Transitions in Teaching Mechanical Engineering During COVID-19 Crisis

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Abstract. The quality of teaching in mechanical engineering greatly depends on the practical application of the fundamental theory taught. During COVID-19, limited access to in-class lectures, practical courses with demonstrator plants, and active student participation forced us, an institute of a mechanical engineering faculty in the German higher education system, to transform the teaching strategy in a limited time of one month. For class sizes of between ~25 and ~700 participants, mainly addressing mechanical, electrical and software engineering students, we share challenges and successes in our transformation strategy during April-October 2020. Furthermore, we present a collection of suitable tools, their functions, advantages, disadvantages, and feedback from three sources to provide profound assessment and adaptation criteria in digital teaching. Using quantitative evaluations of four lectures in automation and information systems over the past five years, we highlight the experience from the students' perspective and evaluate our digital teaching methods compared to well-established in-class formats. This compilation of causes and consequences clarifies the effort involved in achieving the result and discusses the potential of digital teaching or hybrid teaching in engineering.

Keywords: online education, teaching strategy, automation and information systems, mechanical engineering, COVID-19

1 Introduction

Due to the lockdown in Germany starting March 18, 2020 [1, 2], universities were closed for a while and teaching in the summer semester starting mid of April was required to change to online teaching on short notice. To us, the reported changes concern four lectures, and four practical courses (cp. Tab. 1). The decisions and challenges faced contribute to the key results in this work. We introduce the constraints, digital learning tools, interactive teaching methods, and new forms of remote examinations/e-tests to support efficient learning during the global pandemic (cp. Chapter 2). Then, we introduce the teaching procedure and strategy we chose to pursue, explaining the transition from classical classroom teaching concepts to all-digital ones during the pandemic (cp. Chapter 3). Three sources of qualitative student feedback reflect first-hand feedback on the conceptual design, the strategy, and the implementation. We conclude our results in tables with assessment criteria that enable future digital teaching adaptations (cp. Chapter 4). Applying retrospective analysis on the students' participation rates and the lecture evaluations of the past five years, we further evaluate the subliminal perception of engineering students about the online education measures applied. With the numbers and student feedback, we discuss our experiences, challenges encountered, and possible future concepts, as well as the threats to the validity of our study (cp. Chapter 5).

2 Background and Related Work

The unexpected COVID-19 outbreak forced the education strategies of German universities, just as international education institutes, to transform to another level. Bao [1] reported on the sudden change in Chinese education, that "most faculty members face the challenges of lacking online teaching experience, early preparation, or support from educational technology teams." Some faculties struggled with novel technology and a number of limitations to the platforms [2]. Many Chinese universities reported this transition in February 2020 [3]. A delay for the Chinese summer semester was reported for many universities to be one month [3]. In Italy, the Italian Minister of University and Research announced that universities would switch to online lessons (March 2) while imposing the shutdown of all schools (March 4). Due to the autonomy practiced by the 16 German states in educational matters, the approaches to tackling COVID-19 have also been diverse, e.g., the Heidelberg University immediately announced a campus shutdown (March 22), while the University of Passau introduced various measures to implement home office (March 12) and its closure (March 24) [3].

Methods to Encourage Students' Motivation and Participation. Students often lack self-discipline, suitable learning materials, and good learning environments studying self-isolated at home, as important non-verbal communication is reduced or missing [1]. Although it is impossible to control the learners' motivation, the systematic motivational design is effective when used properly [4]. Fryer and Bovee [5] state in a study that the direct contact to the lecturer and his perceived interest in his students' learning success directly influences the motivation of students in e-Learning. Self-reported answers from students show that the efficient use of the study and the need to stick to the schedule is hard, despite other factors, e.g., subject matter, ability to understand the contents, curiosity, are high [6]. Bao [1] recommends measures, e.g., to split lecture recordings into subtopics of 20-25min to help the students to remain focused during their self-study. Flipped classroom models, online practice questions, teleconferencing, and facilitated use of videos may not be a substitute for hands-on learning through operative experience, but ways to mitigate the loss of learning exposure during this time [2]. For more than 20 years, distance-teaching universities (e.g., Distance Learning University Hagen) have been practicing a hybrid system of online courses, virtual seminars, and trainings [7]. The learning progress monitoring is adjusted accordingly, and the students receive feedback. In order to keep the students' learning progress on track, learning progress control mechanisms are essential [8]. However, engineering students require next to the usual syllabus, a deeper practical level, e.g., program and implement the code at a lab-sized production plant [9]. Therefore, in contrast to classical e-Learning platforms/MOOCs (KHANacademy [10], edX [11]) or remote lab approaches (Labshare [12], NetLab [13]), a holistic and interactive platform is required to support students' learning success [9]. Cohen and Magen-Nagar [14] suggest that project-based learning subjects have a significant positive impact on motivational orientations and learning strategies. Thiessen and Vogel-Heuser [8] proposed a web-based training in engineering sciences using Mechanics as an example. The product model maps the teaching of engineering sciences onto the education medium computer, which joins the diverging objectives "didactic quality" and "productivity" of the software development. This toolkit developed for engineering students incorporates theory, exercises, simulation, and scenarios close to the gap to real-world problems, where an appropriate implementation of high-quality education frameworks would cost up to 300t€ [8]. Ping et al. [15] introduced a Problem-Based-Learning-Concept, to motivate students during online teaching, yet, no information on student feedback, results of the concept, or information on evaluation study is given. Kolar et al. [16] stated their experiences with sudden online education in their Mathematical Analysis course (819 participants) at the Faculty of Electrical Engineering and Computing in Croatia. They analyzed the view rates of students of lecture recording during the semester to investigate the learning behavior in online education. However, their teaching concept and the students' feedback were not stated. Barr et al. [17] report from their experience on three distinct teaching patterns they tried during their transfer of a software engineering lecture to an online format. They faced challenges, e.g. practical exercises and group work. However, they did not consider other quantitative data to map to the qualitative student feedback, but only investigated one course instead of a trend spanning several courses and course types. Väljataga et al. [18] and Gaudiot et al. [19] focused on the transition from the teacher's perspective and reported on additional infrastructure and educational technologists necessary for the transition and that "the online classes effectively improved the quality of education" [19].

