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Immersive Paths for Digital Product Engineering: Evaluation of a game-based virtual Gearbox Workshops in Mechanical Design Education

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Abstract: Product engineering and innovation management are going through a transformative phase towards the digital sphere, in which processes, methods and tools are increasingly anchored in the metaverse. The knowledge and effective use of immersive tools and the clear understanding of the possibilities and challenges of immersive product engineering are key aspects that have to be taken into account in the education of future product developers. This paper delves into the significance of immersive tools in engineering and the resulting educational challenges. It specifically investigates a virtual gearbox workshop with elements of game-based learning, comparing it with a traditional physical workshop for mechanical engineering students. Using open participant observation and the standardized NASA-TLX survey as a quantitative assessment tool, the study evaluates the effective transfer of technical, methodical, social and problem-solving skills. The analysis examines the suitability of virtual workshops for introducing new subjects, their compatibility with traditional methods, and the benefits of gamification, while recognizing their limitations.

Keywords: Product Engineering, Game-Based Learning, Mechanical Engineering Education, Virtual Gearbox Workshop

1 Introduction

Product engineering is currently undergoing a major transformation. Influences from artificial intelligence as well as virtual realities such as the metaverse will have a significant impact on the development and design process of products and give rise to new business models (Lass, 2022). We are experiencing a transformation towards digital product engineering in which new, virtual methods are being introduced. A significant proportion of future product engineering will take place in metaverse. The metaverse offers a virtual environment in which creativity, technology and location-distributed collaboration can be realized in an unprecedented way (Rospigliosi, 2022; Tayal et al., 2022).

The metaverse offers a comprehensive, immersive experience that transcends the traditional boundaries of CAD, CAE and digital twins, uniting diverse spaces of action on the Internet and has the potential to represent an alternative to physical reality in a future iteration of the Internet. While virtual testing and simulation have existed for a long time, the metaverse enables integration and interaction on a whole new dimension. It provides a common platform where people from different cultural backgrounds and expertise can come together to exchange ideas, interact and collaborate. Heterogeneous domains and disciplines of different cooperating companies can identify and iteratively integrate needs and user experience at an early stage of product development. Thanks to its versatility and immersive character, the metaverse has the potential to accelerate innovation and drive product development forward. The metaverse promises an immersive environment where ideas can be brought to life through a virtual reality. Virtual prototypes and product designs can be tested, validated and further developed even before physical models are created (Dueser et al., 2023; Essen et al., 2023).

Even after the COVID-19 pandemic, the metaverse and digital educational programmes offer numerous benefits for the tertiary education sector and the metaverse education sector is experiencing a growth rate of approximately 40 %. Global collaboration allows students and teachers from different parts of the world to work together and learn from each other in real time. Personalized learning is made possible by technologies such as AI, which can personalize learning paths and adapt them to the needs of each student. With Extended Reality, students can gain hands-on experience in different subject areas, which can increase their engagement and motivation. In addition, the metaverse offers an opportunity for a continuous educational experience and the possibility of lifelong learning, as professional skills need to be constantly refreshed and adapted to current demands. It opens up opportunities for simultaneous and live participation in events worldwide and promotes a convergence of education, technology, entertainment and gaming. Universities have the potential to play a role as enablers of learning experiences in this new universe. The interoperability of data and digital objects offers scope for new business models and new, digital product development (Olderog, 2022; Bildung im Metaverse, 2024).

The new emerging technologies and the metaverse are opening new spaces for the new generation of designers. It is essential to familiarize them with the use, potential but also the limiting restrictions of the metaverse and digital product development early on in their educational path (Ricci et al., 2023). This research aims to assess the effectiveness of a virtual gearbox workshop as a didactic supplement compared to its physical counterpart. It investigates whether the virtual workshop adequately replicates the learning content and skills taught in the physical workshop, and whether it also enhances virtual development skills while highlighting the benefits and limitations of digital product engineering. The subchapters of the introduction start with explaining digital product development in engineering education to give insights into the research context of this contribution. On this basis, the current teaching model and physical workshop is explained, particularly with regard to the educational objectives and the expected acquisition of competencies, before the new digital workshop which still needs to be evaluated concept is presented.

1.1 Digital product engineering in engineering education

It is essential that students, as the product developers and designers of tomorrow, come into contact with the possibilities and opportunities, but also the restrictions and limitations of digital product engineering and its virtual methods and tools. For this reason, students at the Institute of Product Engineering (IPEK) of Karlsruhe Institute of Technology (KIT) in the fundamental engineering lecture Mechanical Design (MD) are taught specific key competencies based on future skills in accordance with the Karlsruhe Education Model of Product Engineering (KaLeP) (Breitschuh et al., 2014). MD is offered in the engineering and natural science Bachelor degree programs Mechanical Engineering, Chemical Engineering and Process Engineering, Technical Mathematics, Mathematics, Industrial Engineering, Mechatronics and Information Technology, Technical Economics and in the educational science degree programs Natural Science and Technology and Engineering Pedagogics. The approximately 650 students are introduced to the basic content of machine design and construction. The focus is on analyzing existing systems and gaining an understanding of the fundamental elements and functions of technical systems. The course is divided into the subject areas of springs, technical systems, bearings and bearing supports, seals, component connections and gears.

