Online and Blended Labs for Practical Mechanical Engineering

Citation for the original published paper (version of record):
Stöhr, C., Sheihki, S., Langer, R. et al (2023). Online and Blended Labs for Practical Mechanical Engineering. Proceedings of the 19th International CDIO Conference: 805-819

ONLINE AND BLENDED LABS FOR PRACTICAL MECHANICAL ENGINEERING

Christian Stöhr, Veronica Olesen

Chalmers University of Technology, Gothenburg, Sweden

Shahram Sheikhi, Robert Langer

Hamburg University of Applied Sciences (HAW), Hamburg, Germany

Vladimir Kuts, Margus Müür

Tallinn University of Technology, Tallinn, Estonia

Antti Nousiainen, Ari Putkonen, Sakari Koivunen

Turku University of Applied Sciences, Turku, Finland

Yihua Zhang, Jens Kabo, Mikael Enelund, Johan Malmqvist

Chalmers University of Technology, Gothenburg, Sweden

ABSTRACT

Lab training is a key element in most engineering education programs in preparation for engineering profession tasks. Universities worldwide are exploring new possibilities and different forms to arrange online and blended labs as an alternative to pure campus training. This study compares online and blended lab setups in four cases of engineering education at European technical universities. The results show that online and blended labs can achieve similar learning outcomes, with blended labs being particularly effective in combining online learning with hands-on elements. Students reported high levels of satisfaction and teachers noted the benefits of online learning environments, but common challenges included ensuring student engagement, increased self-regulation requirements, and the high effort needed to design online or blended environments. The study provides course design guidelines and discusses implications for future research and implementation in universities worldwide.

KEYWORDS

Online learning, Online labs, Hybrid labs, Remote labs, Blended learning, Hybrid teaching, Standards 5, 6, 8

INTRODUCTION

Lab training is an essential component of most engineering education programs, providing students with the opportunity to engage in experiential and inquiry-based learning activities such as experimentation and testing (Hofstein & Lunetta, 2004). These hands-on experiences allow students to apply and reinforce theoretical knowledge, work with technical equipment and designs, practice teamwork, and analyze and reflect upon experimental data through report writing. However, traditional lab training can be costly, may have limited accessibility, and pose potential safety risks. In response to the COVID-19 crisis and the increasing use of educational technology in education, universities around the world are exploring online and blended lab options as alternatives to in-person training (Graham, 2022). While there is a growing body of literature and case studies on online and blended labs, little effort has been made to compare the benefits, drawbacks, and effects on student learning between different types of lab experiences. This is particularly true for labs with heavy equipment, where often, the only solution for online learning has been videos with no interaction between lecturer and students.

In this paper, we aim to address this gap by conducting a comparative analysis of four learning designs that incorporate online or hybrid labs and were developed at different European technical universities. These learning designs include two cases of using and programming an industrial robot, one case of introducing manual welding, and one case of designing, programming, and testing logic control circuits.

STATE-OF-THE ART

Online labs have been explored as a potential alternative to in-person labs, and while the latter offer the benefits of realistic data, interaction with real equipment, and the ability to collaborate and interact with other students and teachers, they also come with high costs, time and place constraints, and scheduling and supervision needs (Nedic et al., 2003). In the literature, two main types of online labs are commonly distinguished: virtual and remote (Chen et al., 2010). Virtual labs refer to simulated lab environments using software such as Matlab/Simulink, LabView, or Java Applets. Remote labs are lab experiments with real instruments and/or components that are controlled remotely through the internet, either directly or through instructions to on-site staff. Both types of online labs have been studied in terms of their advantages and disadvantages as well as their impact on student learning. Research has also provided case studies examining the design and evaluation of various virtual and remote lab environments with varying levels of technical complexity (e.g., Wang et al., 2015; de Jong et al., 2014; Potkonjak et al., 2016).

There have been numerous studies that have identified potential benefits and risks of virtual and remote labs compared to traditional labs (Potkonjak et al., 2016; Chen et al., 2010; Post et al., 2019; Nedic et al., 2003; Lynch & Ghergulescu, 2017; de Jong et al., 2014). Some of the most commonly cited benefits of integrating virtual and remote labs in higher education include cost reduction and simplified maintenance of lab facilities, as well as the ability to provide students with a safe learning environment that can be accessed from anywhere. Both forms of online labs offer cost-saving advantages, as virtual labs are easier to set up and maintain and involve lower equipment costs, while remote labs can be used more efficiently through shorter time slots and non-stop scheduling. Additionally, online labs offer greater flexibility in terms of access and set-up, as they can be available 24/7 and allow geographically distributed learners the opportunity to collaborate and cooperate with each other and the instructor remotely.

Remote labs also offer the benefit of allowing students to interact with real equipment, while virtual labs enable a wide range of experiments with different components and system configurations that can easily be repeated and allow for greater transparency in the inner workings of lab devices without the risk of damage or harm. However, there are also risks. Virtual labs do have the disadvantage of not actually existing, which can result in a lack of real-life feel and a sense of seriousness for students who may view the virtual lab more as a game, making it difficult to effectively teach about important health and safety issues. Additionally, even in remote labs, students are only present virtually in the lab. There are also risks of oversimplification and lack of natural variation in virtual labs, and adapting virtual labs to a specific class context requires a high level of understanding of the underlying software. Professional development for teachers to create well-designed inquiry environments in online labs can also be a significant challenge.

