Comparative analysis of remote, hands-on, and human-remote laboratories in manufacturing education

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Abstract

In the years 2020 - 2023, different concepts of material characterization laboratories as part of a forming technology course in the third bachelor year at the department of mechanical engineering, TU Dortmund University, Germany, have been implemented and evaluated. With the remote experiment, students were able to perform a standard tensile test for steel and aluminum fully autonomously. A so-called human-remote type experiment was used for the in-plane torsion test, where the instructor was equipped with cameras, microphone and head-set, such that students could control the instructor via web and observe the results of their actions in real-time. With the ability to go back to campus, additional experiments, such as the Nakajima test, which is used to characterize the formability in metals, was performed hands-on by the students in the lab. Through a comparative analysis of students' self-assessment regarding different learning outcomes prior and after the course, it was found that given a choice, students usually prefer hands-on labs over human-remote ones. For digital laboratories, the human-remote lab is the preferred choice over the remote experiment. Analyzing the students' overall course performance, it was shown that all types of laboratories provide a sufficient teaching input to perform well regarding several metrics tested in the course.

1. Introduction

Modern mechanical engineering courses must keep up with the most recent advancements in order to adequately prepare students for successful jobs in research and industry, as mechanical engineering is a discipline that is always evolving. The use of digital laboratories, such as remote laboratories, in engineering education is one area of innovation that has emerged in recent years. Compared to traditional, hands-on laboratory experiences, these digital labs provide a number of advantages, such as improved educational outcomes, expanded accessibility, and lower costs, making it appealing to universities and other educational institutions. At the same time, if well designed and integrated into the learning environment, remote laboratories can be successfully employed to let students achieve various learning goals on different taxonomy levels [1] - [3]. On a broader level, research has shown that digital laboratories can be highly effective tools for teaching various concepts and skills in mechanical engineering, including control systems, mechatronics, and robotics [4], [5]. Remote laboratories, in particular, have been shown to have a positive impact on student engagement and motivation, as well as on student learning outcomes [6].

In contrast, advocates of hands-on laboratories, also referred to as classical or traditional laboratories, often cite various advantages that these types of laboratories offer when used in engineering and, in particular, manufacturing education. For instance, practical hands-on laboratories provide students with a tangible, physical experience that is not possible in a virtual or remote setting. This physical interaction with equipment and processes can help students develop a deeper understanding of the underlying principles and concepts being taught [7]. Additionally, hands-on laboratories allow students to develop practical skills and hands-on experience, which can be valuable in preparing them for careers in manufacturing and engineering [8].

During the lockdowns of the pandemic, many laboratory courses were not prepared to function as digital lab classes, lacking the required amount of digitization, for instance through the use of remote laboratories. Quick solutions regarding the conversion to a digital lab were required, of which one variant emerged as a simple, cost-effective variant, the so-called human-remote laboratory [9]. A human-remote laboratory is a setup in which students control a real human instructor over the internet. In this type of laboratory, the human instructor acts as a physical agent or system, allowing students to control and interact with the laboratory equipment in real-time. Human-remote laboratories offer a unique and innovative approach to laboratory-based education and training. They provide students with a direct experience that is not possible with conventional remote or virtual laboratories, as the human instructor is able to respond to the students' inputs in real-time. Additionally, they can facilitate collaboration and communication among students and the instructor, promoting a more interactive and engaging learning experience. Classical limitations of remote and virtual systems, such as a pre-defined course of events or a limited number of potential parameter to influence, are circumvented by the use of a human instructor, typically an expert of the machine or experiment.

When a new course is being designed or an existing one is being converted to digital form, it is important to understand which type of laboratory should be preferred, given the reduced complexity and upfront investments in digital versions of traditional laboratory experiments. Educators are also interested in the acceptance of the different types of laboratories by students and how that affects learning outcomes. Based on a comprehensive comparison of a remote, a human-remote and a traditional laboratory, all dealing with the same set of experiments, the goal of this paper is to provide recommendations for teachers who are in the process of designing a manufacturing technology lab course or digitizing an existing one. The design recommendations take into account further non-student-related elements, such as time and costs associated with the development of various types of laboratories, based on the authors' own experience in those fields.

2. Methodology

This chapter shall provide an overview of the different types of engineering laboratories, the general structure of the course analyzed in this work as well as the type of questions the students had to answer and how their performance was evaluated. The course analyzed involved different types of laboratories over the last three years, enabling an impact analysis in a constant test environment. The intended learning outcomes remained unchanged, while only the type of laboratory used did.

2.1. Laboratory types

Traditionally, laboratory courses or laboratory units/lessons in mechanical and more specifically, in manufacturing education are performed in a *hands-on* fashion. Students can use tools and machines first hand and are typically guided or aided by one or more instructors. Depending on the specified learning goal, the structure of a session can involve previous preparation by the students, an initial questionnaire regarding the current topic of that lesson and, finally, the actual instruction regarding the process/machine. The authors acknowledge, that most of the readers will be familiar with this type of laboratory session.