The overarching aim is to acquire skills using key examples and key models, such as the spur gear. This addresses the ability to transfer what has been learned to other technical systems, including those not familiar from the lecture. In this way, the ability to independently analyze unknown systems and synthesize new solutions and, in particular, the necessary skills are encouraged.

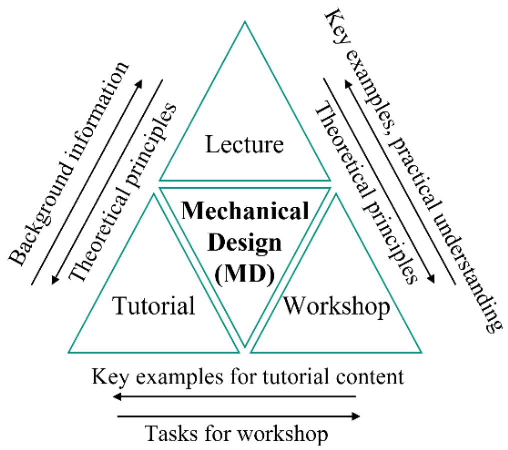


Figure 1. Structural organization of the course Mechanical Design

As shown in Figure 1, in addition to the lecture, students are introduced to design and construction in a three-part on-site workshop series. The overarching teaching goal in lectures, exercises and workshops is to impart the fundamentals of the competence field of development and design in relation to processes, technical systems and system elements, as well as the development and expansion of the students' personal competence profile. The combined MD content serves as a connecting element to various lectures in the advanced semesters of the students. The students' personal skills and competencies profile is promoted in the lectures, exercises and especially in the workshops, and the students' performance in the team is monitored on this basis. The curriculum-based workshop plays a decisive role in this respect. It is the only element of teaching in which students participate actively and as part of a team, thereby proactively demonstrating and developing their competencies and aptitudes. From the outset, the aim is not to replace the physical workshop with a purely virtual workshop, as decision-making skills and other competencies can only be acquired by applying knowledge in real, complex projects (Breitschuh et al., 2014; Matthiesen et al., 2017). It is rather to create a complementary opportunity that conveys the engineering knowledge and competencies imparted in the real workshop and also raises awareness of the benefits and limitations of virtual product engineering.

1.2 Competence transfer and onsite physical workshop structure

Lectures, tutorials and workshops jointly pursue the teaching of key competencies and future skills, which are described in Figure 2 by five overarching competence dimensions (Breitschuh et al., 2014). These competence dimensions form the didactic framework and, so to speak, the foundation not only of the physical workshop, but of the entire university engineering education at IPEK. A virtual workshop and all future educational concepts that aim to teach digital product engineering and the use of the metaverse must be based on those competence dimensions and establish synergies. The skills are explained below and their transfer in the physical workshop is explained. The newly developed, game-based virtual workshop is then evaluated in comparison.