Online Education, Platforms, and Tools. All technical concepts for online education require stable digital infrastructures and platforms [20], yet the robust data on the spread of digital infrastructure in German education is not always available [21]. The platforms and tools used in this study are shortly introduced in this section. Moodle is used as the central learning platform in which lecturers provide materials and many different activities for communication, collaboration, and self-learning [22], e.g., forums or e-tests. For online lecturing and communication purposes that allow learners' engagement from any location, we use a variety of videoconferencing apps such as Zoom [23], Microsoft Teams [24] or meet.lrz [25], whereas the latter is a university-specific-version of the open-access tool Jitsi Meet [26]. A formal tool comparison is given in [27], however, they just compared the basic, non-paying packages. The lectures and exercises were pre-recorded using Camtasia [28], OBS Studio [29], or Microsoft PowerPoint [30]. The *EvaSys* [31] is an online evaluation platform, which is frequently used in German universities (e.g., TUM, LMU, RWTH Aachen, KIT).

3 Teaching Procedure and Strategy

In this chapter, we introduce the structure and strategy applied during the transition from in-class to online lecturing. Starting with the classical way, we explain our concept to transform teaching during COVID-19. Then, we discuss the modern digital learning tools, interactive teaching methods used regarding the characteristics, and the education strategy based on experiences from four lectures and practical courses (cp. Tab. 1).

Tab. 1. Basic information of the four mechanical engineering lectures and four practical courses of this paper

Lecture	Content	Group size
Principles of Modern Information Technology II (IT2); 2nd-sem. undergrads – mandatory	Basics in information techniques like digital technique, electronic communication or modeling [32], C programming, and application to a demonstrator plant (plant exam, Fig. 1).	~ 700
Industrial Software Engineering for Engineers I (Sefi1); 4th/6th-sem. undergrads - voluntary	Interdisciplinary modeling and software engineering, C++ Programming	~ 300
Industrial Software Engineering for Engineers II (Sefi2); Graduate students - voluntary	Specific phases of Software Engineering, such as requirement management or quality assurance.	~ 100
Development of Distributed Intelligent Embedded Mechatronic Systems (ISMLP) Graduate students - voluntary	Conveys a structured development methodology for intelligent mechatronic systems	~ 250
Practical Course	**Content**	
Automation (A-P) - voluntary	Student teams use programming languages of IEC 61131-3 to write code of a automation demonstrator plant, consisting of sorting, filling, closing, and commissioning of bottles.	Before COVID-19: ~ 20 Now: ~ 40
Industrial Software Engineering for Engineers (C++) (Sefi1-P)- voluntary	Extends Sefi1. Students apply their C++ knowledge and implement the control development for the robot FORBOT A4 (Roboterwerk) based on Raspberry Pi.	Before COVID-19: ~ 20 Now: ~ 25
Development of Distributed Intelligent Embedded Mechatronic Systems (ISMLP-P) - voluntary	Extends ISMPL. Students develop intelligent control code using IEC 61131-3, UML, OCL, petri nets, and model transformations.	Before COVID-19: ~ 20 Now: ~ 40
Simulation Technology (SimT-P) - voluntary	continuous and event-driven process simulation with Matlab/Simulink and its state machine toolbox Stateflow.	Before COVID-19: ~ 20 Now: ~ 40

3.1 Classical Teaching Strategy

Lectures and Exercises. A conventional mechanical engineering (mech. eng.) course consists of 13-15 in-class lecture units (90min) and exercise blocks (45min), with the lecture materials provided via Moodle. Some courses offer consultation and mandatory or voluntary practical training. During the in-class lectures, the lecturer introduces the subject's theory, including application examples and motivating methods like polling questions to sample the students' understanding of the content. For direct communication between lecturers and students, students can ask questions in/after the lectures and exercises, and visit the lecturers' consultation hours for face-to-face discussion. For most courses, we invite experts from renowned companies to give guest lectures for integration perspective on academic topics and industrial insights.