In line with a trend towards flipped class-room concepts, manufacturing laboratory classes find themselves in a difficult position, since many of their learning goals are related to hands-on experiences. However, in recent years, many of the manufacturing-related machines have evolved to be non-hands-on. Consequently, more time is spend planning the process, for instance in CAD/CAM environments. The analysis of data is becoming more important in recent years as well. Not just since the rise of Industry 4.0 is the number of sensors steadily increasing, generating an ever bigger amount of data. Along with this trend, the learning goals of laboratory courses shift accordingly – from manual operation of machines towards process planning, observation and data analysis. This enables to use of so-called *remote laboratories* as part of flipped laboratory concepts, given their shifted focus of achievable learning outcomes [2], [6]. Such remote laboratories are fully automated machines setups which can be controlled through the internet, at best anytime. Using those type of laboratories, students are able to perform the necessary experiments, observe the experiments and gather the data in real-time. What sets remote laboratories apart from so-classed *ultra-concurrent laboratories* [10], is the fact that every time a student starts an experiment, a real experiment is performed in an automated fashion, creating a unique set of results. Since the data and video feed in ultra-concurrent laboratories are pre-recorded, the range of experiment parameters available to students is constrained. In remote laboratories, the parameter space is only limited by safety related boundaries. The clear advantage of ultra-concurrent laboratories over remote laboratories is the multi-user capabilities. Due to their ties to actual real machinery, remote laboratories only offer access to a single person at a time. As ultra-concurrent labs are designed using web-based databases, the simultaneous access for many users is facilitated.

As mentioned in Chapter 1, *human-remote* laboratories are based on the virtual control of the lab instructor by the students through the internet [9]. Using any video conferencing software, students are connected to the instructor who is in the actual laboratory. The instructor is equipped with cameras or has placed static cameras for observation around the machines/experimental setup. For audio-based communication, the educator is wearing a wireless headphone with a built-in microphone. The advantages of this concept are the fast and cheap setup as no automation is required. Most universities should be able to implement such a concept fairly quickly. However, an instructor must be present during each experiment of each group. This in turn enables to students to ask direct questions during the experimental session, which is not possible using remote laboratories due to the lack of supervisions.

Figure 1 compares the three laboratory types employed in this course. The comparison further includes the ultra-concurrent laboratories and virtual laboratories, which are also being developed for this course but were not part of the comparative analysis in this work, given they had not been used in the three years investigated.

