., the ability to obtain information and to structure and interpret it, are also described. The third group of competencies is social competencies, which are skills used to act in communication or interaction situations. The personal or self-competence as the fourth competence dimension includes, for example, personal initiative. (Kultusminister Konferenz, 2017; Gessler and Sebe-Opfermann, 2016)

Teaching and Learning Activities describe the work students need to do for achieving the Intended Learning Outcomes. These Teaching and Learning Activities include presence-study time in the university e.g., in frontal lectures or small group exercises and independent learning by the students themselves in so called self-study time e.g., with exercises or books or e-learning content. (Baumann

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and Benzing, 2013; Biggs and Tang, 2020) E-learning opportunities can be synchronous, i.e., have simultaneous interactions, e.g., in chats or video conferences. Alternatively, they can be used asynchronously, i.e., with a time delay, e.g., in discussion forums. (Pfäffli, 2015) Asynchronous learning opportunities such as learning videos often provide the basis for flipped or inverted classroom models, in which the usual activities inside and outside the lecture hall are reversed (Arnold et al., 2018). All these different activities are arranged in a learning environment which encourage students to achieve the by the Intended Learning Outcomes addressed skills (Biggs and Tang, 2011).

The Assessment Task reveals whether a student reached the criteria described by the Intended Learning Outcomes (Biggs and Tang, 2020). For each Intended Learning Outcome, the appropriate form of assessment such as written or oral exams, presentations, portfolios or learning diaries must be chosen (Baumann and Benzing, 2013). The examinations may be graded or only participation may be sufficient as proof of performance. This is differentiated not only according to the type of examination but also according to the examination time. If the assessment takes place continuously during the learning process, for example through weekly tests, this is referred to as formative assessment. If the assessment takes place at the end of the learning process, for example in the form of a written examination, it is a summative examination. (Arnold *et al.*, 2018)

2.2. Individualization of Engineering Design education

Engineering Design is defined as the totality of all activities with which - based on a task - the information necessary for the manufacture and use of a product is developed and ends in the definition of the product documentation. These activities include the pre-material composition of the individual functions and parts of a product, the assembly into a whole and the definition of all details. (VDI 2221, 2019) Students acquire the skills required for this in various courses on the Mechanical Engineering degree programs. Engineering Design courses are those that train designers for the core of their work - synthesis. Even if in basic courses, such as mechanics or materials science Engineering Design-relevant content is also taught. (Albers et al., 2012) Previous practical experience, e.g., by internships or technical professional experience, has been identified as a success factor for students acquiring skills in Engineering Design courses (Žeželj and Miler, 2018; Kannengiesser et al., 2015). However, not all Engineering students have this experience and therefore have different starting points for acquiring skills. In a survey conducted in 2012, frontal lectures were identified as the dominant teaching format in Engineering Design Education, although design projects were considered more suitable for skills acquisition (Albers et al., 2012). In 2018, frontal teaching formats were still identified as dominant in engineering education (Terkowsky et al., 2018). This can be explained well by large numbers of students attending the courses. With typically large learning groups of up to 600 students, there is very little to no interaction between the students and the lecturer. However, in frontal lectures, all students are confronted with the same learning content at the same pace. (Pfäffli, 2015) This explains, why in Engineering Design Education, self-study time is a crucial component in addition to presence-study time in classroom teaching (WiGeP e.V., 2018). However, it is difficult for students to use these self-study times efficiently. Especially in the transition from school to university they are equipped with low self-learning skills (Arnold and Tutor, 2006). A study carried out at the Ruhr University Bochum confirms these challenges for the Engineering Design Education in the first year of study and shows the following problems (Kossack and Bender 2022):

- Students find it difficult organize their self-study time. They often find it difficult to identify learning gaps as well as suitable learning materials to close these gaps.
- Prior technical experience enables students in better acquisition of appropriate knowledge for Engineering Design Education. Students perceive the courses as easier than other students without a prior technical experience and complete their courses with statistically significantly better results.