E-Tests as Midterm Examination. Programming and modeling skills taught are only beneficial in combination to continuous practical application [33]. Therefore, our courses include regular assessments (e-tests). Students need to solve three e-tests and a programming task on a real plant to pass the course IT2 (cp. Fig. 1). We use Moodle with the Compiler Coderunner. It runs the students' code against predefined test cases for automatic feedback and manual correction is required. Before the COVID-19 transition, the e-tests are taken in-class in computer rooms under supervision.

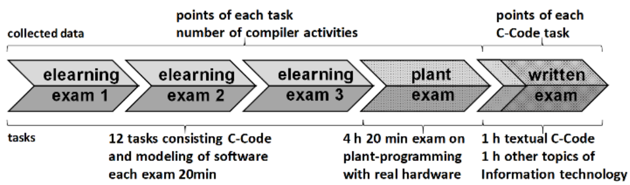

Fig. 1. Overview on regular assessments, plant programming task and written exams [33].

E-Exercises. Students work on weekly voluntary electronic exercises to repeat the lecture content and prepare themselves for the e-tests (cp. Fig. 1) [32]. The e-exercises via Moodle are additionally used for live programming during the lecture. The web-based format enables the access with students' mobile devices [32].

Tutor Office hours (7x 1h per week) support students of *IT2* frequently in their continuous learning. For every tutor office hour, five tutors are available who can help 10-20 students.

Practical Courses and Plant Exam. Smaller student groups apply their theoretical knowledge to practical use cases and model, program, and operate different educational plants of the institute, while following a structural guide and getting support by tutors. With the real hardware, they learn the functionality of actuators and sensors and aspects such as physical side effects. Not only do students benefit from technical but also from team communication and coordination skills.

3.2 Concept for Online Teaching in Summer Semester 2020

Due to the infrastructural weaknesses, breakdowns of web at the beginning of the shutdown, and many employees in home office, asynchronous lectures were recommended [34]. A completely synchronous lecture would require scalable software systems and a good internet connection for both the lecturers and the students [34]. Thus, all lectures were recorded and made available at the initially scheduled lecture online slot, accessible for students during the whole semester. We offered additional interactive question rounds and consultation-hours for individual feedback. Online forums moderated by junior lecturers fostered student collaboration and exchange.

3.3 Transition of Teaching Procedure and Strategy

We had one month to adapt the course materials and transform the lecture contents to benefit the students learning from home. With these constraints, we redesigned our contents (cp. Fig. 2).

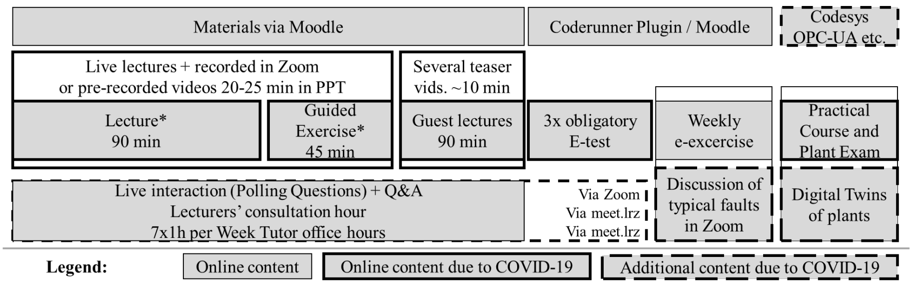

Fig. 2. Overview on transformation of teaching contents during COVID-19 pandemic

Teaching Procedure and Strategy. We decided to either pre-recorded in several 20-25 min sessions or recorded as a 90min session live in Zoom. By providing the usual 90 min-lectures in smaller sections, students obtained a more precise knowledge structure in the curriculum. The videos also buffered faster during streaming due to their reduced file size, which was especially helpful for students abroad with weak internet connections. Recording during live lectures in Zoom offers the opportunity to interact with the students. Questions can be posed and answered, and the vocal speed of the lecturer can be adapted to the students' comprehension of the content. Instead of guest lectures, up to six industrial teaser videos (5-10 min) were offered per course. Due to the simple and fast recording for the guest lectures, the recording function of PowerPoint was selected, without high additional learning or tool handling effort, as several lecturers struggled with the technical skills needed to adapt in-person classes to remote learning [35]. Weekly, the students could solve additional self-tests and hand-in the tasks. The employees corrected the results and discussed anonymized results and typical faults live via Zoom to sensitize the students for the examination [36].

Tutor office hours. During COVID-19, the tutors were available in the online meeting room via meet.lrz (7x 1h per week). If a student required consultation, they could book a meet.lrz-consultation hour with a tutor. Thus, in contrast to the original tutor office hours, the online tutor office hours were mainly 1:1-consultations. Students who did not have any questions but preferred to listen to the questions of fellow students used the Moodle forum or the live-session for that purpose.