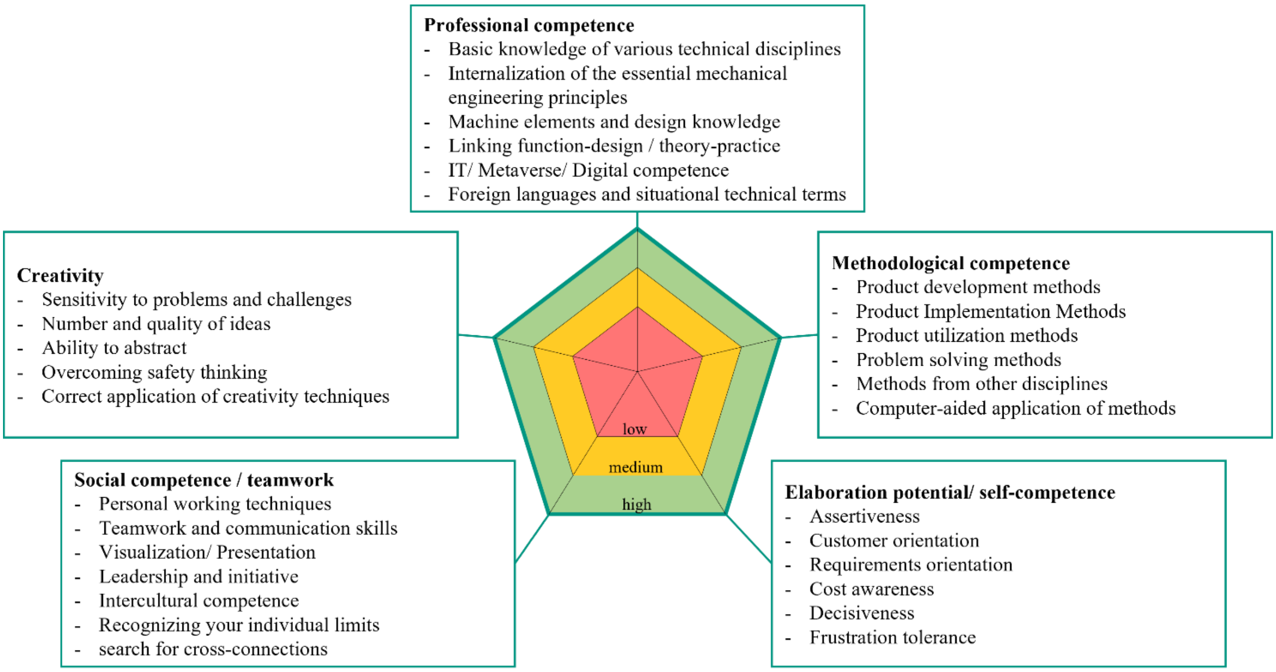
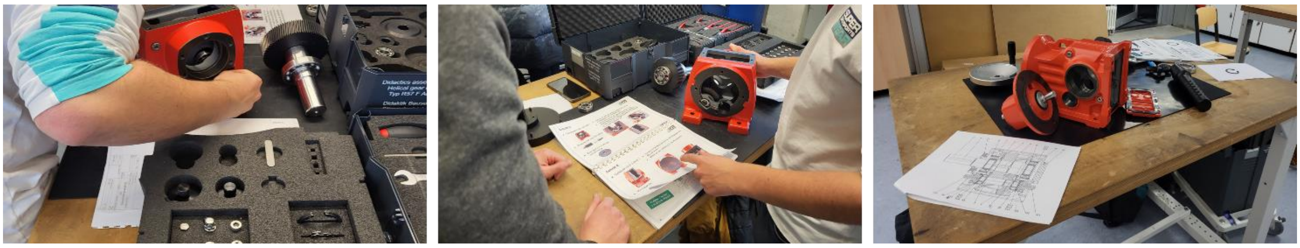


Figure 2. Five-Dimension Competence Model

These five dimensions of competence also serve as assessment dimensions with which students can be given specific feedback on their individual and group performance in the workshop. The competence dimensions developed are based on specific learning frameworks (Breitschuh et al., 2014) and industrial experience (Hassan, 2014; Matthiesen et al., 2017). Participation in the lecture accompanying workshop with three project sessions is mandatory. Knowledge from the lecture is tested in colloquia at the beginning of the project session. Passing the colloquia and completing the workshop assignment is a requirement for successful participation in the written MD exam. In regards to content, the students analyze, assemble and disassemble a spur gear and a bevel gear. Picture 1 shows the assembly of the spur gear during the physical workshop.


Picture 1. Assembly of the spur gearbox in the physical workshop

2 State of the Art

A significant amount of product engineering in the 21st century will take place in the metaverse. Today, there are already various areas in product engineering with innovation processes where metaverse-based approaches offer support. It is essential that students are taught about the opportunities, possibilities and limitations of digital product engineering and the metaverse and experience them in the field (Dueser et al., 2023).

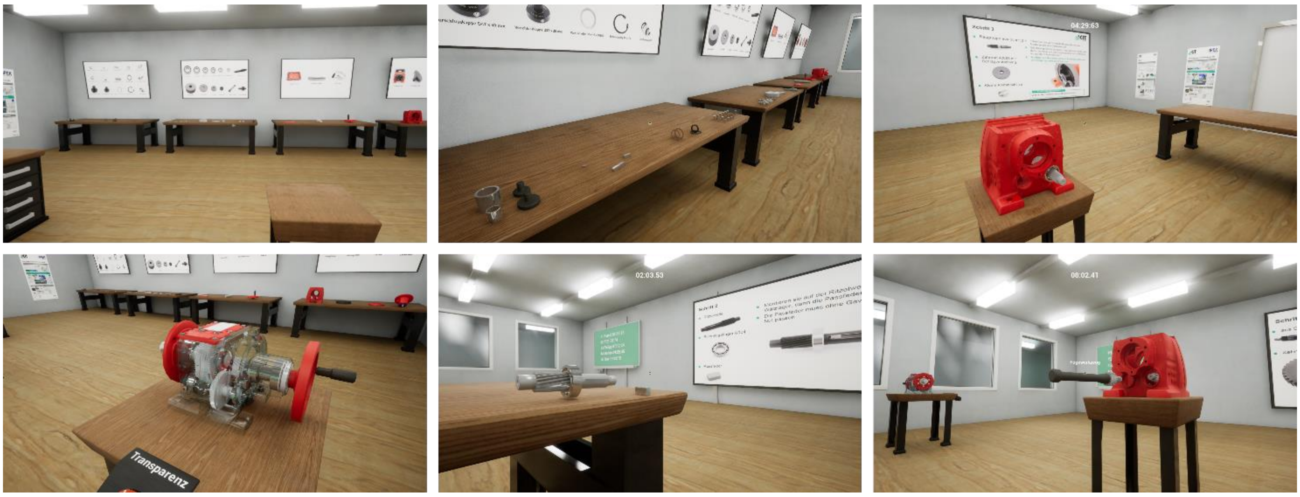
Digital tools are becoming increasingly important in education due to the COVID-19 pandemic. One learning strategy that can be implemented with the help of digital media is the integration of game-based elements in a context free of games. Because everyday use of computer games by children and young people is constantly increasing, it can be concluded that gamification is playing an increasingly important role in educational contexts (Schuldt, 2020). Learning games should be preceded by a specific learning objective while retaining the game character. The gamification approach is proving to be useful and promises potential in terms of learning success. For example, skills conducive to learning are developed and encouraged. Furthermore, educational games have been shown to increase motivation, especially intrinsic motivation