The studies on digital learning opportunities in the field of Engineering Design Education cover digitalization of face-to-face events due to the pandemic and include the implementation of numerous didactic concepts such as project-based learning (e.g. Kerpen (2021)), blended learning (e.g. Whitehead et al. (2021)), gamification (e.g. Gonzales-Almaguer (2020)), as well as the development of automated

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evaluation options (e.g. Hoppe *et al.* (2021)) or new visualization concepts (e.g. Zorn *et al.* (2021)). However, individual differentiation of the learning content has not yet been investigated systematically. We have therefore proposed the development of an adaptive e-learning environment as individualized learning support for structuring the self-study time. In this, the learning environment is adapted to the individual needs of the user, e.g., by identifying the level of knowledge through frequent assessments (Rey, 2009; Berger and Moser, 2020; Stoyanov and Kirschener, 2004). A prototype implementation for the subject area of fits, dimensions and tolerances is presented in Kossack and Bender (2023). Its use has already been shown to have a positive effect on the acquisition of professional competencies (Kossack et al., 2023a) and the homogenization of initial knowledge-heterogeneous groups (Kossack et al., 2023b). The cross-university development of e-learning resources for technical drawing as part of Engineering Design courses has already proved successful (Dillenhöfer *et al.*, 2023). Therefore, the aim is to analyze the Engineering Design Education in Mechanical Engineering degree programs in Germany to identify the potential for developing a cross-university adaptive e-learning environment for Engineering Design Education.

3. Method

In Germany, presently 26 universities offer a Bachelor of Science degree program in Mechanical Engineering. Due to the different university access paths e.g. by a general matriculation standard or vocational training with specific qualification in Germany, it can be assumed that students have heterogeneous prior technical knowledge. In the degree programs under consideration, students specialize in a subject area such as materials science or automotive engineering from the third year of the standard period of study or can at least choose individual courses. To be able to develop e-learning materials for as large a group of students as possible, the focus is on Engineering Design courses in the first two years of study. A title analysis was carried out in course catalogues to identify relevant courses using the following keywords: *Engineering Design*, *Drawing*, *Representation*, *Machine Element*, *CAD* similar as presented in Albers (2012). The course descriptions for these identified courses were analyzed. In addition to the Intended Learning Outcomes, the course descriptions also specify the presence-study time in hours per week and often the distribution between lectures and tutorials, as well as the total workload for students and the form of examination. The information in the course descriptions differ in some cases, these course descriptions also contain literature recommendations and the number of participants. To determine the potential for e-learning courses, it is necessary to examine in more detail how the presence-study time takes place and what is made available or even suggested to students to use in their self-study time. Additionally, 12 lecturers from 12 universities were willing to take part in an about 20-minute oral interview. Two of these interviews took place in person and ten by telephone or video call. The 12 lecturers answered questions for a total of 20 Engineering Design courses in the Mechanical Engineering degree program. The basis for the interview was a guideline developed for this purpose. The guideline contains items on the number of participants or the distribution of presence-study time in lectures and exercises. If possible, some of these items were answered with the course descriptions, so not all lectures were asked all questions. In addition, based on the research questions, the guideline contains questions on the detailed structure of presence-study time, guidance for self-study time, the use of e-learning and functions in the learning management system, existing knowledge heterogeneity and how to deal with it, feedback that students receive on their own performance and the extent to which the pandemic has changed teaching in the long term.

4. Results

The investigation covered 26 universities with a total of 82 Engineering Design courses in the Bachelor of Mechanical Engineering, which are compulsory for all students on the degree program and are scheduled in the first two years of study. Ten of these courses run over two semesters and 72 courses over one semester. The individual universities include between two and five courses. The degree program schedules show that Engineering Design courses at four universities start in the second semester and otherwise in the first semester. Information on the number of participants is available for 20 courses. These courses are attended by 130 to 600 students. The analysis of the curricula and internship guidelines of the 26 universities shows that all universities include an internship as part of the bachelor's degree program. A part of the internship of four to eight weeks is often recommended to be completed before the start of studies. However, almost all universities only require an internship at some stage, e.g., up to the fifth semester or until registration for the bachelor's thesis. A detailed analysis of the internship guidelines shows that students can gain experience in a wide range of subject areas. Students can choose three of the following areas: Machining Manufacturing Processes, Forming Manufacturing Processes, Primary Forming Manufacturing Processes, Thermal Joining and Separation Processes or Manufacturing, Testing and Assembly Processes in the Production Process. And even within these categories, there is a wide variety of possible content in which students can gain technical experience. It can therefore be assumed that the students' prior knowledge as acquired during internships is very heterogeneous. In our survey, the lecturers confirm this as a challenge and attempt to compensate this initial heterogeneity of knowledge for example by integrating practical exercises with machine elements.