According to Brinson (2015), who conducted a review of 56 studies, learning outcomes from virtual or remote labs were equal to or better than those from traditional labs. For instance, Wang et al. (2015) found that students using a virtual physics lab had greater depth of practice in process skills, comprehensive skills, and reflection skills of scientific inquiry compared to those in traditional lab environments. A review by Post et al. (2019) also found positive results in terms of gain of conceptual knowledge, student engagement, and student satisfaction with regard to remote labs. However, they also noted that the review of learning outcomes was superficial, as most articles did not focus on that aspect and further research is needed. Potkonjak et al. (2016) also highlighted the limited generalizability of most online labs, which are typically adapted to a specific educational context. Some authors have emphasized the need to improve learning in online labs through more careful design and coordination of group and individual activities (Corter et al., 2011). Others have argued that online labs, while valuable in education, cannot completely replace traditional lab environments and their usage should be balanced with the simplicity and physical experience of the student actually being in the lab (e.g., Scheckler, 2003; Sicker et al., 2005).

A suggested way to address some of the drawbacks of online labs is to combine remote labs and virtual labs into hybrid labs (Rodriguez-Gil et al., 2017; Henke et al., 2013; Lei et al., 2018). These labs offer the scalability and cost-effectiveness of virtual simulations, as well as the authenticity of remote labs. While still relatively new, initial evidence suggests that this format is engaging for students and has educational potential (Rodriguez-Gil et al., 2017). Hybrid labs have also been used to refer to the combination of online and real lab sessions. However, there has been little research on this format so far. This type of learning design aims to provide students with the flexibility of remote or virtual labs, as well as real-world hands-on experiences (Zhu, 2010). A recent study in chemistry (Enneking et al., 2019) found that, compared to traditional labs, this format resulted in similar cognitive and psychomotor development for students, but the students were less able to see real-world connections and spent less time reflecting on underlying concepts.

The results of studies on the effectiveness of virtual and remote labs in replacing physical labs are thus mixed, highlighting the need for careful design and adaptation to the educational context. While there is some evidence to support the use of virtual and remote labs, particularly in terms of cost efficiency and flexibility, further research is needed to fully understand the potential of hybrid solutions, which combine the benefits of online and traditional lab environments.

METHOD

This comparative case study (Goodrick, 2014) aims to explore the experiences, challenges and best practices of conducting online labs in engineering education. Four cases of blended and online labs were included in this study based on their participation in the Prameco project. Data was collected through teacher reflections on open survey questions.

The participants in this study were four teachers who reported on their experience conducting online labs in higher education. An open-ended survey was designed to elicit reflections from the participants on their experiences and challenges of conducting online labs. The survey consisted of eight open-ended questions along the dimensions: lab set-up, learner performance, activity and satisfaction, teacher workload, experiences benefits and drawbacks of the lab as well as design recommendations. While we asked the instructors to describe their experiences and challenges in their own words, we invited the integration of further data sources like student evaluations or experiences of co-teachers into the answers. While this approach has clear limitations in terms of the rigor of the data collection methods applied, it enables the integration of different data sources from the four cases that otherwise might be incomparable. The survey was distributed to the participants via email in November 2022 and answers received in December 2022.

The responses to the open-ended survey questions were analyzed and summarized under the themes (1) set-up, (2) student experience, (3) teacher experience and (4) design recommendations. After the data from each case had been analyzed, the cases were compared to identify similarities and differences in the experiences and challenges of conducting blended and online labs. This comparison allowed for a deeper understanding of the factors that influence the success or challenges of online labs.

RESULTS

Set-up and context

In this section, we briefly present the four different lab set-ups as they were implemented in the different universities.

Case 1 Remote live lab: Using and programming an industrial robot (Turku University of Applied Sciences)

The online lab session titled "Introduction to industrial and collaborative robots" was held for students in their second and third years. The session was conducted via Teams due to COVID-19 restrictions, with groups of around 20 students participating. The session lasted for two hours and included interactive elements such as online polls and quizzes. Students were able to see the robot, the robot's user interface and the teacher through video streams and communicate with the teacher through voice and chat. The demonstration was divided into three parts: a warm-up poll to assess students' prior knowledge and ensure they could connect to the online services, a demonstration of various robot capabilities, and a final discussion and poll to assess understanding. The demonstration covered topics such as moving the robot, using the gripper, modifying motion instructions, using the force sensor, and relative motion commands. There were brief discussions and polls after each topic to encourage student participation.