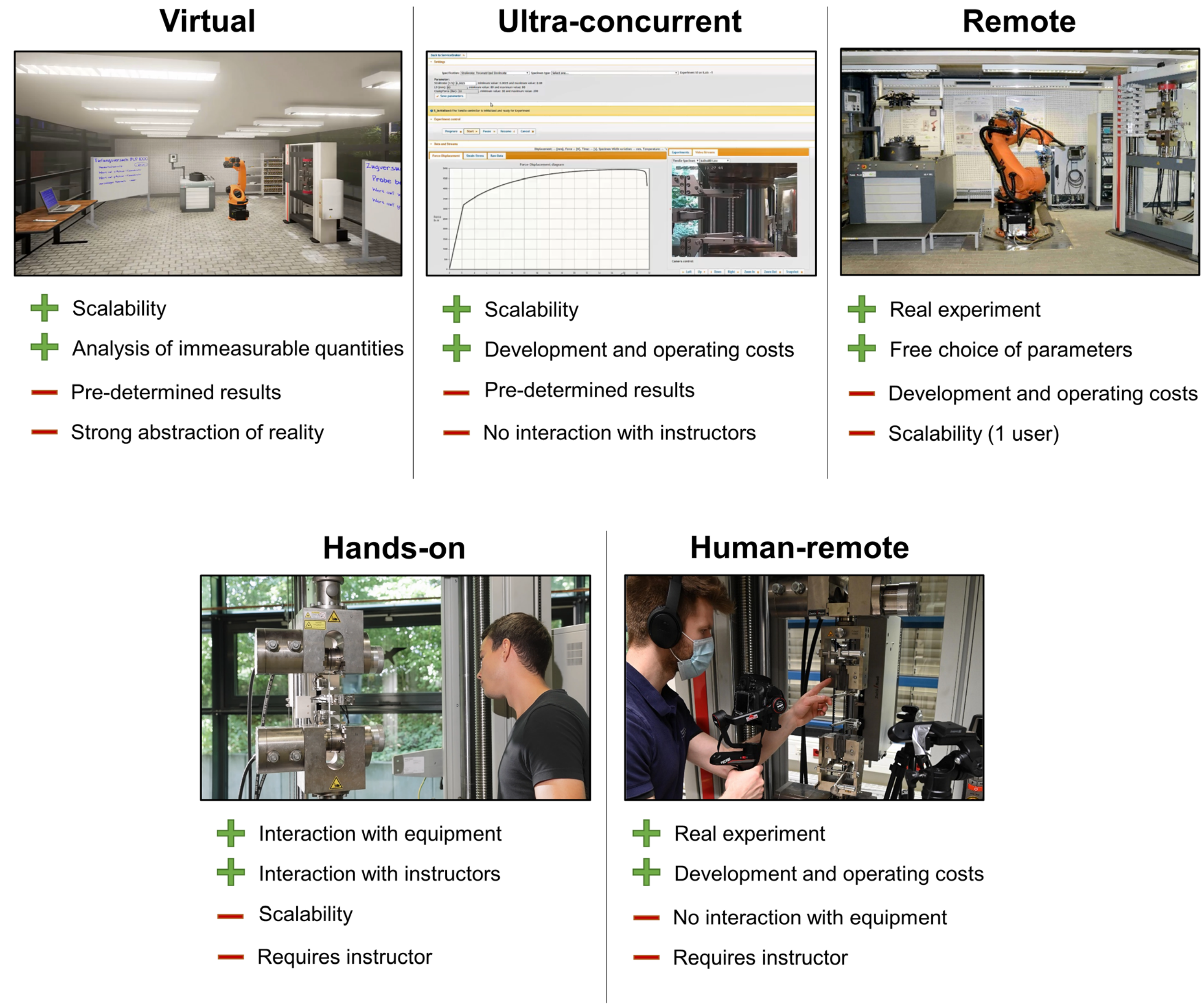

Figure 1: Comparison between five different types of laboratories used in manufacturing education. The same experiment, in this case the tensile test, is depicted by all types.

2.2. Course structure and variations across different years

The course *Material Characterization in Metal Forming* is part of the curriculum for mechanical and industrial engineers at the Technical University of Dortmund. For some of the mechanical engineering students, especially those specializing in the subject of manufacturing engineering, this course is mandatory whereas for the rest it is an elective course in the 5th semester (3rd year). The students had an introduction to forming technology in their first semester and should have completed the basic courses on material science as well. The course has an equivalent of 5 credit points which totals to around 150 hrs of time spend on this course. The course is a complete re-design of the traditional laboratory courses, previously found in the first master semester of older student batches. The redesigned course was first introduced to the winter semester of 2019/20. It is an entirely flipped course design, where the basic topics, including stresses, strains, anisotropy and the different material tests, e.g. the tensile test, are covered by online video lessons. To incorporate gamification aspects, each video lesson requires the completion of a brief test in order to advance to the next lesson. Other source materials, most importantly the EN ISO standards for the various material tests, are also provided in addition to the video content. Students have to carry out various material characterization tests, collect data, analyze and process that data and derive material characteristics, which are important in the field of metal forming. This includes the flow curve of a material, the Young's modulus, elongation at break and the forming limit diagram. In groups of four, the students are tasked to write concise reports about the various tests with a focus on the interpretation of the results and the insights derived by analyzing the test and the data. The course is completed by an online group presentation with a subsequent oral exam.

On its first run, the course was able to proceed as planned and ended before the start of the Corona pandemic in February 2020, as the course is designed to have the final oral exam prior to the start of the actual exam period of the same semester. Only 26 students participated in the course that year, as it was a first test run. For that reason, the data from the class of 2019/20 is not included in this analysis. By design, the course incorporates remote laboratories, see Figure 1, as well as traditional hands-on elements. In the following year, 2020/21, the TU Dortmund was under full lock-down regarding on-campus activities, wherefore the hands-on part had to be adapted to what has been termed *human-remote laboratory*, cf. section 2.2. A total of 149 students enrolled in the course in this year. The significant increase in the number of participants can be explained by the lack of alternatives. Many institutes did not or could not offer their laboratory courses in that year, due to missing remote and human-remote capabilities. The next year, 2021/22, was a mix between human-remote and hands-on laboratory session, since short-term lock-downs (re-)occurred frequently but in an unexpected way. The number of students participating that year was 93. In class of 2022/23, all material tests were performed in a hands-on manner. 68 students chose to take the course in this year. In all years, roughly 10 % percent of students were international students. The course language is English, but reports can be optionally written and results be presented in German.

2.3 Feedback and performance evaluation

Two methods have been employed to gather the data required for drawing conclusions about setting up or the digitization of existing lab courses. The first step entails evaluating the performance of the students. The students in the three years under study received the same source materials, took the same tests on similar equipment, had to analyze the data in relation to the same task, wrote reports, and delivered a presentation that included an oral exam. The type of laboratory, i.e. remote, human-remote or hands-on, they used to conduct the experiments and collect the data was the main variable that had changed across the three years. The report evaluation, the quality of the results presentation, and the oral exam performance all contribute to the student's overall grade. For all three contributions, an extensive evaluation matrix is used, to ensure objective and comparable grading of the students within one and across multiple years.

In addition, the students had to answer two questionnaires, one at the very beginning of the course and one towards the end, but before the presentations and oral exam. The questions were identical in both questionnaires and look the following:

Please, rate your personal level of proficiency (from 1 = "low level" of proficiency to 10 = "high level" of proficiency) regarding…

1. handling laboratory equipment, measurement tools and software for experimentation.
2. planning and executing common engineering experiments.
3. choosing, operating and modifying engineering equipment.
4. recognizing whether or not experimental results or conclusions “make sense”.
5. improving experimentation processes on basis of results, that do not “make sense”.
6. identifying strengths and weaknesses of engineering specific theoretical models as a predicator for real material behavior.
7. converting raw data from experimentation to a technical meaningful form.
8. applying appropriate methods of analysis to raw data.

Given the aim of this paper, only the assessment questions 1, 2 and 4 will be analyzed in detail. For the second questionnaire, an additional question was added which targeted the subjectively perceived reasons for the change in their answer. The question was as follows:

If you feel your answer has changed compared to the beginning of the course, what element of the course would you say has caused the change most significantly?

The answers the students could select for the aforementioned questions varied from year to year depending on the laboratory types used because one of the main objectives of this analysis was to evaluate the impact of the various laboratory types across the various years. If the students felt there had been a change between the beginning and end of the course, they could only select one response for each aspect, leading to a binary self-assessment of the most important influencing factor on the change. The table below provides the answers on a per-year basis.