(Wilson et al., 2009). It has also been established that people react differently to games and certain gamification elements (Bartle, 1996).

By integrating gamification elements into the learning process, learners can be motivated to actively participate in the learning process through game mechanics such as point systems, rewards and achievement levels, leading to an increase in motivation and engagement. This improved engagement can in turn lead to a better understanding of the learning content as learners are motivated to engage more deeply with the material, leading to improved learning outcomes. In addition, gamification encourages social interactions, whether through cooperative tasks or competition among learners, which in turn contributes to improved learning outcomes. Games often provide a safe environment in which learners can make mistakes and learn from them without worrying about negative consequences, which can increase willingness to learn and boost self-confidence. (Epema and Iosup, 2014; Wiggins, 2016; Cudney and Subbash, 2016)

Moreover, to harness the potential of digital tools in education and address the evolving landscape of learning methodologies, innovative approaches such as gamification have gained prominence. A digital gearbox workshop was developed for this purpose, in which students analyze, assemble and disassemble technical systems and get in touch with the technical system and their properties. The digital learning application is the result of a final thesis in cooperation between IPEK at KIT with SRH University of Applied Sciences Heidelberg (Amar, 2023). IPEK provided the didactic framework concept and the mechanical engineering tasks, while SRH designed the gamified virtual environment. In the long term, the virtual workshop will also be offered to students as a supplementary voluntary offer, serving as a digital and immersive tool. The application is designed for virtual reality glasses. However, due to the large number of students, conventional computers with mouse and keyboard controls are used in this study. In the virtual space, students can completely assemble a spur gear from scratch. The digital workshop is implemented as a game in which the players have to assemble the gearbox under a running timer. The timer runs until the gearbox is completely assembled. The player can also choose between two levels of difficulty. The environment realistically represents a workshop room in whose surroundings the physical workshop also takes place. The components are systematically arranged according to subassemblies on workbenches and labeled accordingly on illustrations hanging on the walls. Assembly tables provide space to first assemble individual components and then the entire spur gear.

The next assembly step is always shown on a further illustration. Players can use a complete gearbox as a guide, the housing of which can be displayed transparently at the touch of a button to illustrate the internal arrangement of the components. There are two more screens in the room. One screen shows the assembly instructions described in individual work steps. The second screen functions as a leaderboard and shows the ranking list with the 5 fastest players, which are ranked by name and time. The leaderboard function and the two difficulty levels have been implemented as gamification elements and have already been successfully evaluated. First, the gearbox housing is placed on a table and then the necessary components are installed in the gearbox housing step by step using the pick and place function. Some components must first be pre-assembled on another table. Picture 2 shows various scenes from the virtual gearbox workshop (Amar, 2023).



Picture 2. Scenes from the virtual gearbox workshop

Before delving into the assessment of game-based learning elements like the introduced virtual gearbox workshop, it is important to note that the already developed virtual workshop has not yet been implemented in a regular environment, namely an ongoing semester with MD students, embedded in the regular lecture, exercise, and physical workshop schedule. There is insufficient evidence as to whether game-based learning elements such as the introduced virtual gearbox workshop are suitable for promoting and transferring the required competence profiles from Figure 2 and to what extent a virtual, gamified workshop in the tertiary education sector can demonstrate the possibilities, but also the limitations, of digital product engineering in complement to an onsite physical workshop.

3 Research Approach

The purpose of this research is to determine the extent to which a virtual gearbox workshop can replicate a physical gearbox workshop and act as a didactic supplement. Although preliminary considerations and assumptions were already made during the planning phase of the virtual workshop, however, the virtual and physical workshops have not yet been compared in reality. It is examined whether the learning content and skills taught in the physical workshop are also reflected in the virtual workshop and whether the virtual workshop additionally reflects virtual development skills as well as the benefits and limitations of digital product engineering. The current state of the art leads to the need to answer the following research questions:

• First research question (RQ1): What skills can be taught and encouraged in a virtual workshop?

• Second research question (RQ2): When is the most appropriate timing of the virtual workshop in relation to the physical workshop?

