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Opportunities and Shortcomings of Model-based Online Laboratories in Mechanical Engineering – Findings from a Guided Laboratory Study

Abstract

During the coronavirus crisis, labs had to be offered in digital form in mechanical engineering at short notice. For this purpose, digital twins of more complex test benches in the field of fluid energy machines were used in the mechanical engineering course, with which the students were able to interact remotely to obtain measurement data. The concept of the respective lab was revised with regard to its implementation as a remote laboratory. Fortunately, real-world labs were able to be fully replaced by remote labs. Student perceptions of remote labs were mostly positive. This paper explains the concept and design of the digital twins and the lab as well as the layout, procedure, and finally the results of the accompanying evaluation. However, the implementation of the digital twins to date does not yet include features that address the tactile experience of working in real-world labs.

Keywords

Remote, Model-Based Laboratory; Digital Twin; Evaluation Survey

1 Introduction

In the summer semester of 2020, due to the coronavirus pandemic, key teaching labs in courses such as mechanical engineering could not be held as face-to-face labs. This also affected multifaceted labs offered in advanced study programs. The complexity of these laboratories also stems from the combination of several disciplines. This results in students having to become familiar with test benches which, alone in terms of the number of components used, go beyond laboratory test benches as used in basic studies. In addition to subject-specific skills, personal skills are also addressed—for example, communication skills and coping with tasks in group work.

The face-to-face laboratory "Fluid Machinery" in the bachelor's degree program in mechanical engineering at Offenburg University of Applied

Sciences also had to be replaced by a virtual laboratory. The implementation of the laboratory experiment was solved via a so-called digital twin. The corresponding technical concept is explained in detail below. The question now arose as to what extent the virtual laboratory offered the same impetus for students to acquire skills—perhaps even opening up new perspectives—or whether important incentives were simply lacking. The main focus in the summer semester of 2020 was on ensuring that the virtual lab was available in the first place; the above questions were then investigated in the winter semester of 2020/2021 by researchers conducting extensive surveys to accompany the course.

2 General concept of the laboratory

It has already been mentioned above that the concept of the course is multifaceted.

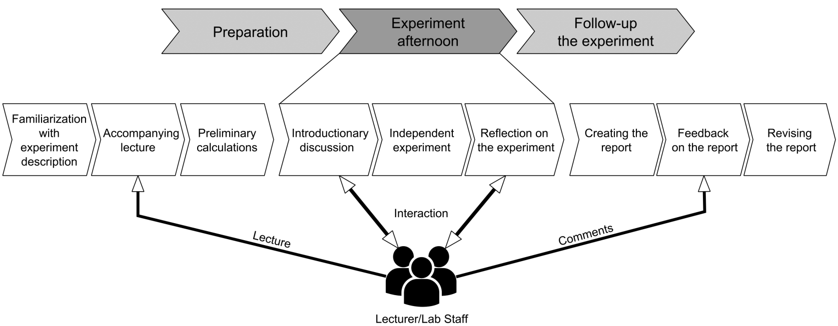


Figure 1: Follow-up of the different phases of the Laboratory from preparation to revision of lab reports.

On the timeline, there is a sweep from the preparation of the experiments to the feedback to be given on the experimental reports which have to be compiled about the experiments.

In principle, these elements were able to be retained in the implementation of the virtual lab. However, the discussion on the test benches could not take place in the real laboratory. Therefore, presentations were prepared with photographs, flow diagrams, and schematic diagrams in order to provide the students with a link to the real systems.

The lecturers had the impression that, also with this format, cognitive activation of theoretical prior knowledge was possible through a classroom discussion, as is also carried out in a real laboratory. Student perceptions were asked for in the surveys discussed below. An obvious deficiency of the virtual laboratory is that the students do not have tactile access to the test rigs. In the further course of the laboratory afternoon, however, the students succeeded in understanding the digital twins of the laboratory experiments with the result that they were able to carry out the laboratory experiments independently. As in a real laboratory, the lecturers follow the students during the implementation of the virtual lab and provide ideas through interim questions by encouraging the students to reflect on and explain their strategies and decisions during their actions. In addition, these questions stimulate the linking of the work in the laboratory to the theoretical basis discussed in the lecture. In this phase, the students work actively together in laboratory groups of two to three participants. The students have to organize themselves in carrying out the laboratory test. For example, they have to agree on who will use which strategy to set the parameters in the virtual test facility, who will document the values measured, and who will be responsible for ensuring the plausibility of the measurement results.