Table 1: Potential reason for the subjectively perceived change in their self-assessment. The different learning setups in the different years explain the differences in the options the students can choose from.

Semester	Winter 2020/21	Winter 2021/22	Winter 2022/23
Potential reason for change	Videos	Videos	Videos
		Hands-on lab sessions	Hands-on lab sessions
	Remote Tests		
	Human-Remote Tests	Human-Remote Tests	
	Self-Studying	Self-Studying	Self-Studying
	Working on the reports	Working on the reports	Working on the reports
	None of the above	None of the above	None of the above
	No change occurred	No change occurred	No change occurred

While the students answered the second questionnaire, they could not access their own answers from the first report. Hence, the self-assessment, if or if not a change had occurred, was subjective. This will be used to verify the impact of the selected reason for the change.

3. Results & Discussion

In this section, first the results from the self-assessment questionnaire are discussed on a per-question basis, spanning all three years. The performance evaluation is used as an additional source for verification of the findings.

In the manufacturing industry, and hence the education of future manufacturing engineers, being able to perform and analyze experiments or processes in a production environment is a key skill for said engineers. Consequently, it defines one of the most important learning outcomes in laboratory classes. However, in most of the curricula at German technical universities, students do not have any such classes during their first two years. This explains the relative low rating of about 4.9 before the beginning of the course, see **Figure 2**, since the students may or may not performed any internships which might have given them the opportunity to perform such tasks on their own. After the course, the students rate their proficiency on average 1.77 points higher on average across all three years. The lowest increase of 1.38 is observed during the Covid year of 20/21, where students had no access to real laboratory equipment hands-on. The increase of 22/23 is about 0.2 points lower compared to 21/22, however, the initial rating is higher by the same amount. The relative change is on a comparable level. The increase in confidence regarding the self-assessment of the students' skills is expressed by the reduction of the standard deviation of about 0.45 points. Not only do the students attest that they have achieved the intended learning outcome, but they can more confidently tell to what extent this improvement happened. Again, during the year 20/21 in reduction of the standard deviation is the lowest, indicating a remaining

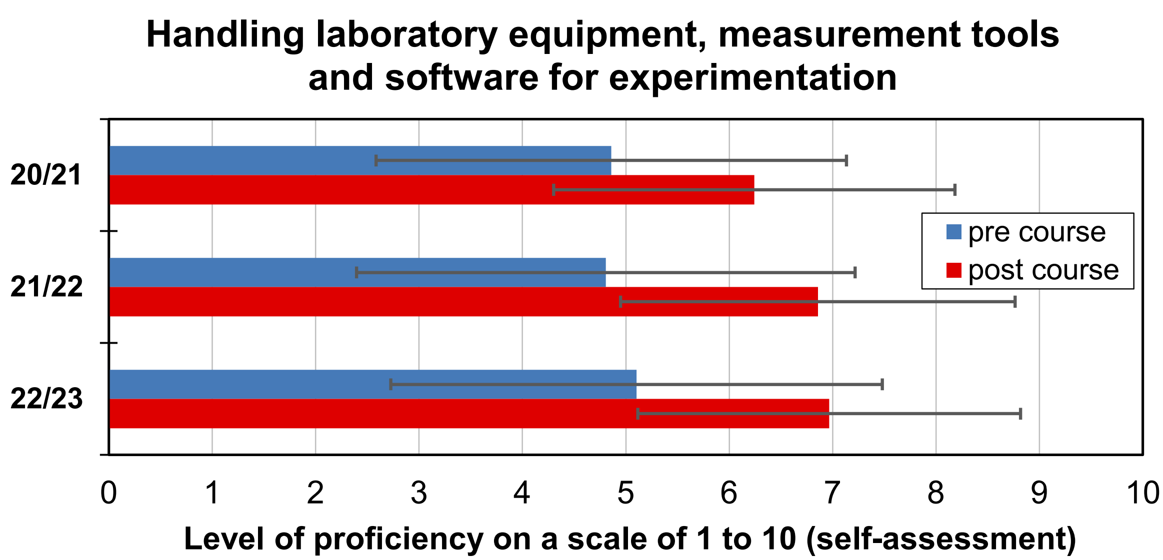

Figure 2: Students' self-assessment regarding learning goals focused on handling equipment, tools and software.

high uncertainty how to rate their level of proficiency. The results show that any type of laboratory can be used to improve the students subjectively perceived ability to handle laboratory equipment.

Comparing the remote and the human-remote laboratory setup in the year 20/21, it is apparent that the students clearly prefer the human-remote setup over the remote one, see **Figure 3**. Videos and working on the reports, which includes the processing of the data, play only a subordinate role. If students have the direct comparison between human-remote and hands-on laboratory, the choice comes to the hands-on laboratories, even more strikingly than in the previous comparison. In view of the learning outcome of *handling* equipment, this result is coherent in the sense that the very words handling and hands-on have a large overlap. In the year 22/23, where all labs were performed in a hands-on way, the remaining aspects of the course are not of significant importance to the students. It can be concluded, that for learning outcomes related to the operation of equipment hands-on laboratories are the preferred choice. But more importantly, if a digitization is desired, human-remote setups perform better than expensive remote laboratories.