Regular assessments (e-test). As the assessments were already e-tests in Moodle, they were not required to change their form. However, the e-tests and the supervision with Proctorio faced challenges in ensuring the equal treatment of students in examination situations due to technical issues, e.g., computer availability, fluctuations in the students' internet quality, high server load, and thus longer loading times due to simultaneous access to the platform by students. Towards the end of the assessment, all students submitted their programming tasks at once, which resulted in an overload in Coderunner compiler. Therefore, we changed the format to an asynchronous one later.

Plant Exam. While parts of digital twins were already available and thus reusable for the practical courses, those for the *IT2* plant exam had to be created from scratch. The digital twins were provided via Moodle in the e-exercise format as it is well-known by the students. Further, Moodle enables mutual access and lower technical infrastructure requirements than virtual machines so that all ~700 students were able to participate without major coordination effort. However, graphically complex simulations and the joint commissioning of the whole plant had to be dropped because of this technical compromise and the sudden transfer to online teaching.

Digital Twin in Practical Courses and Connection to Real Plant. Practical courses were fully transformed into online courses. Simulation models are developed as a digital twin of the real plant and is used for testing and validating the manufacturing control code. The goal is to correctly automate the simulation in order to be able to later commission the manufacturing behavior directly on the specified system. As an overview of the implementation of such a digital twin, a simulation model is developed using the diagram "Stateflow" of Simulink®. The simulation environment focuses on the states and transitions of the manufacturing behavior (processes). In the states, actions are assigned to actuators, while the transitions are mostly related to sensor signals. Meanwhile, the control code is written in Codesys® following the standard IEC61131-3. In order to connect the simulation model to the Codesys, OPC-UA is used. In this case, the global variables that have to be sent from the Codesys to the Matlab simulation environment are written into the OPC-UA server. Therefore, on the Codesys side, it is necessary to activate the "Gateway" and get the IP address and port for the OPC-UA connection. On the Matlab simulation side, a function is provided to connect to the Codesys and receive the variables from Codesys via the OPC-UA connection with the provided IP and port on the Codesys. Finally, the variables received in this function are transferred to the plant's simulation (Stateflow) model, and it reacts to these variables accordingly. For transforming this practical course into an online one, significant efforts have been made with the development of the digital twin, i.e., developing a simulation and connecting it with the programming environment of control code. Considering the efforts to adapt the scripts and materials for students to study from home, around 80 hours have been invested to achieve this. Major challenges with online-practical courses are multifold: objective adaptation, student experience, hardware, and software limitations. However, the immersive experience can hardly be provided as students have to work independently at home and communicate with other students and the lecturers via web-conferences. Hence, a series of introductory videos on the machine operation, software handling, and method application were recorded for students to explore the unknown course intuitively with guidance. Four groups of 40 students from June to September 2020 participated in the practical courses. Most of them have shown their appreciation for the new form of such an online course and completed this practical course successfully.

4 Qualitative Student Feedback

Even though concepts on good distance learning are well known, sophisticated frameworks could not be introduced on such short notice. Although the online transformation of the educational contents requires the redesign and creation of new audio/video contents, the digital contents and the therefore induced larger datasets repays the extra effort with additional statistics for further analyses and knowledge of the students' learning behavior. This section introduces the monitoring and evaluation strategies and the results of three sources of qualitative student feedback. We conclude our learnings in tables providing strategies and tools for future digital teaching adaptation (cp. Tab. 3 and Tab. 4).

4.1 Digital teaching evaluation

The mech. eng. student council conducted an informal evaluation at the end of the summer term 2020, among students of all semesters regarding the digital teaching concepts of the different mech. eng. lectures to collect and rate the different experiences of both – students and lecturers. The results were a collection of methods that students rated as "best practices". Students liked the possibility to access learning material in advance to enable a self-determined learning pace but also clear guidance by when the learning material should be worked on. The self-tests we offered contributed well to this concept. Further, the possibility to get in touch with the lecturer live, e.g., via web conference, was strongly emphasized in all lectures. Using Fig. 3, we show the maximum number of online viewers simultaneously during the webinar, excluding panelists (hosts), we could identify the phenomenon that the dropout rate is evidently lower compared to the in-class lectures. At the final lecture (cp. Fig. 3, Week 12), the participation rate is counted by Zoom as 291 students. In contrarily, although we could not count the students' in-class participation, the final lecture's participation only reaches 150 students at its maximum. The students' participation numbers in the weekly tutor consultation hours show great decrease in the first three weeks, yet seem to be rather constant in the weeks 4-11. In the final week, the participation rate slightly increases. Regarding questions in the forums, we could identify similar decreasing effects, i.e. for weeks 1-4 – 83 questions; for weeks 5-8 – 58 questions, and for weeks 9-12 – 46 questions.