Case 2 Hybrid virtual lab: Using and programming an industrial robot (Tallinn University of Technology)

The practical lab work "Pick and Place Boxes" is part of the course "Industrial Robotics and Advanced Manufacturing - project" for last year's master's program in Industrial Engineering and Management. In previous years, the lab work was conducted in a computer classroom with around 20-30 students participating. The teacher used a projector and whiteboard to explain the task and demonstrate how to use the ABB RobotStudio software to move the robot, teach positions, and write a robot program for picking and placing a box. Students were then tasked with completing the program to have the robot pick and place multiple boxes onto a plate. At the end of the lab work, students demonstrated their completed programs on their own computers. This lab work was one part of several tasks that students had to complete in order to build a virtual robotic production line for a company or factory by the end of the course. In 2022, the lab work was held in a hybrid format, with 4 out of 30 master's students participating online. The teacher used a PowerPoint presentation and the ABB RobotStudio software, an extra screen to monitor the chat as well as a speakerphone to transmit and record their voice. The lab work was transmitted and recorded using BigBlueButton. Students participating online needed to install the ABB RobotStudio on their computers and use two screens, one for monitoring the teacher's work and the other for working with the software.

Case 3 Hybrid lab: Introduction to manual welding (HAW Hamburg)

The lab event related to the "Joining Technologies" lecture at HAW-Hamburg is part of the fourth semester and typically has around 45-70 students. Previously, students were divided into groups of 10-15 for each lab event, which included common welding and joining processes such as such as electrode and gas metal arc welding. The new lab setup includes three stages: *Lab on demand* (short online videos teaching the basics of various processes in preparation for the live labs), *digital live labs* (interactive online demonstrations of the welding process for all students, with several cameras at different angles and student input on different parameters), and *practice welding* (small groups of 10-15 students on site to apply their knowledge). Each stage is completed by a small test students have to pass to continue. By digitizing the lab event, staff can teach all students in the course at once and students can prepare with the Lab on Demand content at their own pace. The labs also expand upon the previous offering of just manual electrode welding to include gas metal arc welding as well.

Case 4 Remote or hybrid lab: Logic control (Chalmers University of Technology)

The course "Logic Control" is given to approximately 100 first-year students and focuses on programming a Programmable Logic Controller (PLC) and a microcontroller, as well as signal conversion through electronic components to enable communication between the two systems. The course includes a few lectures at the beginning, but the main learning activity is a group project task. In a traditional on-campus format, students work on the project in the lab with access to physical components and the ability to test their results continuously. The course has been adapted to one purely online format and one hybrid format. In the online format of the course, students prepare solutions to the project task using simulators at home and are guided by the teacher in online consultation sessions. They must also submit a progress report each week. Twice during the course, students can test their solution with physical hardware during online sessions of 30-45 minutes. During these sessions, the teacher demonstrates the equipment and how the students' work functions. The students must answer questions about their preparations, describe the function of different components, and guide the teacher on how to connect vital parts of the electronics. The function test is used as part of the assessment of the students' knowledge. In the hybrid format, students prepare much of their work at home using simulators and online consultation sessions. They then test their solutions themselves in the lab on five occasions during the course and show them to the teacher. The students can choose to come online to two of the testing occasions. The progress reports are not used in the hybrid format due to the more continuous testing opportunities.

Student experience

In this section, we summarize the teachers' reflections regarding intended and achieved learning outcomes, student activity and engagement during the labs as well as their overall satisfaction with the set-up in the four different cases.

Case 1 Remote live lab: Using and programming an industrial robot (Turku University of Applied Sciences)

The learning objectives of the remote live lab were the same as those of traditional lab exercises - to provide students with an opportunity to learn the basics of collaborative robot operation and programming. The session allowed students to learn through equipment demonstration and lecture, but the learning outcome was potentially not as effective as traditional hands-on lab exercises. However, the perceived learning outcome was good, as most students reported understanding the topics well according to a poll taken after the session. On a scale from 1 to 5, with one representing "I didn't understand" and five representing "I understood well," each of the five topics scored over 4.2, with an average score of 4.3. Unfortunately, there was no report assignment or similar measure to verify the learning outcome for this course implementation. The teacher felt that the students were actively engaged and learning during the session, but this is difficult to confirm. To encourage student participation and engagement in the demonstration and lecture, they were designed to be interactive with discussions and polls. While students were responsive to direct questions, there was not much spontaneous discussion outside of the transition between topics and the closing part of the session. This may be due to the inherent delays in video meeting apps making communication difficult or frustrating. Collaboration assignments between students were not included in this session, but they were identified as an important and necessary aspect for future implementations. The overall response to the two implementations was positive, with no negative feedback received. However, it is difficult to accurately estimate student satisfaction, as this was not measured through a specific survey. Some students may have been disappointed that they were unable to practice with the robot on their own due to COVID-19 restrictions, while others with long commute times may have appreciated the convenience of not having to travel to school.