In the following, the central results are presented regarding the Intended Learning Outcomes (section 4.1), the Teaching and Learning Activities (section 4.2) and the Assessment Tasks (section 4.3).

4.1. Intended learning outcomes

Professional, methodological and, in some cases, social competencies are described in the course descriptions at very different levels of detail. Even though the focus of this analysis is rather on the teaching and learning formats and less on the specific Intended Learning Outcomes, the curricula and course descriptions show the correspondence in the thematic structure: the courses begin with the solids and machine elements as represented in norms and standards (see Figure 1).

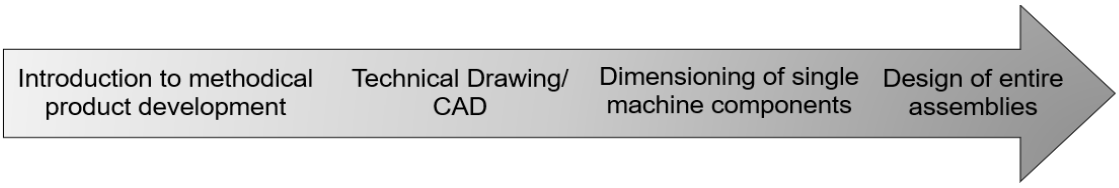

Figure 1. Time progress of Engineering Design courses in Mechanical Engineering degree programs

In the courses, technical drawings must be created both by hand and using a CAD programs. As the degree program progresses, individual machine elements (bolts, bearings, axles and shafts, shaft-hub connections such as feather keys or transverse press fits, clutches, and brakes) through to complex assemblies such as gearboxes are calculated, conceptualized, and designed. Students often receive a brief introduction to the methodical development of technical products, either at the very beginning of the subject or along the semester. Teaching and Learning Activities

4.2. Teaching and learning activities

The analysis of the course descriptions provide information about the total time expenditure for students in Engineering Design courses. This total expenditure for students is divided into presence-study time and self-study time. Furthermore, the presence-study time is often differentiated into lectures and exercises in hours per semester during the lecture period. The total expenditure of the Engineering Design courses in the first two years of study as compulsory courses for all students on Mechanical Engineering degree programs is between 360 and 720 credit points. The median is 548.07 and the arithmetic mean is 540 hours. Half of the universities have a total workload of between 450 and 607.5 hours (see interquartile range figure 2). This total workload is divided into self-study and presence-study time. The proportion of self-study time predominates with 200 to 415 hours. This amounts to an arithmetic mean of 311.96 hours and a median of 283.5 hours. Due to the position of the median in the interquartile range, there is a greater dispersion in the case of upward deviations than in the case of downward deviations. The presence-study time amount to between 122 and 378 hours. The arithmetic mean is 236.44 hours, and the median is 241.5 hours. The self-study time of the entire courses at the individual universities in relation to the total workload for students' range between 37% and 77.5%. The

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arithmetic mean is 57.6% and the median is 60%. The completion of projects is counted as part of the self-study time, particularly in the case of very high expenditure of self-study time.