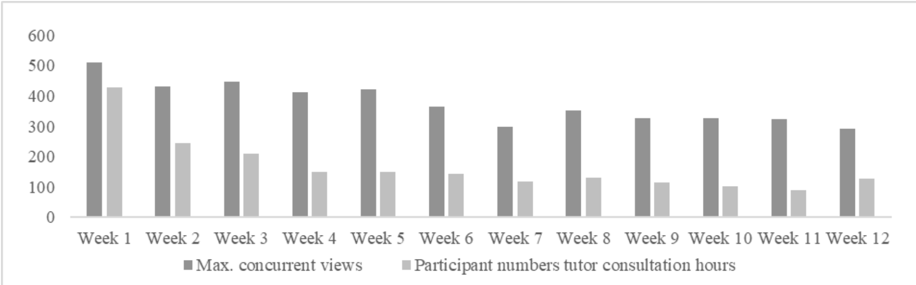

Fig. 3. Weekly numbers of "Principals of Modern Information Technology II" (IT2) during COVID-19 pandemic via Zoom

4.2 Results of the student representative interviews

We conducted interviews with elected **student representatives** of the semester. Two interviews of 45 min, the first one after one month of online teaching and the second in the middle of the semester, revealed the attendees' general perception of *IT2* (based on a questionnaire with 350 students). The students mainly addressed the technical issues they have encountered with the e-tests, which we were also aware of. Longer loading times e.g. due to unstable internet connections, shortened the students' test time. The weekly Zoom live sessions were extremely popular to address problems and react to the students' requests. A third of the students wish for more information or even a database about mistakes typically made in *IT2*-exams. 70% of the students did not know how to book a tutor office hour. Yet even through instructions were sent over different channels, the numbers only increased slightly as students seemed to prefer forums For the lecture script, the students wish to have more examples of application and a summary per chapter for better structure. Students wish for a full set of exercise videos and more vocal explanations during programming.

4.3 Lecture-based evaluations with EvaSys - qualitative results

Lecture-based evaluations were conducted via the EvaSys platform. This section presents students' most mentioned preferences during online teaching. For the coding of the students' opinions, we applied the pattern coding method by Miles et. al [37]. The cohorts' characteristics can be taken from the following table (cp. Tab. 2).

Well-liked features

- Students wish this online format to continue similarly post-pandemic for flexible study environment, esp. independent of time and location.
- At first, the students were overwhelmed by the amount of material and lost track. Yet, when they got used to the new organizational form and they got along even better with the course material.
- Students enjoyed that some lectures uploaded the pre-recorded contents entirely within the first weeks or even already in March. This allows for free time management, and they ask for it to be continued.

- The students appreciated that their improvement suggestions from the forums and consultation hours were taken up.
- "A lot of effort is put into the requests and wishes of the students. A lot of attention has been paid to the fact that everyone has the opportunity to ask questions and that everyone understands the basics."

Suggestions for improvements

- In the beginning, e-tests were carried out synchronously. Based on the geographical distribution, students had to get up early/stay up late to take the e-tests; 1,3 % of the students accessed the e-test from UTC +4 to UTC+13, 3,5 % from UTC-3 to UTC-10, while 95,1 % had no issues (UTC-2 to UTC+3).
- Students wish to attend the lecture in a in-class session of the lecturer
- Students remark that if they use all additional offers, everything becomes very tight in terms of time
- Students state that there are too many e-tests in addition to the practical courses
- We received suggestions to structure the Moodle lecture pages more clearly, to make important information visible despite the increasing scope of material.
- The assessment dates were later than usual due to the lecture re-planning, which led to higher learning effort for students towards the end of the semester.
- Technical problems occured during the e-tests; therefore, solutions for a fair evaluation were negotiated with students and faculty.
- Students describe the problem that they do not dare to ask questions in the Moodle forum if there is low activity.

Tab. 2. Cohorts' characteristics in regard to their study program

IT2		SEFI2	
Mechanical engineering	**82.90%**	Mechanical engineering	**53.80%**
Chemical Engineering	**10.60%**	Mechatronics and robotics	**24.40%**
Mechatronics and robotics	**2.70%**	Automotive Engineering	**4.20%**
Mechanical Engineering	**0.50%**	Mechatronics and Informatics	**3.40%**
Technical and Man. Business Administration	**0.40%**	Medical techn. and assistance sys.	**2.50%**
SEFI1		**ISMLP**	
Mechanical engineering	**49.80%**	Mechanical engineering	**42.20%**
Electrical Engineering and Information Techn.	**21.50%**	Mechatronics and robotics	**25.10%**
Technical and Man. Business Administration	**5.70%**	Mechanical engineering design, production and management	**6.30%**
Ergonomics - Human Factors Engineering	**3.40%**	Automotive Engineering	**4.60%**
Computer Science	**3.40%**	Medical techn. and assistance sys.	**3.00%**
Management and Technology (TUM-BWL)	**2.70%**	Mechatronics and Informatics	**2.60%**