In addition, they have to agree on who in the group will respond to the lecturer's questions and, if necessary, support each other in answering them. After the experiments, a joint discussion on the results takes place. This has the particular goal of cementing the knowledge gained with regard to the theoretical foundation from the lecture. At the end of the afternoon in the laboratory, this discussion leads to a conversation about the expected content and form of the report. When creating the report, additional skills such as the evaluation of data, theoretical modeling, and the presentation of results are addressed. The students have several weeks to prepare the reports. As a rule, these are created based on a division of labor. The students receive critical comments from the lecturers on the content and form of the reports. If necessary, the reports must be corrected until a minimum standard is reached, which is sufficient for the laboratory certificate. From the lecturer's point of view, this last section (the creation of the reports and their critical discussion) is independent of whether a real laboratory or a virtual laboratory is used.

3 Digital twin as a means to a virtual laboratory

3.1 Digital Twin concept

Besides classical hands-on laboratories, other lab types have been established in recent years, such as purely virtual labs and remote labs, in which lab installations are remotely controlled by students (Ortelt et al., 2021). In addition, a mixture of these elements is possible, which can be labeled as hybrid laboratories (Zapata-Rivera and Larrondo-Petrie, 2016).

The digital twin concept is a relatively new development originating from product lifecycle management (Grieves and Vickers, 2017) and is often described as a crucial element in the context of digitization/industry 4.0. (Jones et al., 2020). Such a digital twin is a digital representation of an object in the real world including all its properties, information, and behaviour (Haag and Anderl, 2018 ; Adamenko et al., 2020). The main difference from usual digital models is the data exchange between the physical object and model in both directions (Kritzinger et al., 2018). Due to this direct physical-to-virtual connection, the application of digital twins is also advantageous within a modern lab concept.

3.2 Design of the Digital Twin in the machine lab

In the machine lab, the implementation process starts with the first prototype dealing with the radial fan test rig of the machine lab (García, 2019). Figure 2 gives an overview of the digital twin concept, including the main data streams occurring during its operation.

The digital twin itself was created by using the multidisciplinary modeling language "Modelica" within the commercial environment “Dymola”. The communication between the digital model and the data acquisition (DAQ-) software of the rig (“LabVIEW”) was the main obstacle in the development but was finally realized by using the Middleware TISC Simulation Server (Kossel et al., 2006). By comparing model results and values measured, the developers continuously improved the digital twin until the model and test rig showed almost the same operating characteristics and reproduced process values in high agreement.

As can be seen in Figure 2, the digital twin may be operated in two ways using different graphical user interfaces (GUI). On-site in the machine lab, the digital twin and real test rig may be operated in parallel, exchanging the necessary information in real time. In contrast, the digital laboratory events are carried out solely with the model using the GUI of the simulation

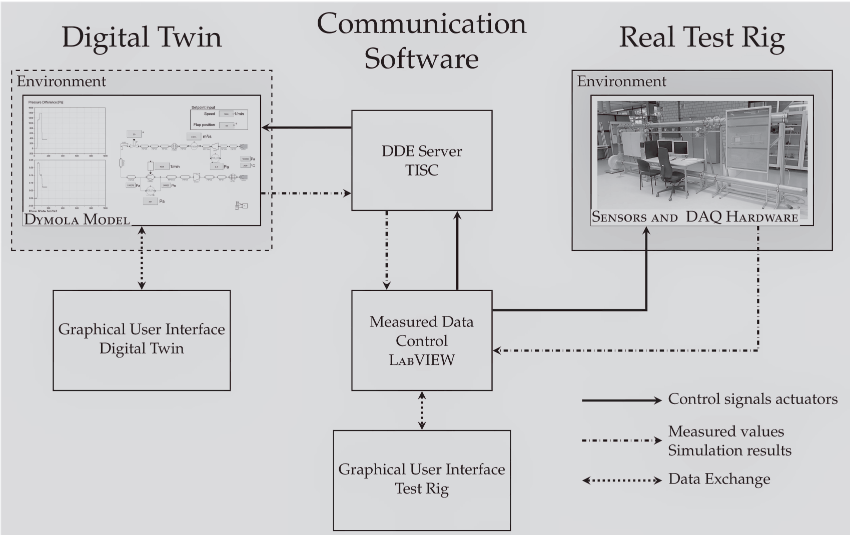


Figure 2: Basic scheme of the digital twin radial ventilator test rig in the fluid machinery lab at Offenburg University

environment. The design of the GUI allows the digital twin to be operated in the same manner and produces the same results as the facilities in the real laboratory. In this way, the students are able to concentrate on the experiment itself without being disturbed by other technical details of the model's environment.