Case 2 Hybrid virtual lab: Using and programming an industrial robot (Tallinn University of Technology)

The intended learning outcomes of the lab work were for students to understand how a pick-and-place task is carried out by an industrial robot and to be able to teach robot positions in ABB RobotStudio, write a robot program, and simulate its work on a computer. The students also learned that some positions can be calculated and/or shifted in the robot workspace using corresponding functions. All students who participated in the lab work on campus successfully demonstrated their working robot solutions and programs at the end of the class. Of the 4 online students, only one asked for help multiple times and only 2 out of the 4 showed their end result through the virtual classroom software. The other two students completed the lab work several weeks later at the university, stating that during the online session, they were unable to observe the lab activities and use the software at the same time on their computers, despite that the teacher had asked for student input throughout the lab work to check for understanding and offer assistance. The student engagement during the lab work was different between online and on-campus students. In this teacher's experience, Estonian students are generally quiet and do not ask many questions, so the teacher made an effort to go around the computer class and offer assistance as needed. It was more difficult to interact and get responses from students when participating in the lab work online. To encourage student engagement, the teacher redesigned the slides to include questions that all students had to answer and asked for students' names at the beginning of the lab work. Overall, the students' perception of the new setup compared to traditional labs was positive. Two of the online students were happy to be able to participate in the lab work at all as they would have missed the session otherwise and the two other students appreciated a detailed video about the lab work for self-study purposes that the teacher recorded with the virtual classroom software. However, as a limitation the teacher observed that some students tended to postpone the lab work and extend the presentation of their results.

Case 3 Hybrid lab: Introduction to manual welding (HAW Hamburg)

In terms of learning outcomes, the main goals for this lab were for students to gain basic knowledge and skills in various welding technologies, including practical welding skills in electrode and gas metal arc welding. The students were able to achieve these learning outcomes and found the practical welding skills particularly valuable. In addition to learning theoretical knowledge about welding and cutting technologies and processes, the students were also able to observe these processes in action and discuss them with the lecturers during the online live lab events. This combination of being told the knowledge and seeing it demonstrated allowed for a more comprehensive understanding of the material. When it comes to student activity, the new setup has allowed for students to be more self-sufficient in their preparation for the final exam or stage tests, as they are able to collaborate and study together. However, the number of students actively participating in discussions has not seen a significant increase, even though opportunities for discussion and questioning have been expanded. Regarding student satisfaction, feedback on the new setup has been largely very positive. The students particularly appreciated the ability to have more practical welding time and the flexibility in terms of time and location offered by the blended format. The high-quality lab-on-demand videos were also seen as a helpful resource that is available at any time. Other benefits included more practical welding time as result of the course design and the ability to have more and deeper technical discussions due to the basic knowledge gained through the online pre-lab events. On the other hand, some students experienced minor technical issues (i.e., with their internet connection) and there was a lack of a "just in time" option for asking questions during the lab-on-demand portion. Additionally, it has proven difficult to build a "sense of community" in an online setting.

Case 4 Remote or hybrid lab: Logic control (Chalmers University of Technology)

Both the online and the hybrid versions of the course were intended to have the same learning outcomes as an on-campus version of the course, including the ability to work in a group to plan and execute a project, present logical solutions for Programmable Logic Controllers (PLCs) and microcontrollers (MCUs), manage program environments and design control programs for PLCs and MCUs, design components and circuit diagrams, and troubleshoot and verify function. However, it was difficult for students to reach the learning outcome of "realizing electrical circuits" in the online format, as they were not able to physically connect the components themselves. The level of troubleshooting was also lower in the online lab, as the teacher had prepared much of the circuit to minimize the risk for mistakes. In terms of grades, the number of students passing the course was similar between the remote, hybrid and on-campus formats, and highly dependent on their performance and participation in preceding courses. In terms of student activity, all formats saw students being engaged in their projects. However, students tended to finish projects somewhat later in the online format, and those who struggled with planning had a harder time getting started and needed additional encouragement, e.g. through the weekly progress reports. Overall, students were satisfied with the online version of the course and were glad to see their projects working in the online lab. However, they would have preferred to be in the lab to test their projects themselves. In the hybrid format, an element of preparations in the simulators was added in comparison to an on-campus format. That made it somewhat harder for the students, because they had to plan their time better and they sometimes had to troubleshoot their solutions twice, both in the simulator and in the lab.

Teacher experience

In this part, we summarize the teachers' perspectives on workload, benefits and drawbacks of their lab sessions based on their experiences.

Case 1 Remote live lab: Using and programming an industrial robot (Turku University of Applied Sciences)

The teacher assessed the concept of online live lab as a more efficient and effective way to teach and demonstrate the use of equipment, but also stated that it required additional effort compared to traditional lab work. Preparing and running the labs required more work compared to traditional labs (one to two workdays spread over several days), due to the additional steps involved in setting up and designing a demonstration, but also because of the lack of experience with the new setup. Running the remote live lab session was more stressful for the teacher, due to the required multitasking between programming the robot, running quizzes, controlling presentation, explaining the theory and practice of robot programming, managing the different video streams and angles, and monitoring chat, all at the same time. From the teacher's perspective, the benefits of online live labs include the ability to provide safe demonstrations to a large group of students, as well as the ability to record and access the content later, allowing students to review the material at their own pace. It also allows the teacher to interrupt the exercise more frequently to ask conceptual and reflection questions to improve the learning outcome. Additionally, for some students, a guided demonstration may be a better way to learn than self-directed learning. However, they acknowledged some drawbacks of using online labs, such as the lack of certain aspects of work or skills that cannot be learned remotely (e.g., using manual measurement tools). Additionally, not all subjects or applications are well-suited for online labs, as video recording certain equipment or display terminals may be difficult or impractical. Furthermore, online labs lack social interaction and can negatively impact motivation. Finally, the organization of online labs can be complex and requires additional work, which can be challenging for teachers who are unfamiliar with the equipment, software, and methods.