• Third research question (RQ3): Can the virtual workshop function as a complementary activity to the physical workshop?

The focus of the research approach is on the development of new hypotheses of the facts under investigation and is suitable for the purpose of the study. In practice, the approach enables research to be as transparent and adaptable as possible. The available capacity in the form of test participants is utilized in order to achieve a high density of data and information. In order to underpin the open approach, the data is collected using both qualitative and quantitative methods (Döring and Bortz, 2015).

3.1 Participant observation and description of participant groups

To answer research questions RQ1, RQ2 and RQ3, a participant observation of a total of 59 students who completed both the virtual and physical workshop was conducted. To answer RQ2, the students are divided into three test groups, depending on whether the virtual workshop was completed first followed by the physical workshop, or vice versa, or whether the virtual workshop was completed before and after the physical workshop. The qualitative open participant observation (Lindenmann, 1924), which is a method of field research in the social sciences. Through special proximity to the test person, insights are gained into the actions, behavior or impacts of behavior. With the help of participant observation, the actions and behaviors of the participants can be continuously mapped over time. Participant observation is suitable as a non-reactive method to avoid distortions, for example due to self-presentation by the students (Döring and Bortz, 2015). Participant observation is implemented in all test groups with the help of 11 different observing tutors during the digital workshop. The tutors each observe a randomly selected participant and use an observation protocol designed for the digital workshop as a guide. All tutors are familiar with the subject matter so that they are able to provide assistance in the event of any queries from students and carry out the participant observation in an appropriately structured manner. The respective notes on the observation protocol are standardized for the intended qualitative content analysis through the prior briefing. All tutors were therefore briefed on the content of the observation and the wording to be used on the provided observation protocol before the observation was carried out. The temporal and situational conditions during the workshop are constant.

The study comprises a total of three test groups, each with 40 participants and a control group with 169 participants. The number of test groups serves the goal of generating data that is as diversified as feasible. In addition, the division into three groups is mandatory for the research questions under investigation. All groups consist of students who are required to take part in the mandatory lecture-accompanying gearbox workshop. The selection of participants for all subject groups is random. Gender, age, semester and study degree are equally distributed in the test and control groups.

Test group A first completes the digital workshop and then the physical workshop. Once the students have completed the digital workshop, they immediately answer a survey relating to the digital workshop. After completing the physical workshop, they answer the NASA-TLX survey. Test group A comprises 40 students, 20 of whom were observed.

Test group B completes the digital workshop at the end of the physical workshop. This group also answers a survey directly after the digital workshop. This is the same survey as in test group A. The NASA-TLX survey is also completed after both workshops. Test group B comprises 40 students, 20 of whom were observed.

Test group C is the only group to complete the digital workshop twice. Once before the physical workshop and once after it. After each run of the digital workshop, the survey on the digital workshop is completed. This test group also receives the same survey as groups A and B. The NASA-TLX survey is also completed after the virtual and physical workshops. Test group C comprises 40 students, 19 of whom were observed.

The control group comprises 169 students who only complete the physical workshop. The control group then answers the NASA-TLX survey.

3.2 Surveys

Two different surveys were conducted in terms of content and time. Surveys in the form of questionnaires are suitable as a reactive method for obtaining direct feedback from the study participants in order to answer RQ2 and RQ3 in addition to the participation observation. From this, generalized statements about the reality of experience can be obtained (Döring and Bortz, 2015). One is a qualitative, partially standardized survey used exclusively for the digital workshop for the response to RQ2. The survey consists of factual questions (age, gender, course of study, semester, etc.) as well as open questions aimed in particular at the timing of the workshop, gamification elements and improvements and challenges of the digital workshop. Questions from the quantitative standardized survey NASA Task Load Index (Hart and Staveland, 1988; Hart, 2006), which is assigned to the human factor methods, are used for the survey of the overall workshop and is used for answering RQ3. The NASA-TLX is a multi-dimensional subjective workload assessment rating tool that gives an overall workload rating based upon a weighted average of six workload sub-scale ratings. The choice of questions for the NASA-TLX is based on the intended comparison of the participants from test groups A, B and C with the control group in terms of mental demand, temporal demand, physical demand, effort and frustration level:

- Mental demand: How much mental demand and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
- Physical demand: How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
- Temporal demand: How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
- Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?
- Frustration level: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

The NASA-TLX survey including the five sub-scales is presented to the participants after the physical workshop. They are asked to rate their score based upon an interval scale divided into 20 intervals, ranging from low (1) to high (20) (Stanton et al., 2013). The question of performance, which is included in the original NASA-TLX, is not asked in this survey. As the physical workshop is not graded and the virtual workshop is a supplementary voluntary offer, the focus of this study is not on recording performance. This survey is also intended to examine any differences in perception with regard to the overall workshop that may arise as a result of the digital workshop. Furthermore, the methodology ensures reproducibility (Stanton et al., 2013).

4 Evaluation and Results

The study results are explained below, sorted according to the research questions.