The virtual lab is conducted via an online conference system with groups of 2–3 students. The digital model is opened within the simulation program on the computer of a lab assistant, who shares his/her screen. Through the assistant transferring control of their keyboard and mouse, the other participants are able to use the GUI on their screens and conduct experiments. This procedure prevents the students from installing the appropriate program and getting familiar with its handling. However, the lab's future development focuses on an autonomous operation by the students, e.g. by transferring the model in an executable program or by providing the model via a Web platform.

4 Design of a survey for evaluation of the laboratory

4.1 Overview

The combination of theoretical lectures, in which technical skills are developed, and application-oriented laboratories, in which these skills are transferred and thus methodological competence is refined, are traditionally an integral part of engineering degree programs. A particular characteristic of universities of applied sciences is the significantly higher proportion of application references in the curricula. As already mentioned, this connection is also a determinant in the laboratory's Fluid Machinery, which is offered in the sixth semester of the bachelor's program in Mechanical Engineering at Offenburg University of Applied Sciences. With the help of digital twins, a total of three experiments are carried out, the results of which are interpreted by the students in reports. Normally, experiments are conducted both in the laboratory on site and then supplemented by the capabilities of virtual digital twins. Due to the limitations of the COVID-19 pandemic, this was not possible during the study period.

4.2 Didactic structure

The didactic structure of the course is based on the approach of situated learning, and here, especially on the concept of the Cognitive Apprenticeship Model (CAM), which can be divided into four to six phases: first, the demonstration of expert knowledge by the lecturer; second, a scaffolding of student activities; third, decreasing support from teaching staff while increasing the students' sense of competence; and fourth, continued support in the learning process during independent experimentation as needed (García-Cabrero et al., 2018). Whereas the first phase relates to the theoretical lecture, all further phases are applied in the laboratory. The laboratory experiments are introduced by discussions between the lecturer, assistant, and two students to ensure the theoretical classification of the practical laboratory test. In the process, both declarative and procedural knowledge are transferred to practical problems within the three laboratory experiments, whereby methodological, social, and personal skills are stimulated and developed in addition to technical ones. By writing down the practical experiences, students have the chance to reflect on their learning progress and establish connections with other module contents during their discussions with their fellow students.

If we focus on the perspective of classroom research, the following connections can be noted: Determinants in terms of lecturer and student behavior in connection with the context of the course influence teaching or learning success. Lecturer behavior is characterized by the ability to structure and by clarity, rhetorical competence, motivation, activation, processing depth, communication, and leading discussions. In addition, there are variables on the student side that affect the success of a course: prior knowledge, diligence, and participation during the class. In addition, contextual factors such as the topic, the requirements (in our case mainly related to the structure and design of the digital twins), and the existence of performance certificates influence the teaching/learning success of a course (Rindermann, 2003).

4.3 Description of surveys

In order to analyze the effects of the didactic concept and its practical implementation, two surveys were conducted to contrast the direct observations and assessments of the lecturers with the student evaluations and views. The first was conducted after the first laboratory experiment in order to use the results to potentially modify and optimize the course. The second survey was conducted at the end of the course to reflect on and balance the overall growth in competence. Both surveys were composed of quantitative single-choice questions and qualitative open-ended questions to give students the opportunity to elaborate on additional aspects that they felt were necessary to describe the course and its impact on learning. Limited participation, interaction, and communication opportunities due to the COVID-19 pandemic were also considered in the second survey.

After the first laboratory experiment was conducted in mid-November 2020, 1 in 2 students were asked to answer the seven-question survey created in the learning management system. Participation was voluntary and thus not an integral part of the experiment or of the credit to be earned. Of 35 students enrolled in the course, 29 participated, a rate of nearly 83 percent. In the second survey, which was much more comprehensive with 25 questions and was conducted two months later in mid-January 2021, 26 out of 35 students participated, corresponding to a rate of 74 percent.

The questions in the two surveys, which are formulated in combination with different 5-point Likert scales, and the results are summarized in Table 1. The second column indicates which questions were raised in the respective surveys. As statistical parameters, the average and the standard deviations are given. Three further questions allowed the students to express their views in free text responses.