Case 2 Hybrid virtual lab: Using and programming an industrial robot (Tallinn University of Technology)

According to the teacher, the shift to remote laboratory work required some adjustments to the traditional workload and methods, but it also provided new opportunities for flexibility and accessibility for students. The teacher reported that the workload prior to the lab work has increased slightly, with an additional 1.5 hours required for doing the lab work, as well as a maximum of 20 minutes to watch late responders' lab work results. During the lab work, the teacher spent time testing broadcasting options and different equipment, preparing slide shows, and working with the lab work itself. Despite the increased workload, the teacher reported several benefits, a major one being the flexibility it provides to students. They can attend the lab work online from anywhere they are, allowing them to continue their education even when they cannot physically come to the university. Additionally, the teacher was able to record the lab work, which allows students to revisit things when they have forgotten something. There were also drawbacks and challenges. The teacher reported that it can be difficult to know if the recording was switched on or not, and if the correct part of the lab work is being streamed. Additionally, there is a risk of not hearing questions from online students when helping students in the class, and not being close enough to the microphone to be heard by online students. Furthermore, the teacher may forget to repeat questions asked in the class or on the online platform, leading to confusion for online students. However, with the proper preparation and resources, these challenges can be overcome to create a successful remote laboratory experience for students and teachers alike.

Case 3 Hybrid lab: Introduction to manual welding (HAW Hamburg)

The remote live laboratory setup was assessed to have both benefits and drawbacks. The teacher stressed the more efficient and effective way to teach and demonstrate the use of equipment, but also pointed toward the additional work and challenges regarding communication and feedback. Regarding the workload, the teacher reported that although the total number of lab appointments may have been reduced, more preparatory and follow-up work was required to ensure and improve the quality of the labs. This included the time spent scripting, filming, editing, and translating lab on-demand videos, as well as scripting and setting up online lab events. However, the teacher noted that the total workload per lab remains the same, with the majority of the additional work being shifted from preparing for individual lab events to preparing for digital and online alternatives. Numerous benefits of this new lab setup were mentioned. More students were able to attend lab events while maintaining a high level of quality, and there was a higher level of teaching quality for each individual student. Additionally, the further qualification of employees in the areas of digitization and teaching was promoted, and a new technical infrastructure (such as a computer supported, video and sound equipped welding station) was developed. The teacher also noted that staff can now focus more on teaching and less on repeating lab events multiple times. However, there were also drawbacks to this new setup. The teacher notes that communicating with reserved students can be more difficult due to the indirect communication that takes place online. Additionally, there is no direct feedback from students to the teacher through facial expressions or other nonverbal cues. The teacher also mentioned that moderation and teaching can be unfamiliar at first, as speaking to a blank screen rather than speaking directly to students in person can take some getting used to. There is also an element of indirect involvement in the lab through online tools. Altogether the teacher concluded that it is important to consider the pros and cons before implementing a similar setup in other educational settings.

Case 4 Remote or hybrid lab: Logic control (Chalmers University of Technology)

Overall, teachers reported that the hardware and software used in the online and hybrid formats functioned well and supported student learning, as well as student-to-student and student-teacher interaction. In the online format, the teacher workload increased in both the preparation and execution of lab sessions mostly due to the weekly reports and the tests that were conducted in groups of two. These additional tasks added an extra 8 hours of work to the teacher's workload. It was noted that the online consultation sessions were effective in that they allowed to meet and guide more students in an online session than in a lab session and thus were a way to reduce teacher workload. The hybrid format used some extra teacher time in the first setup of simulation tasks and assignments. However, once that is done, there are less lab sessions compared to an on-campus course and the teacher can meet more students in the online consultations. Thus, the hybrid format is more efficient in teacher workload. Despite the increased workload, there were several benefits to the pure online lab setup. One of the biggest advantages was that students could test their solutions and see them work in real equipment, rather than just in simulations. The experience where they saw their concept work provided a valuable learning opportunity for students and allowed them to better understand the concepts they were learning. There were also several drawbacks and challenges. One of the most significant challenges faced was helping students who were struggling to keep up as in particular quieter and less motivated students were found to be less likely to attend consultation sessions and complete their projects on time. Teachers reported that it was easier to motivate these students in a traditional lab setting. Additionally, function tests were an important aspect of the assessment in the course, and were also the only time students could use physical hardware. However, it was sometimes difficult to differentiate between helping and assessing students' knowledge in the remote testing sessions, which can lead to confusion. It was more difficult to keep track of individual student progress within a group in the online format. Thus, written tests and oral discussions are important in online and hybrid formats to determine individual grades.

DISCUSSION

This study was set out to present and compare four cases representing different forms of online and hybrid lab setups in engineering education using teacher reflections as empirical base. Only the first case represents a pure remote online lab, while the other three are different forms of hybrid setups. The comparative analysis of the four cases highlights different perspectives of the teachers about how their workload, necessary equipment, benefits and risk as well as student learning change when shifting from traditional labs to online or hybrid lab sessions. It should be noted that unlike previous research, the shift to a pure online format and a hybrid format has been prompted by the Covid-19 pandemic in most of the cases, which may significantly impact the delivery and student experiences in lab settings (Gamage et al., 2020). As such, the effects of the pandemic and changes in teaching staff have been included in our results, though we have attempted to remove these influences as much as possible for the sake of comparison. However, some residual effects may remain.