4.1 RQ1: What skills can be taught and encouraged in a virtual workshop?

Following the participant observation, a qualitative content analysis is carried out (Kuckartz, 2016). This evaluation process comprises several consecutive steps:

Step 1: Development of evaluation categories

Step 2: Creation of a coding guide

Step 3: Coding of the content

Step 4: Quantifying summary of content

The most frequently mentioned categories are shown in Figure 3. In the observation sheets, the observing tutors repeatedly describe elements that can be assigned to different competencies or superordinate thematic clusters. The coding guide was created using the previously developed evaluation categories. It leads to a quantifiable representation of the observed thematic clusters. These can be classified into three sections: the fields of competence and the positive and negative factors.

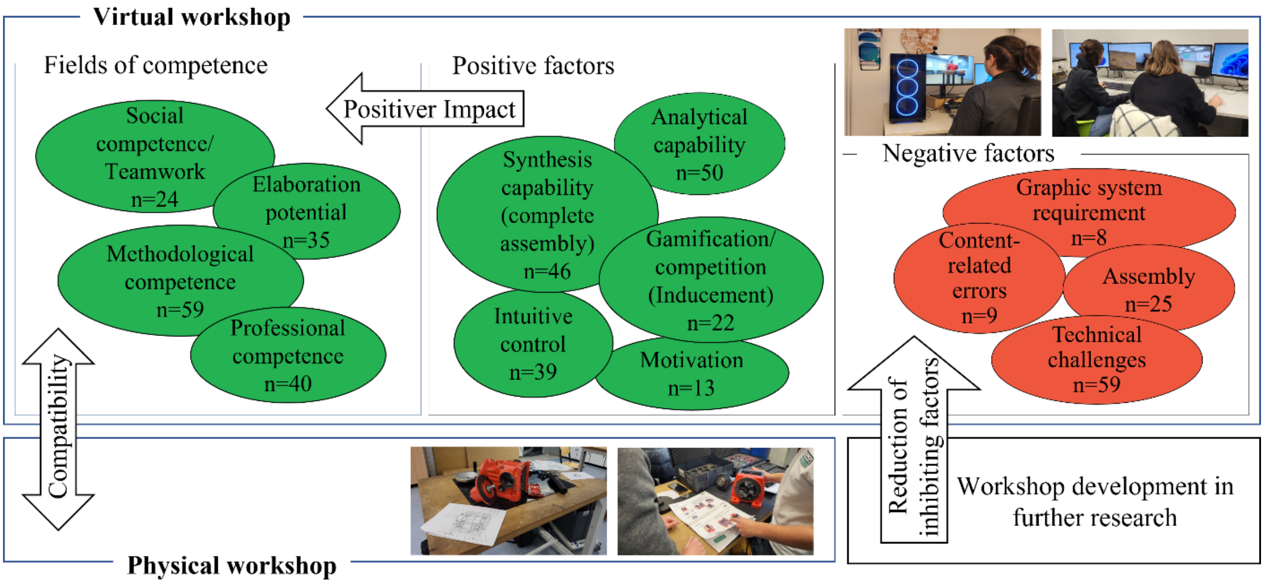


Figure 3. Results of the qualitative content analysis of the open participant observation (sum of all test groups)

Social competence is exhibited by 24 observed students, which is evident, for instance, in their interactions and mutual support during the workshop. Potential for elaboration is displayed by 35 students, as seen in their frustration tolerance, resilience and willingness to retry after encountering assembly errors. Methodical competence is evident in all observed participants through their interaction and adeptness in navigating virtual reality. Professional competence is demonstrated by 40 students, for example by applying the knowledge taught in the lecture and putting it into practice.

In addition to the field of competence, positive factors are also identified: Synthesis capability through a successful complete assembly is demonstrated by 46 students. Analytical capability, exemplified by the correct pre-assembly of gears, feather keys, and shafts, is demonstrated by 50 students. It is observed that 22 students are encouraged, for example by looking at the leaderboard and trying to assemble the gearbox correctly in a shorter time. Without consulting the instructions first, 39 students intuitively use the game control. Motivated behavior, such as persistently attempting tasks again after making mistakes and showing interest, commitment, and initiative, is demonstrated by 13 students.

Negative observations include 8 students frustrated by graphic resolution and occasional motion stuttering. Content errors affect 9 students, such as incorrect component labeling in user instructions. Students' frustration with limited assembly flexibility is highlighted in 25 instances. All students encounter technical challenges; for example, the feather key proves difficult to align in its intended notch during gameplay. Furthermore, the competence dimension of creativity, which is presented in Figure 2, is not observed. The predefined assembly steps do not create any alternative courses of action in which students could contribute creativity skills.