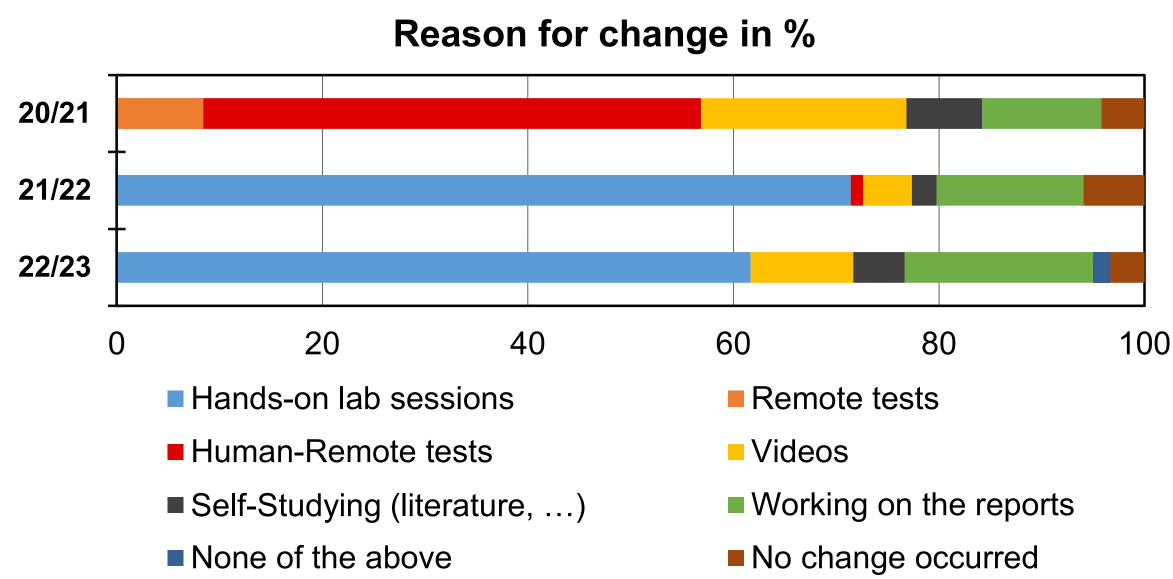

Figure 3: Students' response citing the single most significant aspect of the course that influenced a potential change in their perceived skill improvement, see Figure 2.

A multitude of factors support the relevance of this finding. For one, remotizing an existing laboratory comes at a high cost. This spans equipment, material and labor which included the overall development time. The advantages are the 24/7 availability of such an experiment and the independence of any specific instructor or operator. To achieve this level of autonomy, the upfront costs typically outweigh the investments of a digitization based on the human-remote approach. Additionally, almost no development time is required for the setup of such a digital lab. For such a learning environment, instructors require a special training, which includes the proper handling of the cameras but also how to interact with the students based on just an audio stream.

The results regarding the second assessment questions, which focuses on the planning and execution of experiments, yield a similar result. All the statements made regarding Figure 2 can be adapted to the analysis of **Figure 4**. A difference is observed regarding the overall rating after the course. As especially the planning is fairly detached from the work done in the lab, the students have a greater overall improvement to report. It shows that for less *hands-on* intense learning outcomes, any type of laboratory helps to improve the students' abilities. Another trend to observe is the increase in initial confidence. In both questions, the class of 22/23 reported the highest pre course values. Interestingly, this particular class started their studies during full lockdown, namely 20/21, which should have given them even less hands-on experience compared to the class of 20/21 which started in 18/19. Technically, there are no hands-on learning setups in the first two years, but during lectures in the experimental hall and other activities at the different institutes or student jobs, students can get some first experiences in laboratories, which the class of 22/23 did not have.

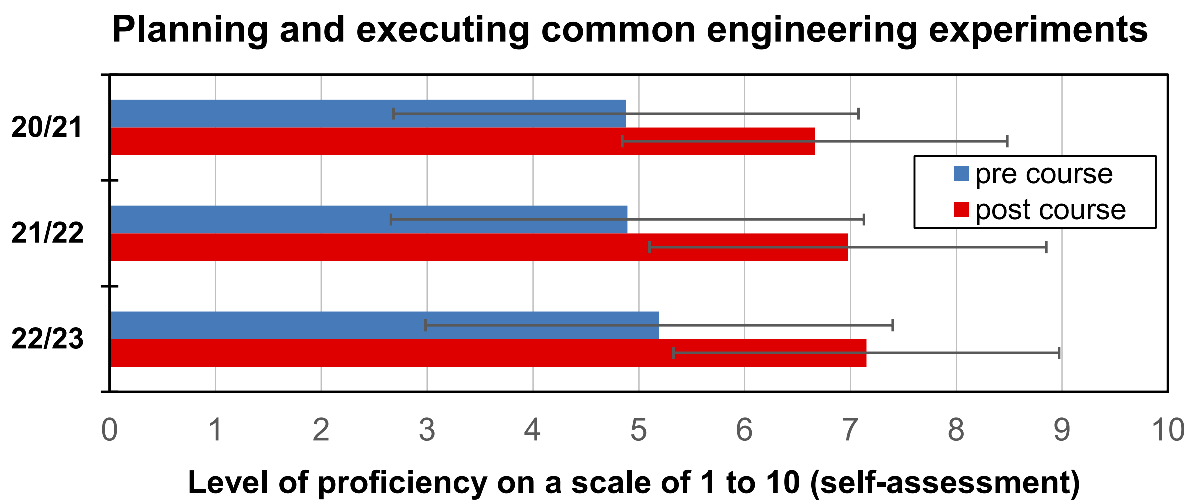

Figure 4: Students' self-assessment regarding learning goals focused on planning and execution of experiments.