All teachers reported additional effort required in the preparation phase of the lab setups though those could partly be compensated through the opportunity to engage a larger group of students in activities compared to the traditional activities. As teachers become more experienced with the new lab setup, higher effectiveness in the preparation might also reduce workload in the future. During the session, teachers were also partly struggling with additional effort requirements in online and blended setups, such as the need to be multitasking, the additional effort of engaging online and campus students at the same time, as well as difficulties regarding student assessment.

In terms of learning outcomes, the cases show that online and blended laboratory setups can achieve similar results that in specific combinations of learning activities can even foster deeper learning as found in case 3. The comparison indicates better learning outcomes for blended set-ups, in which the benefits of online learning can be effectively combined with hands-on elements, while pure online lab exercises are potentially not as effective as indicated by the results from the remote live lab case 1 and the online participants from case 2. Nevertheless, students generally reported high levels of satisfaction, appreciating the flexibility and adaptability of the learning environments. In sum, those results confirm earlier studies suggesting that students achieved similar throughputs in online, hybrid and traditional learning environments (e.g., Brinson, 2015; Enneking et al., 2017) and expressed high levels of satisfaction in each format (Post et al., 2019; Corter et al. 2007). They also mirror global trends of leading engineering education institutions towards "*student-centered learning to large student cohorts through a blend of off-campus personalized online learning and on-campus hands-on experiential learning"* (Graham, 2018, 45, see also Graham, 2022)

Teachers reported increased possibilities for active learning and highlighted advantages of online learning environments over traditional laboratories such as teaching or demonstrating single equipment use to large student groups. On the other hand, they also consistently reported problems to engage with online students and a lack of spontaneous discussion. Thus, the importance for explicit interactive elements such as interactive elements such as online polls and quizzes was stressed. All teachers mentioned the increased accessibility and flexibility of online and blended labs as a main benefit together with the ability to provide safe demonstrations to a large group of students. However, the struggle to engage online students also is an indicator for higher demands on students' ability to regulate and organize their learning (Stöhr et al., 2020). Further, online labs also lack certain aspects of work or skills that cannot be learned remotely, reiterating the superiority of blended labs over pure online solutions (see also Olesen et al., 2021).

DESIGN GUIDELINES

Altogether, the analysis shows that the shift to remote and hybrid lab sessions require carefully considered adjustments in the learning design (see also e.g., Potkonjak et al, 2016), resulting in more work for the teachers. In all four cases, it is noted that the implementation of online and hybrid lab formats poses new challenges for teachers and students, and it is important to carefully design and execute these sessions to maximize their effectiveness. We conclude this paper with a number of design guidelines based on the teacher input from the four cases.

All four cases recommend using good hardware and investing in necessary equipment to ensure a smooth and effective online lab experience. Case 1 emphasizes the importance of making the lab work interactive by posing questions and encouraging students to propose solutions. Case 2 recommends designing the session to prioritize student participation and interaction. It suggests a variety of strategies to enhance participation, such as providing preliminary learning assignments, incorporating pauses for discussion, using quizzes, and assigning group tasks. It also recommends enlisting the assistance of a colleague to manage the presentation and chat and evaluating the possibility of equipping the lab space with audio visual (AV) equipment for remote learning sessions. Case 3 emphasizes the importance of familiarization with multimedia infrastructure, investment in hardware, development of streaming routines, and extensive preparation. Further, it highlights the importance of good hardware, moderation, and tailoring concepts and scripting to specific labs and lab topics. Case 4 recommends finding simulators that work for testing project results and meeting with students to assess individual performance. All four cases also recommend familiarization with multimedia infrastructure and the development of streaming routines as important for the success of the online lab. A list of the design recommendations can be found in Table 1.

Table 1. Guidelines: Implementing a online or blended lab set-up

Guidelines: Implementing a online or blended lab set-up
• Utilize best practices and proven equipment that align with your specific requirements and needs.
• Prioritize student participation and interaction, experimenting with ways to improve engagement.
• Assign preparatory learning tasks to prepare students for the session.
• Incorporate breaks between topics to allow for discussion, taking into account the potential delays of video meeting apps.
• Utilize online polls and quizzes, and group discussion or writing tasks during the session.
• Provide students with opportunities to direct the course of the demonstration and to test their own hypotheses.
• Ask questions directly to students
• Consider assigning a reporting assignment and instructing students to take notes during the session.
• Utilize an assistant to manage the presentation, video streams, and chat during the session to allow the teacher to focus on teaching.
• Invest in dedicated AV equipment for remote learning sessions such as multiple movable cameras, tripods, microphones, and pre-configured computers with software.
• Allow for ample teacher preparation time, including multiple test runs to familiarize yourself with the new setup.
• Be mindful that there is no one-size-fits-all solution and each lab event and topic may require its own unique setup.
• Meet with students to assess individual performance

CONCLUSIONS AND FUTURE WORK

In conclusion, this study aimed to present and compare four cases of different forms of online and hybrid lab setups in engineering education, using teacher reflections as the empirical base. The findings of the study indicate that while online and blended laboratory setups can achieve similar results to traditional labs, blended or hybrid setups seem to provide better learning outcomes. Additionally, it was found that the implementation of online and hybrid lab formats poses new challenges for teachers and students, and it is important to carefully design and execute these sessions to maximize their effectiveness. Considering these findings, the study provides a number of design guidelines based on the teacher input from the four cases, including the use of good hardware and investment in necessary equipment, the use of interactive elements such as online polls and quizzes, and the need for explicit strategies to engage online students. Further comparative research is needed to gain more insight into the area, such as meta studies and comparisons of multiple single-case studies to validate the transferability of our guidelines to other programs and lab contexts.