The questions can be grouped into different categories. Group 1, the construct of teaching behaviour with the variables of structuring and clarity, rhetorical competence, activation, depth of processing, communication, and leading discussions was mapped by questions 1–3, 6.

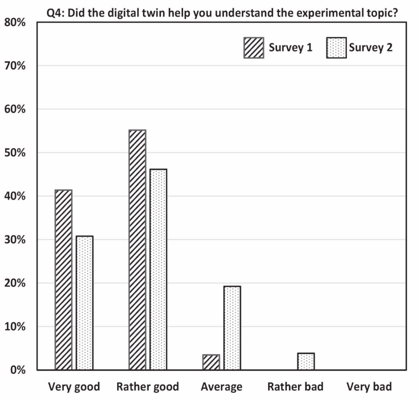
Group 2, the impact of interacting and engaging with the digital twins, as it relates to the current situation and possible future developments, was mapped in questions 4–5, 7–9.

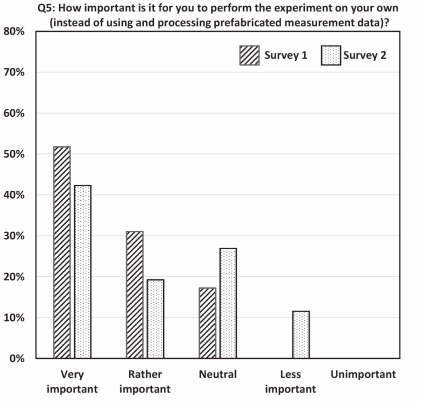
Group 3, questions 12–13 addressed the specific constraints caused by the COVID-19 pandemic. The social, methodological, and personal contextual conditions and their impact on perceived skill development were mapped by group 4 questions 14–15, 17–22.

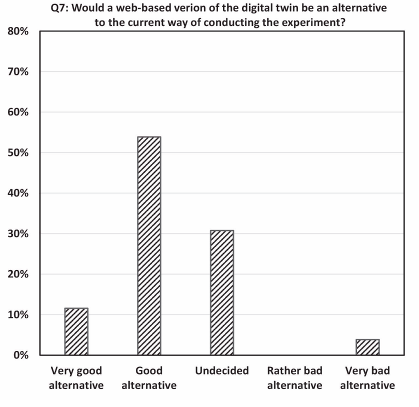
Table 1. Question and results of survey (Sur.) 1 and 2