Similar to the evaluation of the self-assessment between question 1 and 2, the results regarding choosing the reason for the change, see **Figure 5**. show a similar trend. The human-remote laboratory is considered to be more expedient compared to the remote lab and the hands-on type is ranked above the human-remote tests. However, in absolute values, all laboratory types play a slightly less significantly role in terms of preparing the students for experiment planning. Watching the videos is for some students, the main contributing factor in improving their skills in this field. On the other, also more students than in question 1, state that no change has occurred. This is not supported by the data, comparing Figure 2 and Figure 4. For the second question the average increase is 1.94 points whereas in question 1 the average increase was only 1.77 points. A possible explanation is that those students, who reported an increase in their skills, rated the increase higher than in question 1, while at the same time, more students answered that *no change had occurred* and also self-assessed no increase in their proficiency.

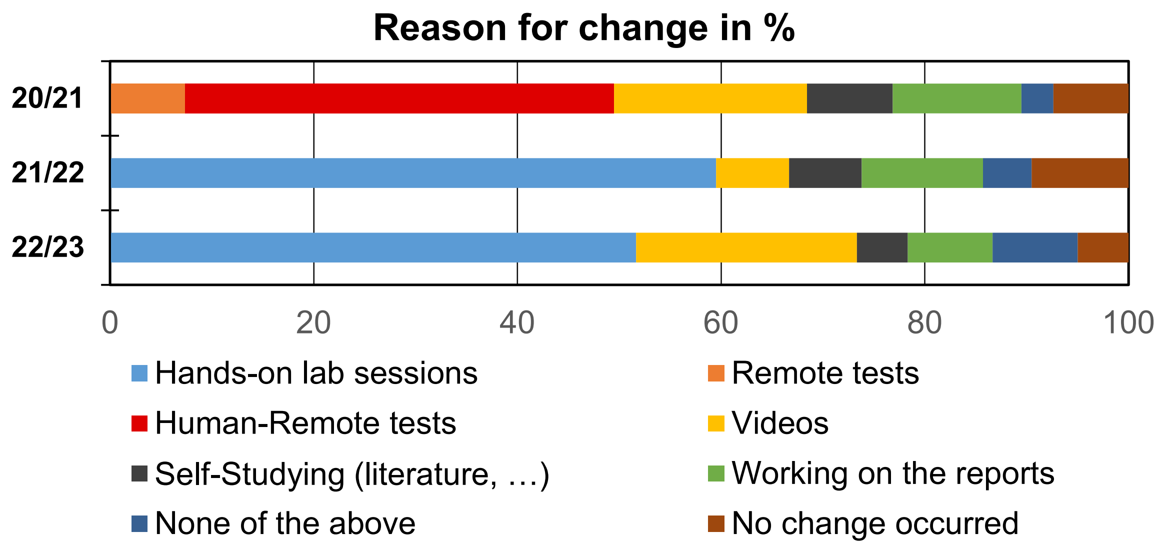

Figure 5: Students' response citing the single most significant aspect of the course that influenced a potential change in their perceived skill improvement, see Figure 4.

Aside from the learning goals, which are geared towards the actual experimentation, another key skill of any engineer is the critical analysis of results. One has to understand, if or if not the results or the data to begin with, can be trusted. In manufacturing laboratories, potential sources of errors can involve the material, the machine, the testing equipment, the human operator and also the processing of the raw data. As can be seen from **Figure** , the students rate their proficiency initially higher than in question 1 and 2. This is surprising, given that the learning

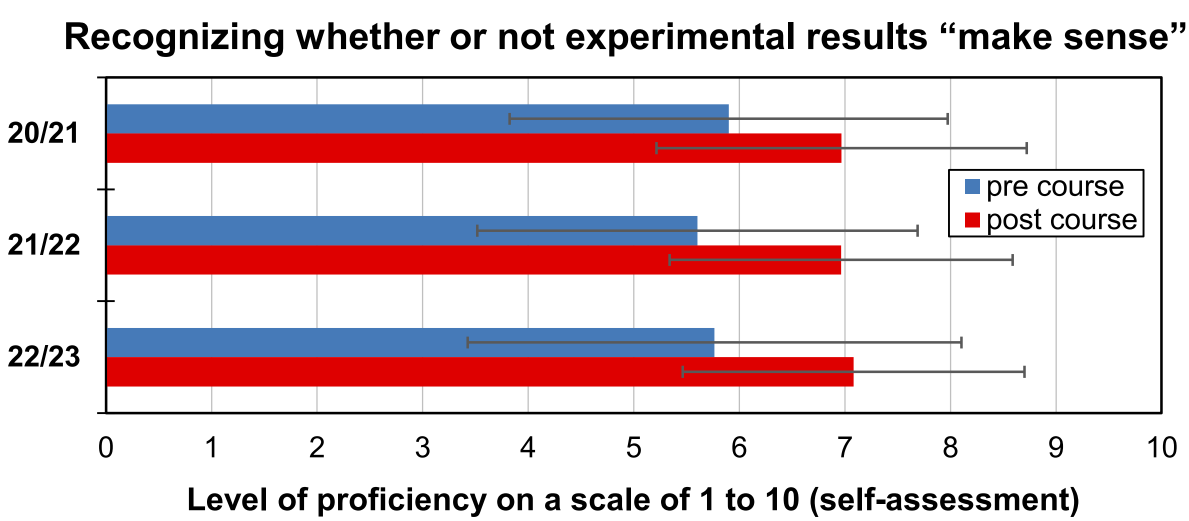

Figure 6: Students' self-assessment regarding learning goals focused on the critical analysis of results.