FINANCIAL SUPPORT ACKNOWLEDGEMENTS

The work was funded by the European Union Erasmus+ programme, grant number 2020-1-DE01-KA226-HE-005760. This is gratefully acknowledged.

REFERENCES

Brinson, J. R. (2015). Learning Outcome Achievement in Non-traditional (Virtual and Remote) versus Traditional (Hands-on) Laboratories: A Review of the Empirical Research. *Computers & Education*, *87*, 218–237. https://doi.org/10.1016/j.compedu.2015.07.003

Chen, X., Song, G., & Zhang, Y. (2010). Virtual and Remote Laboratory Development: A review. In *Earth and Space 2010: Engineering, Science, Construction, and Operations in Challenging Environments*, 3843–3852.

Corter, J. E., Esche, S. K., Chassapis, C., Ma, J., & Nickerson, J. V. (2011). Process and Learning Outcomes from Remotely-operated, Simulated, and Hands-on Student Laboratories. *Computers & Education*, *57*(3), 2054–2067. https://doi.org/10.1016/j.compedu.2011.04.009

Corter, J. E., Nickerson, J. V., Esche, S. K., Chassapis, C., Im, S., & Ma, J. (2007). Constructing Reality: A study of Remote, Hands-on, and Simulated Laboratories. *ACM Transactions on Computer-Human Interaction*, 14(2), 7-es. https://doi.org/10.1145/1275511.1275513

de Jong, T., Sotiriou, S., & Gillet, D. (2014). Innovations in STEM Education: The Go-Lab Federation of Online Labs. *Smart Learning Environments*, 1(1), 3. https://doi.org/10.1186/s40561-014-0003-6

Enneking, K. M., Breitenstein, G. R., Coleman, A. F., Reeves, J. H., Wang, Y., & Grove, N. P. (2019). The Evaluation of a Hybrid, General Chemistry Laboratory Curriculum: Impact on Students' Cognitive, Affective, and Psychomotor Learning. *Journal of Chemical Education*, *96*(6), 1058–1067. https://doi.org/10.1021/acs.jchemed.8b00637

Gamage, K. A. A., Wijesuriya, D. I., Ekanayake, S. Y., Rennie, A. E. W., Lambert, C. G., & Gunawardhana, N. (2020). Online Delivery of Teaching and Laboratory Practices: Continuity of University Programmes during COVID-19 Pandemic. *Education Sciences*, 10(10), 291. https://doi.org/10.3390/educsci10100291

Goodrick, D. (2014). Comparative Case Studies, *Methodological Briefs: Impact Evaluation* 9, UNICEF Office of Research, Florence.

Graham, R. (2018). *The Global State of the Art in Engineering Education*. Massachusetts Institute of Technology (MIT): Cambridge, MA, USA. https://www.rhgraham.org/resources/Phase-1-engineering-education-benchmarking-study-2017.pdf

Graham, R. (2022). *Crisis and catalyst: The impact of COVID-19 on global practice in engineering education*. Massachusetts Institute of Technology (MIT): Cambridge, MA, USA.

Henke, K., Ostendorff, St., Wuttke, H.-D., & Simon, St. (2013). Fields of Applications for Hybrid Online Labs. *2013 10th International Conference on Remote Engineering and Virtual Instrumentation (REV)*, 1–8. https://doi.org/10.1109/REV.2013.6502899

Hofstein, A., & Lunetta, V. N. (2004). The Laboratory in Science Education: Foundations for the Twenty-first Century. *Science Education*, 88(1), 28–54. https://doi.org/10.1002/sce.10106

Lei, Z., Zhou, H., Hu, W., Deng, Q., Zhou, D., Liu, Z.-W., & Lai, J. (2018). Modular Web-Based Interactive Hybrid Laboratory Framework for Research and Education. *IEEE Access*, *6*, 20152–20163. https://doi.org/10.1109/ACCESS.2018.2821713

Lynch, T., & Ghergulescu, I. (2017). Review of Virtual Labs as the Emerging Technologies for Teaching STEM subjects. *Proceedings of the 11th INTED conference,* 6082–6091.