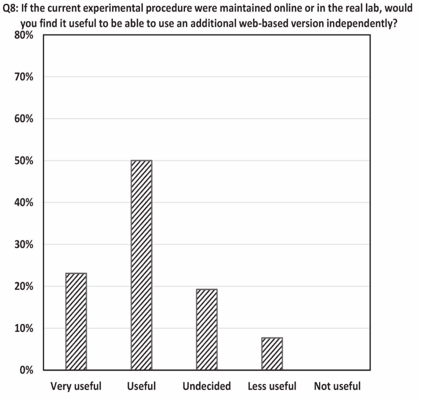
No.	Sur.	Question	Quantity 1	Quantity 2	Quantity 3	Quantity 4	Quantity 5	Percentage 1	Percentage 2	Percentage 3	Percentage 4	Percentage 5	μ[12]	σ[13]
1	1	Did the materials help you prepare for the lab?[1]	12	14	2	1	0	41%	48%	7%	3%	0%	1,7	0,74
	2		11	10	5	0	0	42%	38%	19%	0%	0%	1,8	0,75
2	1	Did the discussion at the beginning of the lab help you relate to the lecture?[1]	12	13	3	1	0	41%	45%	10%	3%	0%	1,8	0,77
	2		11	9	6	0	0	42%	35%	23%	0%	0%	1,8	0,79
3	1	Did the discussion at the beginning of the lab help you understand the experiment?[1]	18	10	1	0	0	62%	34%	3%	0%	0%	1,4	0,56
	2		14	8	4	0	0	54%	31%	15%	0%	0%	1,6	0,74
4	1	Did the digital twin help you understand the experimental topic?[1]	12	16	1	0	0	41%	55%	3%	0%	0%	1,6	0,55
	2		8	12	5	1	0	31%	46%	19%	4%	0%	2,0	0,81
5	1	How important is it for you to perform the experiment on your own (instead of using and processing prefabricated measurement data)?[2]	15	9	5	0	0	52%	31%	17%	0%	0%	1,7	0,76
	2		11	5	7	3	0	42%	19%	27%	12%	0%	2,1	1,07
6	1	How balanced did you find the proportions of theory/discussion and practical activities?[3]	0	8	21	0	0	0%	28%	72%	0%	0%	2,7	0,45
	2		2	12	12	0	0	8%	46%	46%	0%	0%	2,4	0,62
7	1	Suppose a web-based version of the digital twin existed which you could access independently in terms of time. Would this way of conducting the experiment be an alternative to the current way of conducting the experiment?[4]	3	14	8	0	1	12%	54%	31%	0%	4%	2,3	0,82
8	1	If the current experimental procedure were maintained online or in the real lab, would you find it useful to be able to use an additional web-based version independently?[5]	6	13	5	2	0	23%	50%	19%	8%	0%	2,1	0,85
9	1	Would working independently with a web-based version allow for a better understanding of the experiment content?[6]	3	12	5	6	0	12%	46%	19%	23%	0%	2,5	0,97
10	1	Which of the experiments contributed most to your understanding of the lecture content in fluid machinery?[7]	6	3	6	1	10	23%	12%	23%	4%	38%		
11	1	Which of the experiments contributed least to your understanding of the lecture content in fluid machinery?[7]	2	3	4	17	0	8%	12%	15%	65%	0%		
12	1	In the context of online teaching, have you had more or fewer professional and personal interactions with other students than before?[8]	1	1	5	4	15	4%	4%	19%	15%	58%	4,2	1,11
13	1	With fewer face-to-face interactions between instructors and students, is it more difficult for you to effectively absorb knowledge?[9]	13	6	5	1	1	50%	23%	19%	4%	4%	1,9	1,09
14	1	How important is group work in the context of labs to you?[2]	12	5	8	1	0	46%	19%	31%	4%	0%	1,9	0,96
15	1	Would you appreciate if lab reports were no longer carried out as group work, so that the responsibility for results is clear? [10]	4	22	-	-	-	15%	85%	-	-	-	1,8	0,36
16	1	Do you perceive the requirements placed on laboratories in the mechanical engineering course (preparation, lab reports) as inconsistent?[10]	21	5	-	-	-	81%	19%	-	-	-	1,2	0,39
17	1	Are expressive and communication skills as well as oral and written presentation techniques on specialized topics encouraged in the mechanical engineering course?[1]	1	12	7	6	0	4%	46%	27%	23%	0%	2,7	0,87
18	1	Should a course on (technical) communication be included in the curriculum?[10]	16	10	-	-	-	62%	38%	-	-	-	1,4	0,49
19	1	Does this course make it easier for you to ask questions when you do not understand something?[11]	1	5	11	7	2	4%	19%	42%	27%	8%	3,2	0,95
20	1	Did you learn to formulate your spoken contributions more comprehensibly in this course?[1]	1	5	13	4	3	4%	19%	50%	15%	12%	3,1	0,97
21	1	Does this course make it easier for you to get to the heart of what you are saying?[1]	0	4	16	5	1	0%	15%	62%	19%	4%	3,1	0,70
22	1	Are you better able to assess where you stand professionally as a result of this course?[1]	0	9	12	2	3	0%	35%	46%	8%	12%	3,0	0,94

[1] Scale: 1 = Very good; 2 = Rather good; 3 = Average; 4 = Rather bad; 5 = Very bad
[2] Scale: 1 = Very important; 2 = Rather important; 3 = Neutral; 4 = Less important; 5 = Unimportant
[3] Scale: 1 = Far too much theory; 2 = Too much theory; 3 = Balanced; 4 = Too much practice; 5 = Far too much practice
[4] Scale: 1 = Very good alternative; 2 = good alternative; 3 = undecided; 4 = rather bad alternative; 5 = very bad alternative
[5] Scale: 1 = Very useful; 2 = useful; 3 = undecided; 4 = Less useful; 5 = Not useful
[6] Scale: 1 = Significantly better understanding; 2 = Better understanding; 3 = No change; 4 = Worse understanding; 5 = Significantly worse understanding
[7] Scale: 1= Radial fan; 2 = Piston compressor; 3 = Pelton water turbine; 4 = None; 5 = All
[8] Scale: 1 = Significantly more; 2 = More; 3 = Equal; 4 = Less; 5 = Significantly less
[9] Scale: 1 = Much more difficult; 2 = More difficult; 3 = Equal; 4 = Less difficult; 5 = Much less difficult
[10] Scale: 1 = Yes; 2 = No
[11] Scale: 1 = Much more easier; 2 = Easier; 3 = No change; 4 = More difficult; 5 = Much more difficult
[12] Average value $\mu = \frac{\sum_{i=1}^{5}(x_i \cdot N_i)}{N_{Total}}$ with x = Scale factor; N = Quantity
[13] Standard deviation $\sigma = \sqrt{\sum_{i=1}^{5}(x_i - \mu)^2 \cdot \frac{N_i}{N_{Total}}}$