4.4 Comparison of Activity, Implementation Strategies, Tools, and Functions

We conclude our learnings in the following two tables providing a comparison of strategies and tools for future digital or hybrid teaching. Tab. 3 summarizes the implementation strategies required for our teaching plans. The implementations of the methods of Tab. 3 are represented in the "function" columns of Tab. 4. There, we compare systems and tools at which point these are suitable for distinct functions, group sizes, and operations. According to Kuo's definition [38], a small class has less than 25 students, whereas a large class has more than 75 students. Based on actively participating students, *IT2* and *Sefi1* are considered large classes, *ISMLP* and the practical courses *Sefi1-P* and *SimT-P* are medium classes and lecture *Sefi2* and the practical courses *A-P* and *ISMLP-P* are small classes in Tab. 4. The operation section indicate our use of the tools in lectures, exercises, or exams, where the assignment of the "student usage" refers to the sum of all courses considered with a stepwise assessment of 0-25-50-75-100 %. The symbols "+, o, -" rate at which point the tools are suitable for the function. In case, a function is only applicable in combination with another tool or implicate large implementation efforts, "o" for restrictedly suitable is assigned. According to the Microsoft support in March 2020, the maximum capacity of MS Teams is 250 people in one meeting [39], while in contrary, Zoom suits better online teaching [40].

Tab. 3. Advantages and disadvantages encountered by authoring chair in teaching procedures and strategies; *Student feedback from qualitative evaluations (cp. 4.1, 4.2, 4.3) [percentage % of/number of participated cohort].

Type of activity	Implementation	Advantage	Disadvantage	Student Feedback*
Lecture and exercise	Pre-recorded 20-25 min. sections	Clearer knowledge structure in the curriculum; self-paced learning	Lack of interaction between students and lecturer	Clear structure [13%/71], easier to follow [3%/71], good learning motivation [1%/71], application examples and questions after each block requested [21%/71]
	Live session	Lecturer can react to students' questions and feedback	Different time-zones may hinder participation	Recording function enables easier repetition, discussion [14%/71] & question with lecturer after each section desired [10%/71]
Self-evaluation	Polling in lecture	Quick call for content repetition, feedback; Short pause between contents	Only feasible in Live sessions	Helpful in parallel to live lecture [3%/71]
	Regular assessment (e-test)	Individual modeling and programming tasks; no manual correction required	Large organizational effort for student slots and technical infrastructure (in-class and online)	Technical issues (e.g., unstable internet connection) shortened test time [31%/71]
	e-exercises	Voluntary e-Tests for repetition; no manual correction required		Optimal for learning control, one e-excercise a week is well received [34%/71]
	Self-test	Additional material for	Manual	Optimal for learning

		repetition; cross-topic exercises possible	correction required	control, correction and feedback by tutors are well received [10%/71]
Q&A	Forum	Allows exchange between students; asynchronous Q&A	Static tool; no verbal discussion	Easy system for Q&A, not available for every lecture, FAQ desired [7%/71]
	Tutor office hour	Address more students' questions at once; interactions between students	Tutors must be employed and educated; only available during tutor hours	Difficult booking procedure even if multi-channel instructions [4%/71]
	Weekly live session	Interaction with students; General feedback; regular organizational information spreading	Although session is voluntary, not viewing the contents might cause missing information	Wrap-up with Q&A and examination training (exam exercises) is well received [37%/71]
	One-to-one session	Deep-dive into one student's questions; more individual consultation	Time-consuming at large participation numbers	Fast responses, lecturer available in predefined time-slot is well received [10%/71]
Link between academia and industry	Guest lecture	More in-depth understanding / industrial insight; students apply knowledge in exercise	Great effort in creating guest lecture/exercise content for a one-time event	-
	Motivational video	Industrial insights on more topics of the curriculum	Only coarse introduction of academic topic in industry	-

5.1 Quantitative validation – Course and examination assignment statistics.

Fast feedback and large amounts of student learning data offer a better understanding of the participants' learning behavior. Thanks to tool-integrated analytics functions, participation rates, and evaluation results, we reconstruct certain behaviors and correlations to assist our students with learning from home effectively. The descriptive data were extracted from different cohorts with divergent characteristics. The statistics of four lectures (undergraduate - IT2, Sefi1; graduate - Sefi2, ISMLP) of different course sizes as well as evaluation, examination, and participation rates (cp. Fig. 4, 5, 6), were selected for the monitoring and evaluation analysis. With the analytical features in Panopto, views, downloads, and the number of minutes transmitted over time can be obtained automatically for each video and course. We selected seven out of 24 questions from EvaSys on students' understanding, participation, motivation, and learning effort, to elaborate on the divergence over the past five years. For all courses, the latest statistics of the COVID-19 pandemic (SoSe 2020) were compared to the pre-COVID learning context (SoSe 2016-2019).