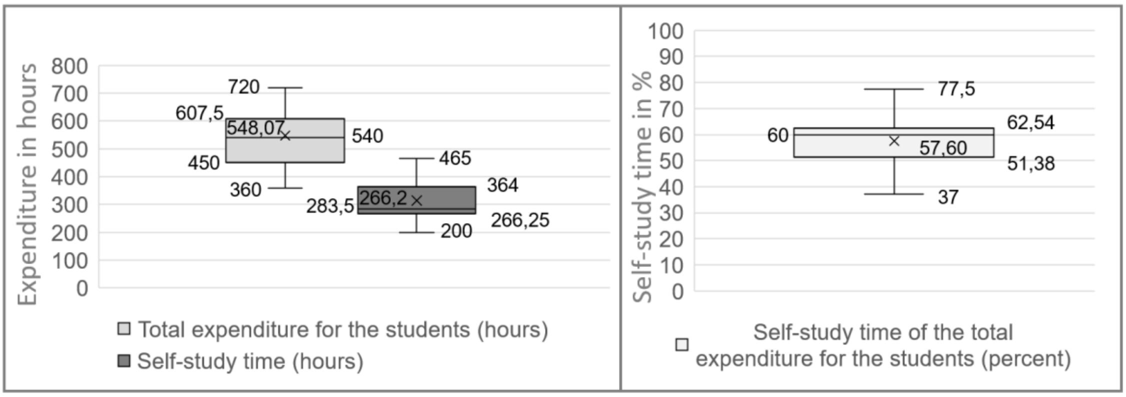

Figure 2. Total expenditure for the students and self-study time in Engineering Design courses

For the detailed analysis of the presence-study time, the interviews with the lecturers are evaluated. The results are illustrated in Figure 3. These show that, apart from one university, frontal lectures take place according to a pre-planned schedule. One university uses the flipped classroom model and provides students with videos to present content and designs the classroom lecture exclusively based on questions as posed by the students. Four lecturers mentioned the live creation of drawings during the lecture as an important component of the presence-study time. In addition to the content conveyed in the lecture, exercises are provided in the presence-study time at all universities for the acquisition of skills for the application of knowledge. These exercises take place in different formats. In 10 of the 20 courses, also the exercises are frontal for the entire group of students attending the lecture. However, most lecturers integrate short individual work phases for the students. At one university, exercises are offered asynchronously online. Small group exercises with up to 20 students are carried out in six courses. These are again mainly conducted frontal but are also used to hand in and discuss homework. In addition, CAD tutorials are held in these small-group exercises. Alternatively, students work with illustrative objects such as gearboxes under supervision in small groups. Consultation hours are offered for eight courses in addition to frontal and/or small group exercises. In these sessions, students receive support in completing homework or project work, some of which is part of a formative examination as an individual or group assignment. However, correcting homework or discussing individual solutions in detail during consultation hours as individual learning support requires a high level of personal resources on the part of the lecturer, especially for large groups of students. Lecturers see the heterogeneity of knowledge as a major challenge, especially at the beginning of the degree program, and try to do justice to this with the enormous amount of correction required for individual feedback. For the self-study time, students at all universities are provided with lecture material either in the form of lecture slides, scripts, or recorded videos. In addition, exercises, homework, or old exam tasks are made available at all universities. In some cases, the solutions are discussed in the lectures, either in the consultation hours with the students' individual solutions or an example solution in frontal large group exercises. In some cases, the student's solutions are collected and corrected which provides them with feedback on their performance. In some Universities, individual tasks are required for admission to the subject exam (compare 4.3). For seven courses, students receive exemplary solutions to these tasks for comparison with their own solutions. Some of the documents are provided sequentially during the semester and students are given a time structure for completing tasks to hand in or discuss in class. The materials for all courses are provided via a learning management system such as *Moodle* (Moodle Contributors, 2023) or *Ilias* (ILIAS open-source e-learning e.V., 2023). In eleven courses, the learning management system is not only used to provide the materials and to contact the students, but other functions and activities such as Test, Survey or Forum are also used. For eight courses, electronic tests are offered for learning assessment, which are used exclusively for self-monitoring and are not included in the official course assessment.