4.2 RQ2: When is the most appropriate timing of the virtual workshop in relation to the physical workshop?

Immediately after the virtual workshop, the students in test group C, namely those who completed the virtual workshop before and after the physical workshop, were asked about the ideal timing of the virtual workshop. 46 % of students found the digital workshop after the physical workshop to be more helpful. Some students have verbally stated that they find it easier if they have already had contact with the individual components of the gearbox beforehand, i.e. in the physical workshop. The gearbox is only fully assembled for the first time in the third and final session of the physical workshop. This makes it easier for the students to subsequently assemble the gearbox in the virtual workshop. 31 % consider the virtual workshop to be more useful before the physical workshop. 8 % of the participants had no preference and 15 % did not state a preference.

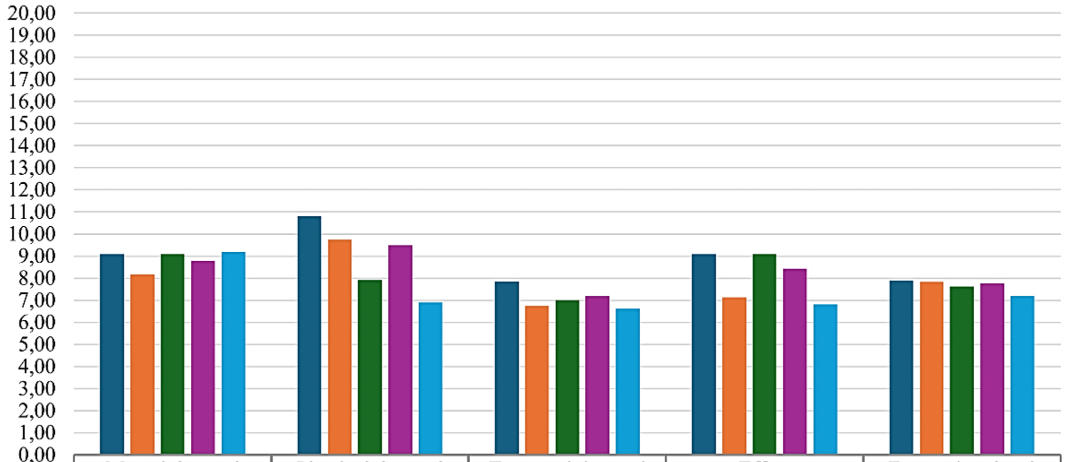
The results of the participant observation also confirm this thesis. The participants from test groups B and C, i.e. the groups that completed the virtual workshop at the end, have fewer problems overall with navigating and controlling in the virtual workshop than the participants from test group A, that conducted the virtual workshop before the physical one. Furthermore, there is a tendency in test group B and C for the inducement to assemble the gearbox in the shortest possible time. This could also be due to the fact that the students already know the procedure from the physical workshop and can apply their knowledge in the virtual workshop. The participants in test groups B and C are more committed to achieve a new high score through the fastest complete gearbox assembly. In these test groups, the gamification aspect of the leaderboard is observed the most and the students are motivated through this. Moreover, the time required for the final assembly of the gearbox shows that the students in groups B and C are on average 4:30 minutes faster than test group A. In comparison, more students from these groups also successfully complete the virtual workshop than in test group A.

Consequently, it makes more sense to implement the virtual workshop after the third and final session of the physical workshop.

4.3 RQ3: Can the virtual workshop function as a complementary activity to the physical workshop?

The third research question can be answered with a yes. The virtual workshop can be a useful supplement and extension to the physical workshop. While in the physical workshop, the gearbox assembly can be carried out using different approaches and creative solutions, in the virtual workshop, the assembly instructions are carried out step by step. Comparing the competence dimensions from Figure 2, which are included in the physical workshop, with the observed competencies in the virtual workshop, shown in Figure 3, it can be concluded that, with the exception of creativity, the same competencies can be observed in game-based virtual workshop. In particular, the fact that the virtual workshop does not have to be held on site, but that students can carry it out from home to practice and repeat what they have learned in the physical workshop, is a beneficial aspect.

The evaluation of the NASA-TLX questions, which is shown in Figure 4, indicates no significant differences in workload between test groups A, B, C and the control group The NASA-TLX survey was completed by 83 participants across all test groups and 169 participants of the control group. It is noticeable that not all students in the test groups completed the NASA-TLX survey in full. The survey is voluntary and the difference may be due to a possible lack of interest. The calculated average values for mental demand, time pressure, physical activity, effort and frustration all fall within a range of 6.6 to 10.8. The virtual workshop and the physical workshop are therefore comparable. The virtual workshop can be seen as a complementary offer and both formats are pedagogically compatible due to the similar workload. This allows the competence dimensions and, especially, the haptic aspects of the established physical workshop to be taught together with the competence dimensions and the new virtual experience of the game-based virtual workshop. Both workshops can be taught in symbiosis with each other.