Tab. 4. Assessment of tools and their possible functions; + well suitable; o restrictedly suitable; - not suitable; x applicable; for column “Group size”: suitability assessment of function/ratio of implementation effort to impact, for column “Operation”: operation introduced by authoring chair

Tool	Description	Function												Group size			Operation**			
		Video recording	Live lecture /exercise	Practical block	Polling	Regular assessment	E-exercise	Self-test	Q&A Forum	Tutor hour	Weekly live session	One-to-one session	Peer review by fellow	Large (> 75)	Medium (25-75)	Small (< 25)	Lecture	Excercise	Exam	Students Usage [%]
Zoom	Web conferencing + Collab.platform	+	+	+	+	-	-	-	-	+	+	+	+	+/+	+/+	+/+	x	x		100
Meet.lrz		-	-	o	o	-	-	-	-	o	-	+	o	-/+	o/+	+/+		x		25
MS Teams		+	-	+	+	-	-	-	o	o	-	+	+	-/+	o/+	+/+		x		25
OBS Studio	Screen recorder	+	-	+	-	-	-	-	-	-	-	-	-	+/+	+/o	+/-		x		25
Camtasia		+	-	+	+	-	-	-	-	-	-	-	-	+/+	+/o	+/-				0
Power Point	Recording function	+	-	o	-	-	-	-	-	-	-	-	-	+/+	+/+	+/+	x	x		100
Panopto	Video platform	+	-	o	+	-	-	-	+	-	o	-	-	+/+	+/o	+/-	x	x		100
Moodle	Learning platform	-	-	-	+	+	+	+	+	-	o	o	+	+/+	+/o	+/-	x	x	x	100
Coderunner	C-Compiler plug-in for Moodle			+		+	+	+						+/+	+/+	+/-			x	100
Eclipse, Codesys, Codeblocks	IDE			+		o	o	o						+/+	+/+	+/+	x	x		25
Modelio, MATLAB, UPPAAL, MySQL, etc.	Course-specific tools			+		o	o	o						+/+	+/+	+/+	x	x		25
TUM Exam	Exam platform			-		o	o	o						+/+	+/o	+/-			x	75
Proctorio	E-tests Proctoring			+		o	o	o						+/+	+/+	+/-			x	25

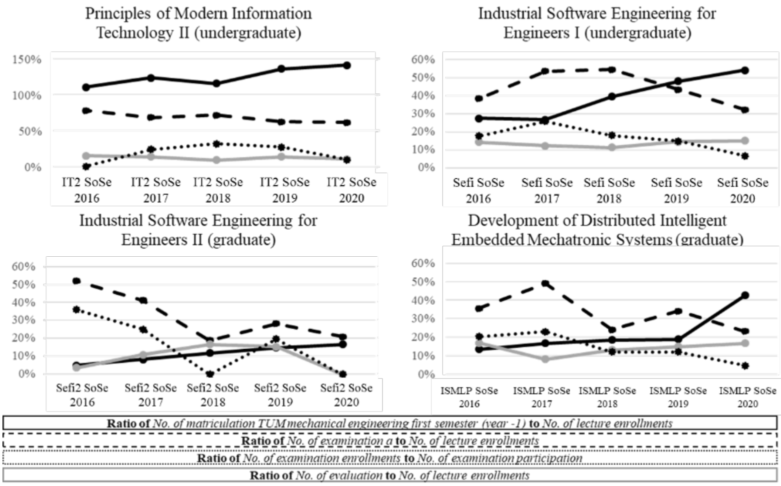

Fig. 4.. Among the enrollment, course, and examination ratios of the past five years; two data points of the Sefi2 evaluation (2020, 2018) missing due to low participation rate.

Analyzing the ratio of *No. of matriculation mechanical engineering first semester (year -1)* to *No. of lecture enrollments* (cp. Fig. 4), the interest in our lectures has been increasing over the past five years, even more during COVID-19. This is an indication for the online teaching format that offers more opportunities to study flexible regarding the time and location. Comparing the ratio of *No. of examination participation* to *No. of lecture enrollments* of 2019 and 2020, fewer students who enrolled in lectures participated in the exam during COVID-19 amongst all lectures. Similar applies to the ratio of *No. of examination enrollments* to *No. of examination participation*. Fewer students took part in the actual exam during COVID-19 than enrolled for the examinations. As the exams were conducted in form of paper exams in-person at the university, not all students participated, especially international students who studied from home. As all courses are affected, it is to investigate whether students move the exam to another semester due to COVID-19. Using Panopto data, we could map the statistics of all views, downloads, and minutes transmitted over time as well as the examination date (cp. Fig. 5). The lecture recordings were rather watched shortly before the examination date, confirming the result of a previous study on engineering students' participation [41]. *IT2* is the only course with *obligatory* regular assessments during the semester. It is also the only one with steady instead of declining participation rates throughout the semester. This fits the students' evaluation result that weekly learning control mechanisms were beneficial and that obligatory assessments contribute more to regular participation. We elaborated the students' understanding, participation, motivation, and learning effort, students are encouraged to indicate which features they liked and what suggestions they had for improvements. Seven aspects (1-7) are selected to reflect the students' impression of the COVID-19 lecture transformation:

(1) The scope of the material presented is… 1: too small; 5: too large

(2) I attended the lecture regularly. 1: completely agree; 5: completely disagree

(3) The instructor/lecturer explains complex issues well. 1: completely agree; 5: completely disagree