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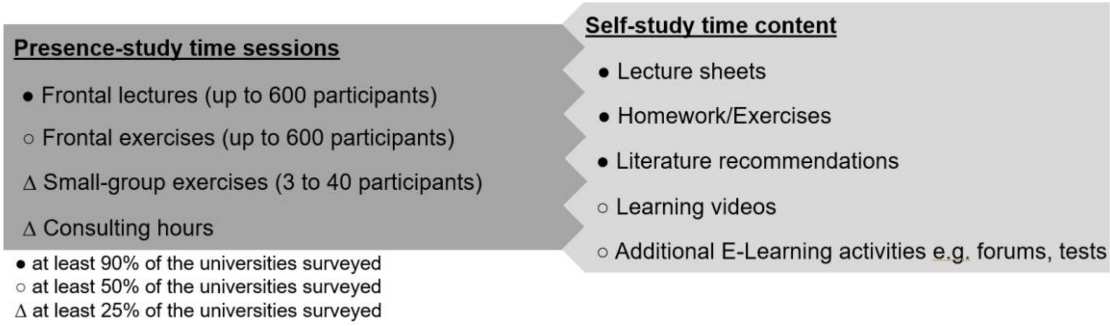

Figure 3. Current teaching and learning activities in Engineering Design courses

In addition, forums are used in which students can assess their individual drawings by means of peer review in a very few courses. According to lecturers, the pandemic has led to digital learning content being created during the lock-down of universities, such as learning videos or digital examination formats. These are being continued to be used as a supplement after the pandemic. In addition, since the pandemic, some consultations are being held in video format instead of face-to-face to prevent students do have to come to the university just for one single appointment, especially during the lecture-free period. Otherwise, no changes to Teaching and Learning Activities due to the pandemic were mentioned.

4.3. Assessment task

Detailed information on the examination performance of the content of 91 semesters was available from 24 universities through the course descriptions and/or the surveys. All these universities have Engineering Design courses in two semesters of the degree program. Of these universities, 22 have a third semester with an Engineering Design course and 21 have a fourth. Courses that have one Assessment Task but run over two semesters are considered in both semesters as part of this analysis. E.g., a course that is scheduled in the third and fourth semesters of the curriculum at a university where other Engineering Design courses are scheduled in the first and second semesters and has a final examination is therefore shown in both the third and fourth course in Figure 4.

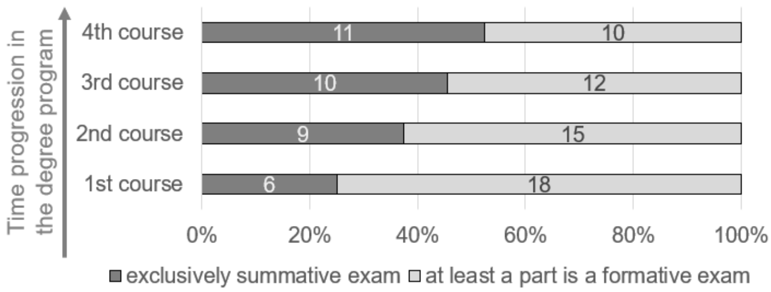

Figure 4. How learning content is assessed along the courses

The examinations are differentiated into an exclusively summative and at least a part formative exam. The summative examinations take place as written or, in one case, as a possible oral examination. The form of the written examination is on paper, via an online examination system or a combination of both after the lecture period. The formative examinations include the completion of one to six assignments during the lecture period and in most cases an additional final exam after the lecture period. This assessment type is typical in courses at the beginning of the degree program. Only six courses have a summative exam and 18 a rather formative exam. These rather formative Assessment Tasks are partly CAD tasks but also the completion of hand drawings. These tasks are in some cases completed by the students during the self-study time (as homework) and in some cases during the presence-study time. Some of these tasks are graded, but in some cases the completion of the task is sufficient for admission to a final exam. In the courses in the 4th semester eleven universities have a summative exam, while ten has a formative. This formative examination consists of the documentation of a design project, which is assessed as a portfolio. This is in some cases supplemented by an oral examination. When looking at how the Intended Learning Outcomes of the individual semesters are assessed, it becomes clear that overall, a summative final

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examination has been identified as suitable by the lecturers in less than half of the cases examined. Especially at the beginning of the degree program in the courses, the submission of drawings and CAD test certificates is an important part of the examination. As the degree program progresses, not only does the percentage of formative examinations decrease, but the type of formative examinations also changes from the submission of individual tasks to the documentation of a design project as a portfolio examination.