Q4: Did the digital twin help you understand the experimental topic?
Survey 1
Survey 2
80%
70%
60%
50%
40%
30%
20%
10%
0%
Very good
Rather good
Average
Rather bad
Very bad


Q5: How important is it for you to perform the experiment on your own (instead of using and processing prefabricated measurement data)?
Survey 1
Survey 2
80%
70%
60%
50%
40%
30%
20%
10%
0%
Very important
Rather important
Neutral
Less important
Unimportant


Q7: Would a web-based verion of the digital twin be an alternative to the current way of conducting the experiment?
80%
70%
60%
50%
40%
30%
20%
10%
0%
Very good alternative
Good alternative
Undecided
Rather bad alternative
Very bad alternative


Q8: If the current experimental procedure were maintained online or in the real lab, would you find it useful to be able to use an additional web-based version independently?
80%
70%
60%
50%
40%
30%
20%
10%
0%
Very useful
Useful
Undecided
Less useful
Not useful

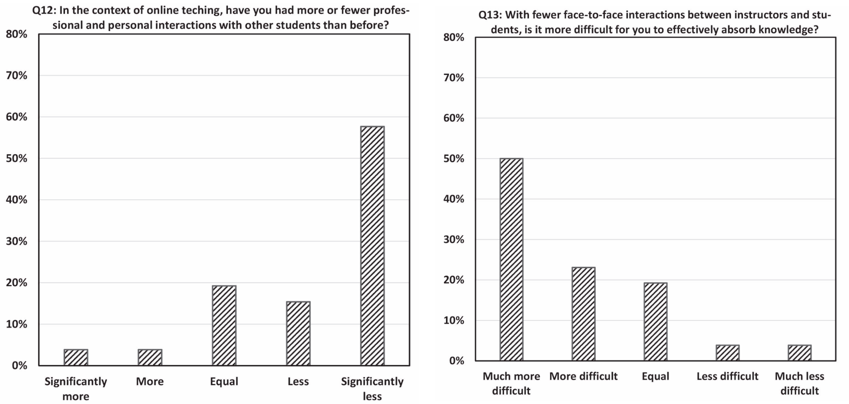


Figure 3: Selected survey results: Questions 4, 5, 7, 8, 12 and 13

5 Discussion of results

5.1 Digital lab experience

The usefulness of the digital twin experiment was addressed by questions 4 and 5 (see upper diagrams in Figure 3). It was rated between very good and good (1.6/1.7) in the first survey after the first experiment was conducted. In the second survey, at the end of the semester, the mean shifted towards good. Also, the distribution of responses widened. Overall, then, the virtual lab appears to be useful to the majority of students. However, the slight deterioration in the ratings and thus the change in perception of the lab could also be due to external factors: first, the special coronavirus situation, which particularly limited the opportunities for contact and exchange among students; and additionally, the special study situation in the sixth semester with several complex labs and correspondingly time-intensive requirements. These factors are indicated by the free text answers.

The preparation concept of the laboratory was addressed in questions 1 to 3. It was also rated between very good and good (1.4 – 1.8). The evaluation shifted only slightly over the semester. Only the evaluation of the dialogue/discussion as an introduction to the experiment was slightly weaker in the second survey. The supplemental free texts hint at limiting the amount of theory to the essentials at the beginning of the afternoon of the experiment. Again, perceived stress seems to apply as an explanatory pattern.

5.2 Communication and group work

The aspects of group work and communication were especially targeted in questions 12 to 14 (see lower diagrams in Figure 3). Communication is perceived as limited and impaired in online teaching. Interestingly, the lower level of habitual direct exchange between students and lecturers leads to a more difficult absorption of knowledge and thus to the reduced acquisition of skills. To compensate for this effect, students predominantly state that their engagement with the digital twins and the subsequent elaboration of the reports in groups provides a framework that is conducive to learning (1.9). Moreover, it can be assumed that the perceived communication problem exacerbates the effect of technical overload in the sixth semester.