goals covered are on a higher taxonomy level than the ones in the previous questions. However, it is rather the lack of exposure to any practical problems in the first two years, that let the students rate themselves too low in the previous questions. Since the rating after the course is on a comparable level, the absolute and relative improvement is less significant than in the previous cases. With an average of around 7 points after the course, the students feel confident in critical analysis of results, indicating an achievement of intended learning goals.

By analyzing the part of the course which influenced the students in improving their critical thinking abilities in the field of experimental analysis, it is revealed that the *working on the reports* is considered most important, see **Figure 7**. The laboratories, regardless of their type, are less relevant in aiding the students to accomplish this learning goal. Improving their skill on critical analysis takes time. That time is typically not available during the lab sessions, which are often limited to one hour per experiment and group. Only when studying individually or in groups and processing the input from the lab sessions during report generation, it is that the students improve their analysis skills. For this to be achieved, the task description for the report must include requirements that challenge the students on a higher learning level. If the reports simply ask for a lab report and the process of the raw data, students will be required to think analytically and put their findings in perspective. Small quizzes provided to the students during the weeks when they are working on the reports help to guide them during this process. Instructors should further be available to response to potential open questions. Here, online conversations were found to be sufficient.

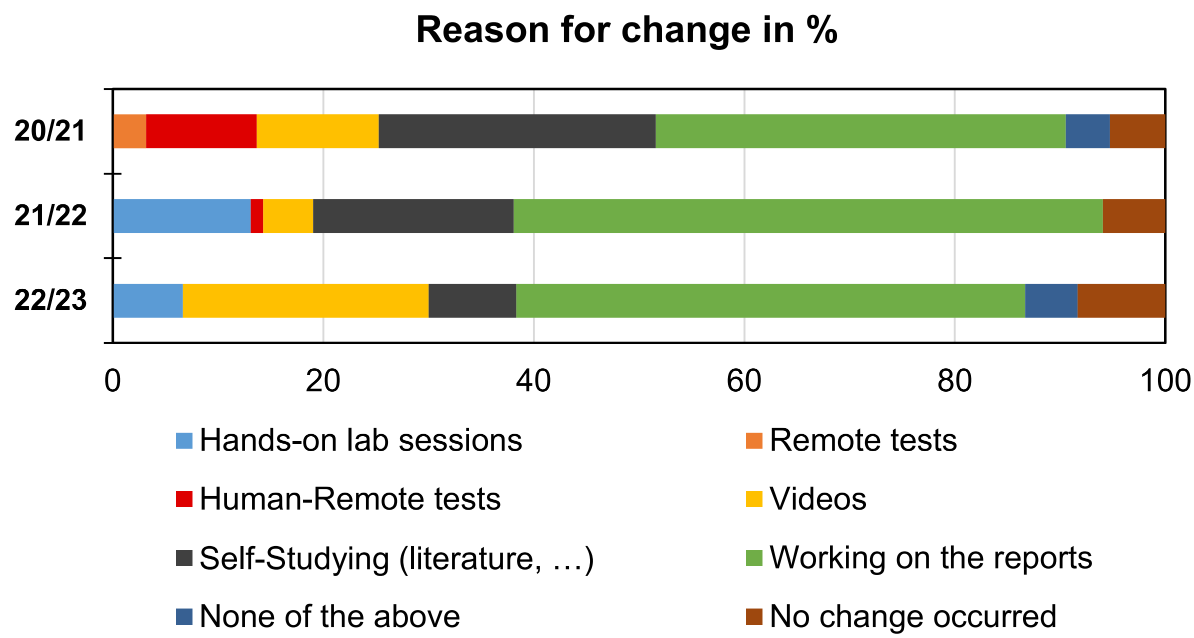

Figure 7: Students' response citing the single most significant aspect of the course that influenced a potential change in their perceived skill improvement, see Figure 6.

To assess if the usage of the different types of laboratories had any measurable influence on the students' performance, the distribution of the final grades for all three years is shown in **Figure 8**. The breakdown of the grade assignment was provided in Chapter 2.3.