5. Discussion

The results for answering RQ 1 (To what extent is the same learning content at different universities addressed?) show a high level of agreement between the topics. Due to the similar content, the cross-university development and use of e-learning materials seems to make sense. However, the analysis of concrete learning outcomes for the individual topics, e.g. classified according to Bloom's taxonomy, is necessary for such a development. The analysis of existing Teaching and Learning Activities for RQ 2 (To what extent does individual support with adaptive e-learning in the self-study time at different universities seem to be appropriate […]?) shows that frontal lectures and self-study times remain dominant in Engineering Design courses. Lectures perceive initial knowledge heterogeneity as a challenge and provide individual support by supervising small groups, consulting hours, online self-assessments, and checking exercise solutions with a high level of personnel resources. The analysis of the assessment tasks for RQ 3 (To what extent do examination forms support the learning process and give students feedback on their performance?) shows that at some universities, only summative examinations are offered; at others, these are supplemented by formative components. As a result, the examinations do not always help students to reflect on their own learning progress. Automated personalized learning support like adaptive e-learning has not yet been used. Cross-university development and use appears to be a meaningful addition to the existing course formats due to the uniform learning content, existing Teaching and Learning Activities and forms of examination to offer individual feedback without a high level of personnel resources and help students structuring the high percentage of self-study time. The results are on the one hand based on the analysis of courses descriptions, which were selected based on the titles of the courses. The contents of the courses were checked, but it cannot be ruled out that Engineering Design courses are not included because they did not have a keyword in the title. Some of the course descriptions contain varying amounts of information. For example, at four universities the information on examination performance was too vague or incomplete, meaning that it could not be considered. In Figure 4, the examinations are grouped chronologically into exclusively summative and rather formative examinations. However, there are sometimes major differences in the type of examination performance as mentioned in section 4.3. However, a detailed quantifiable evaluation of the different examinations is not possible, as the lecturer survey provides much more detailed information on the type of examination than the evaluation of the course descriptions alone. The latest online and freely accessible versions of the curricula and course descriptions have been used for the analysis. The up-to-datedness of these documents could not be checked. When evaluating the proportion of self-study time, times in which students work on an engineering design project with the support of regular consultation hours are sometimes allocated. In contrast, at other universities, seminar rooms are made available for the work on projects and the completion of the project is therefore allocated to presence-study time. On the other hand, conclusions are drawn from qualitative interviews with lecturers. The lecturers were not able to provide information about all Engineering Design courses at the respective university, but obviously focused on their own lectures. Detailed information particularly for the first-year courses on technical drawing and the basics of machine elements is therefore only available for six of the twelve universities surveyed, whereas data from the lecturers' survey on second year courses is available for all twelve universities.

6. Conclusion

The learning content in Engineering Design Education appears to be very similar, at least at a higher level. Existing Teaching and Learning Activities have hardly changed in recent years, frontal lectures and self-study times are still dominant, even if these are often supplemented by small group exercises and consultation hours. Self-study times are assisted by e-learning material and exercises. Due to the regulations governing the internships required for the degree program, a high degree of knowledge heterogeneity among the participating students is to be expected and lecturers regard this as a challenge, especially at the beginning of the degree program. Reviewing exercise results and formative assessments offers individual feedback for the students but requires a high level of personnel resources. Therefore, we see the potential in an adaptive cross-university e-learning offer for Engineering Design courses. In a first step, the analysis focuses on the forms of teaching and not yet the detailed Intended Learning Outcomes. So, despite the intended standardization of teaching (e.g., through the Wissenschaftliche Gesellschaft für Produktentwicklung WiGeP e.V.,) and the use of frequently identical literature recommendations in the courses, the extent to which the courses and degree programs address the same Intended Learning Outcomes should be examined for cross-university development in a next step.

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