Nedic, Z., Machotka, J., & Nafalski, A. (2003). Remote Laboratories versus Virtual and Real Laboratories. *33rd Annual Frontiers in Education, 2003. FIE 2003.*, *1*, T3E-T3E. https://doi.org/10.1109/FIE.2003.1263343
Olesen, V., Stöhr, C., Enelund, M., & Malmqvist, J. (2022). Learning Mechatronics Using Digital Live Labs*. Proceedings of the 18th International CDIO Conference*, 831–847.
Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual Laboratories for Education in Science, Technology, and Engineering: A Review. *Computers & Education*, *95*, 309–327. https://doi.org/10.1016/j.compedu.2016.02.002
Post, L. S., Guo, P., Saab, N., & Admiraal, W. (2019). Effects of Remote Labs on Cognitive, Behavioral, and Affective Learning Outcomes in Higher Education. *Computers & Education*, *140*, 103596. https://doi.org/10.1016/j.compedu.2019.103596
Rodriguez-Gil, L., García-Zubia, J., Orduña, P., & López-de-Ipiña, D. (2017). Towards New Multiplatform Hybrid Online Laboratory Models. *IEEE Transactions on Learning Technologies*, *10*(3), 318–330. https://doi.org/10.1109/TLT.2016.2591953
Scheckler, R. K. (2003). Virtual labs: A Substitute for Traditional Labs? *International Journal of Developmental Biology*, *47*(2–3), 231–236.
Sicker, D. C., Lookabaugh, T., Santos, J., & Barnes, F. (2005). Assessing the Effectiveness of Remote Networking Laboratories. *Proceedings Frontiers in Education 35th Annual Conference*, S3F-S3F. https://doi.org/10.1109/FIE.2005.1612279
Stöhr, C., Demazière, C., & Adawi, T. (2020). The Polarizing Effect of the Online Flipped Classroom. *Computers & Education*, 147, 103789. https://doi.org/10.1016/j.compedu.2019.103789
Wang, J., Guo, D., & Jou, M. (2015). A Study on the Effects of Model-based Inquiry Pedagogy on Students' Inquiry Skills in a Virtual Physics Lab. *Computers in Human Behavior*, *49*, 658–669. https://doi.org/10.1016/j.chb.2015.01.043
Zhu, J. (2010). A Hybrid Online-education Strategy for Delivering Engineering and Technology Courses. *2010 International Conference on Networking and Digital Society*, *2*, 448–451. https://doi.org/10.1109/ICNDS.2010.5479464

BIOGRAPHICAL INFORMATION

Christian Stöhr is Associate Professor at the Department of Communication and Learning in Science (CLS) at Chalmers University of Technology. His research concerns both formal and informal aspects of learning, in particular technology-enhanced learning, lifelong learning and public understanding of science.

Veronica Olesen is Senior Lecturer in Industrial Control and Head of the Mechatronics program at Chalmers University of Technology. Her focus areas are education and development of courses and programs. Her research also concerns automatic control and automation in the pulp and paper industry.

Shahram Sheikhi is Professor of Materials Science and Joining Technology. Currently he is heading the laboratory of joining technology and is the head of a research and transfer center (FTZ3i) aiming to transfer knowledge in the field of applied digitalization by means of continuing education. His research topics include automation in joining technology, the use of robots in surface technology, 3D printing and sustainable production. He has introduced digitalization into teaching and developed new teaching formats for his classes in joining and material's science.

Robert Langer studied Mechanical Engineering (B.Sc.) and is currently doing his Master at the University of applied sciences HAW Hamburg. Since 2020 he is research associate engineer with a background in welding technologies.

Vladimir Kuts is a senior researcher and the Head of Industrial VR&AR Laboratory in the Mechanical and Industrial Engineering department of Tallinn University of Technology. His current research focuses on human-robot interaction methods validation enabled by Immersive technologies Digital Twins.

Margus Müür is a lecturer and the Head of Flexible Manufacturing Systems and Robotics Demo Centre in the Mechanical and Industrial Engineering department of Tallinn University of Technology. His current research focuses on industrial robots and automation.

Antti Nousiainen is a project and research engineer in the School of Mechanical Engineering at Turku University of Applied Sciences with a background in robotics and industrial automation.

Ari Putkonen is a researcher and principal lecturer in the School of Mechanical Engineering at Turku University of Applied Sciences. His current research interests include electric drivetrains of working machines and marine vessels, including vehicle data communication, and learning of mechanical engineering skills in laboratory environments.

Sakari Koivunen is a senior lecturer in the School of Mechanical Engineering at Turku University of Applied Sciences. He specializes in robotics, automation, and the integration of innovative teaching methods in education.

Yihua Zhang is a Ph.D. student at the department of Communication and Learning in Science (CSL) at Chalmers University of Technology. She studies the impact of digitalization on Engineering Education.

Jens Kabo is Senior Lecturer at the Department of Communication and Learning in Science (CLS) at Chalmers University of Technology. His research has explored students' conceptions of concepts such as engineering, social justice, sustainability, and technology and now focuses on aspects of online and digitalized engineering education.

Mikael Enelund is a Professor and Dean of Education at Chalmers University of Technology. His current research focuses on education management and development.

Johan Malmqvist is a Professor in Product Development and Head of Division at Chalmers University of Technology. His current research focuses on information management in the product development process and on curriculum development methodology.

Corresponding author

Christian Stöhr
Chalmers University of Technology
Department of Communication and Learning in Science (CLS)
412 96 Gothenburg, Sweden
christian.stohr@chalmers.se