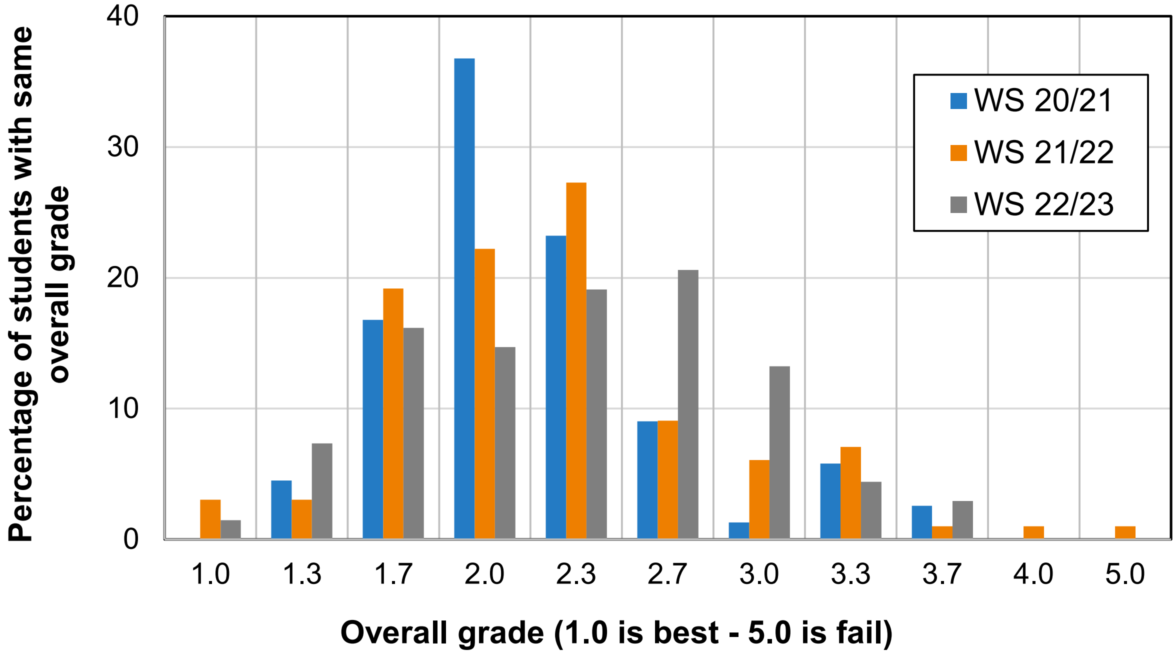

Figure 8: Distribution of final course grades for the years 20/21, 21/22 and 22/23. The grades consist of report evaluation, a presentation and an oral exam.

For all three years investigated, the distribution of final grades shows a comparable pattern. With the exception of the year 21/22, the failure rate is zero, primarily due to the highly distributed assessment. This is largely formative, providing various opportunities for students with diverse strengths and weaknesses to earn percentage points toward the overall score. In general, a trend towards lower overall performance is, however, observable across the three years. Comparing this course's trend with those of other courses of this and other institutes, the picture is very similar. Therefore, one should be careful in correlating the different laboratory types with the overall performance. Since, for instance, the structure and language of as well as the visual appearance of figures in the reports are important grading factors, their decline over the years – and this has been observed in this course – can explain the trend towards lower grades. Students abilities in these fields deteriorate year by year. Incorporating the linguistic operators of in the task description, such as *analyze*, *compare* and *discuss*, into the analysis of the reports, it becomes apparent that many engineering students do not understand (anymore) what the meaning of these operators are. They often focus the reports on the simple *description* of the experimental setup, the process and the evaluation of data. In turn, this negatively affects the report grades and, hence, the overall grades.

By reducing the analysis to the core competences, which are intended to be achieved in this course, the performance across the years is more comparable (not shown). Comparing the three laboratories types regarding the overall student performance, it can hence be concluded that all three laboratory types can be used in manufacturing laboratories to achieve learning goals related to the preparation and conduction of engineering experiments. This widens the set of non-hands-on laboratories, which can be used as potential ways of digitization, by the human-remote type.

4. Conclusion

The purpose of this study was to compare the effectiveness of hands-on, human-remote, and remote laboratories in achieving certain learning goals in manufacturing education, and to determine students' preferences for each type of laboratory. Human-remote laboratories in this context are defined as a type of digital laboratory, where the lab instructor is physically present in the experiment environment and acts as an agent, controlled by the students via internet, to perform the experiment based on the students' input. Results showed that all three types of laboratories were equally capable of achieving the targeted learning outcomes. However, the findings revealed that students preferred hands-on laboratories over human-remote laboratories and human-remote laboratories over remote laboratories when the focus is on digital laboratories.

This study provides valuable insights into the use of different types of laboratories in manufacturing education and highlights the importance of considering both learning effectiveness and student preferences, especially when designing digital laboratory experiences. Human-remote laboratories provide a higher student acceptance at a significantly lower cost, compared to the conventional remote laboratories. The latter usually require special equipment and an automated control system to be operated in a remote fashion. This does not apply, if the human-remote approach is chosen for digitization. The results can be used to inform decisions regarding the selection and implementation of laboratory setups in education and training programs, and to support the development of effective and engaging laboratory-based learning experiences. In conclusion, hands-on, human-remote, and remote laboratories each have their own advantages and limitations, and the choice of laboratory setup will depend on the specific learning goals, resources, and constraints of each educational program.

Future studies should expand the analysis to virtual and ultra-concurrent labs so that all five different types can be accurately compared using the same or similar experimental setups. Another current trend in education stems from the abilities of Augmented Reality devices, which enable a combination of virtual and hands-on laboratories. By using their own hands to interact with the projected environment, users can better identify with the actions of the virtual experiment.

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