	Mental demand	Physical demand	Temporal demand	Effort	Frustration level
Test group A	9,09	10,80	7,86	9,08	7,89
Test group B	8,17	9,74	6,74	7,13	7,83
Test group C	9,08	7,92	7,00	9,08	7,61
Average of test group	8,78	9,49	7,20	8,43	7,78
Control group	9,19	6,90	6,62	6,80	7,19

Figure 4. Evaluation of the NASA-TLX with average values (0-20) according to participant group and sub-scale

5 Conclusion

Participant observation shows that, with the exception of creativity competence, all other competence dimensions are also included in the virtual workshop. In addition, this game-based workshop teaches virtual development skills and demonstrates to MD students the possibilities and limitations of such a virtual workshop and the digital product development tools it offers (RQ1). The participant observation and the survey directly following the virtual workshop show the ideal timing of the virtual workshop is after completion of the physical workshop (RQ2). Here, students can apply and repeat the skills and knowledge gained in the physical workshop. The NASA-TLX indicates that both workshops exhibit similarity in terms of workload, suggesting that the virtual workshop can complement the physical workshop as an additional teaching element (RQ3).

In summary, the presented results indicates that the virtual workshop is a suitable supplement to the physical workshop. The gamification of the virtual workshop has the potential to increase the motivation of the students. It is also positive to mention that the majority of participants had no problems with the game interface and control. By working through the virtual workshop, students can develop, promote and implement various skills. The evaluation shows that the virtual workshop is best placed after the physical workshop. It can therefore be used didactically to intensify and repeat knowledge.

However, the observation also shows where the virtual workshop has its limitations. All participants faced technical challenges, for example when placing items with a particularly small drop area. The observation clearly showed that time and motivation was lost in the virtual workshop due to these challenges. In particular, the inability to use the sense of touch to enable active comprehension was problematic. Furthermore, the constrained movement, the limited effective degrees of freedom and the insufficient realistic assembly of the individual components show a major difference to the real workshop and thus the technical limits of digital product engineering and digital engineering teaching in higher education with the current stage of development.

The study illustrates that while the virtual workshop presents certain limitations, it cannot fully substitute the physical workshop due to technical challenges and digital assembly constraints. The handling limitations underscore the distinctions between virtual and actual gearbox assembly, with the current inability to replicate the haptic experience students encounter in physical settings. Moreover, precise assembly techniques are substituted by the "place and drop" function, and certain assembly tools, like snap ring pliers for circlips assembly, are absent in the virtual environment.

The research results make it clear that the benefits of the virtual workshop are substantial. In particular, the virtual workshop offers the opportunity to apply and promote social competence, digital competence, frustration tolerance, and methodological competence. Additionally, it serves as a platform for developing synthesis capability, which is the overarching aim of the MD curriculum.

However, there are no plans to replace the physical workshop by the virtual workshop. The physical workshop is an integral part of the curriculum and a mandatory prerequisite for participation in the exam. In particular, the haptic learning process, in which the student's tactile or kinesthetic sensory system is activated through touch, movement or practical action, is an essential component in the transfer of knowledge and skills. On one hand, the physical workshop uses haptic feedback to absorb and process information through physical interaction with objects, tools or materials and, on the other hand, the virtual workshop demonstrates the opportunities but also the limitations of an implementation in the metaverse.

The study design also shows potential for improvement, which must be implemented in particular in the future research. For example, the number of participants in the test groups and the control group are different. There is also a longer period of time between the evaluation with the NASA-TLX survey and the implementation of the virtual workshop for the participants from test group A than for the participants of test groups B and C. Furthermore, participant observation is not objective due to possible biases or prejudices of the observing tutors. Although the prior instruction and briefing of the tutors attempts to minimize this bias, it cannot be completely avoided.

6 Outlook

The continuous optimization of the virtual workshop promises the prospect of an even more appealing gaming experience for students and, at the same time, potentially greater success in their teaching. By integrating further gamification elements such as a reward system or the introduction of a multiplayer mode, the game will become more diverse and appeal to different types of players. At the same time, a multiplayer mode and team chat will contribute to the students' social skills. To make the gaming experience even more immersive and at the same time encourage movement, the development of augmented reality application for mobile devices can be considered. The revision of the game graphics and the technical challenges described also offer the opportunity to make the virtual workshop even more effective and appealing. In order to create even more proximity to the physical workshop, the bevel gearbox could be integrated virtually as an additional type of gearbox. More options, the implementation of side quests and different decision paths and solutions should also encourage the creativity that has been absent to date. The optimization of the virtual workshop can then be tested using a standardized survey for game-based teaching. A more homogeneous sample size will allow clearer statements to be made in the further course of the research. Through further research and the constant technical and content-related revision of the virtual workshop, it can become part of the curriculum in the long term.

The challenges of implementing the metaverse in the tertiary education sector must also be addressed in the future. Technological access must be made possible for all students so that no digital gap can arise. The acceptance of educational institutions and educators towards new technologies and methods must also be established and expanded, and technical hurdles and errors must be eliminated. It is crucial to identify these challenges and develop suitable methods and strategies to ensure that the potential of the metaverse can be fully realized for educational purposes and that digital product development is sustainably incorporated into current education.

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