5.3 Web-based digital twin

Questions 7 to 9 (see diagrams in the middle of Figure 3) asked for perceived opportunities offered by web-based experiments. These questions venture a prospective look into the future and focus on the intended more independent engagement with the digital twin experiments. The students evaluate the prospective web-based experiment as a good alternative to the current execution (2.3); the accompanying higher degree of independence is assessed slightly more positively (2.1). However, the students are somewhat more skeptical about whether this form of conducting the experiment, with a lack of guidance and support from the lecturers, will lead to a better understanding of the content (2.5). It should be kept in mind that previous student experiences are based exclusively on the guided variant.

5.4 Curriculum in Mechanical Engineering

Questions 16 to 18 explored the context of the laboratory with respect to the total lectures and laboratories in the sixth semester. The highest score (1.2) was obtained for a question whose subject matter goes beyond the narrow scope of the course under study. Students rated the expectations of all laboratory courses in the sixth semester as highly inconsistent. This results in a substantial cognitive and time burden, which is clearly evident from the extensive free text responses. First, the desire for harmonization can hardly be met due to subject-specific differences; second, dealing with heterogeneous requirements appears to be a goal of academic education. Nevertheless, supporting students in achieving this competence-oriented goal seems reasonable. Students would very much welcome the inclusion of a course on "Professional Communication" in the curriculum (1.4).

5.5 Personal skills

Questions 19 to 22 asked about how the laboratory contributed to the development of personal skills. The improvement of communication skills and personal and methodological competence intended by the concept and implementation of the laboratory course is rated most inconsistently by the students. One reason could be the concrete implementation of the individual seminars; another reason could be that students have not yet had enough experience with competence-oriented course concepts to recognize their advantages.

5.6 Summary

In summary, our key findings can be mentioned on three levels: First, it seems reasonable and appropriate to implement further experiments using digital twins. The concept of introductory theoretical discussions, subsequent independent data collection, and joint interpretation of the results in groups with feedback conducive to learning is viewed positively by the students overall. Nevertheless, the perceived excessive demands in terms of subject matter and time in the sixth semester counteract learning success and the competence-oriented development of the students. Second, these findings should be discussed within the faculty by staff and students. The legitimate question of why this workload overload is not identified in the course evaluations conducted by the central quality management body can be explained in part by the fact that the sample size of such evaluations is predominantly less representative than the surveys conducted in this lab. Third, based on the results at the course level, the discussion about competence-based teaching could be intensified.

In order to be able to make further, detailed statements about the lab concept, in the next step the examination of the digital twins could be compared with that in a real lab. In terms of methodology, a mixed-methods approach could be used in addition to quantitative questionnaires, including participant observations.

6 Conclusion

The coronavirus crisis has highlighted the flexibility of maintaining lab teaching formats if digital lab twins can be accessed. Without this tool, it simply would not have been possible to conduct the lab, which is conceptually designed as a Cognitive Apprenticeship Model, appropriately. The accompanying study showed that it was widely successful in realizing the intended content-related competence goals. The students largely accepted the format as a fully acceptable laboratory event.

The implementation of the digital twins to date does not yet include features that address the tactile experience of working in real-world labs. It is currently still unclear what influence this has on the students' acquisition of skills. There may also be considerable differences in perception between students on this issue, depending on whether they acquire knowledge more by theoretical means or are inspired by tactile experiences.

An important aspect that the study again revealed is the importance of face-to-face communication and interaction between lecturers and students, as well as between the students themselves. In the lab format with the digital twin, it was possible to maintain communication between the lecturers and the students. However, there were breaks in the communication between students. This was solely due to the fact that they could not meet in person in one location but had to communicate via media. Thus, important informal get-togethers in which information is exchanged are probably lacking. As with many online teaching formats, the question here is how this informal communication can be adequately supported. The importance of communication from the students' point of view may also be one reason why online formats without feedback to lecturers were rated unfavorably by the students in the study. This aspect should be strongly considered in the elaboration of virtual laboratories, for which there are enormous opportunities based on virtual twins.

In the study, it was again found that the perception of a course is strongly influenced by the current context of the students' overall situation. Such influences are likely to be even stronger in the extraordinary situation of studying under coronavirus conditions. We, therefore, intend to repeat the study in the future for comparative analysis.

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