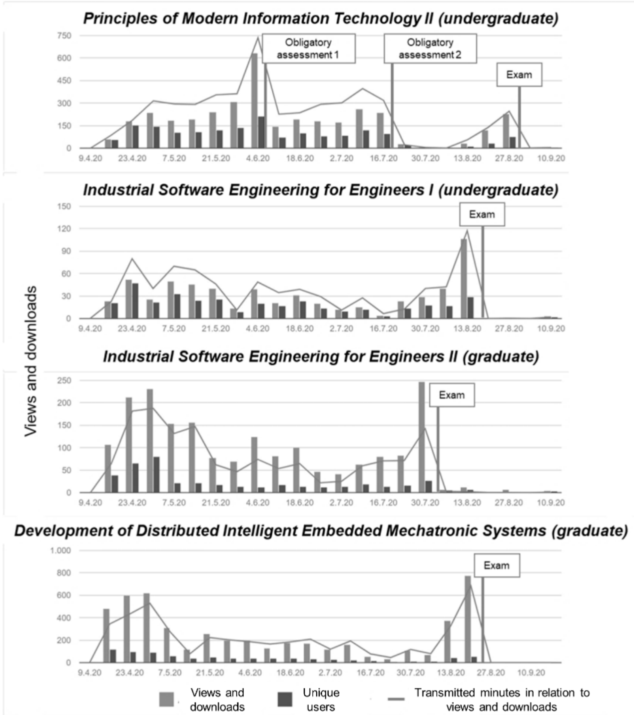

Fig. 5.. Panopto views and downloads for four selected courses

(4) I can explain important key concepts/key issues presented in the lecture. 1: completely agree; 5: completely disagree
(5) The design of the lecture motivated me to study the subject matter. 1: completely agree; 5: completely disagree
(6) Grade the lecture. 1: Grade A (very good); 5: Grade F (insufficient)
(7) How much time did you spend on average for preparation and follow-up of the module (without time for exam preparation or proof of performance) in h/week?

Fig. 6 and 7 present the course comparison over the past five years. Due to the lack of comparable data for Sefi2 during COVID-19, we exclude this course in the following. The quantitative analysis shows that although the scope of material is getting larger and the time invested into the lecture preparation and follow-up increases, the students' perception of the scope of material reaches the lowest point in all three courses, compared to previous years. This phenomenon occurs, although we offered extra material (e.g., self-tests, Zoom sessions). This can be rooted to the extra content offered with the online-lecturing materials that were remarked as positive by the students. Furthermore, the availability of the pre-recorded online lectures offer better opportunities to rework the content due to the recorded sessions and might ease the repetition process, as previously, it was impossible to fully recapture the focus of the lecture in case of missing a lecture or not taking appropriate lecture notes. The additionally offered wrap-up sessions with Q&A and examination training ease the students' own exam preparation, which is not seen as extra learning material.

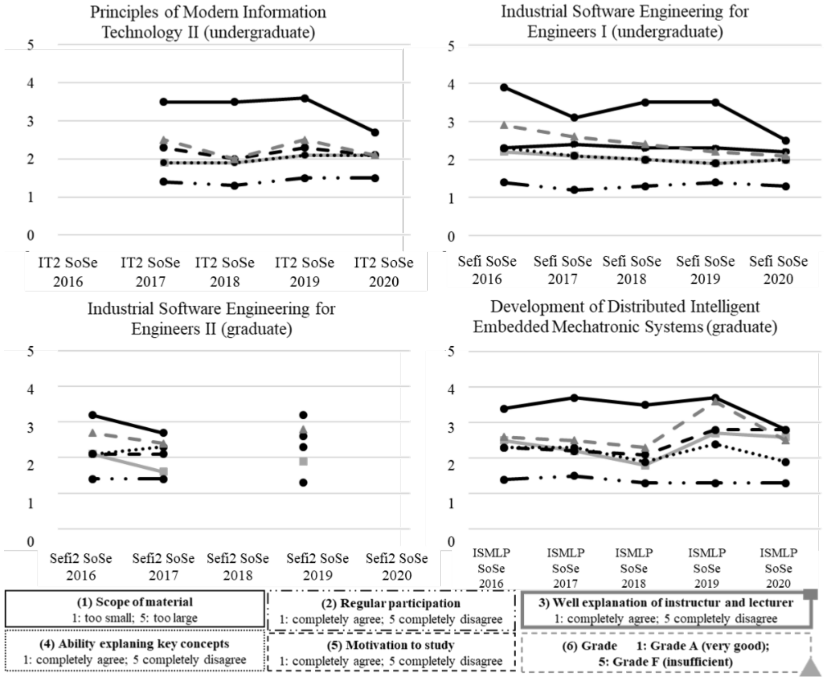

Fig. 6.. Comparison of four selected courses over the past five years addressing aspects (1-6)

Yet, for all selected lectures over the years, students' effort measured in hours increases. A larger number of students invested several hours into preparation and follow-up of the lecture (cp. Fig. 7). Students might better manage the range of the contents and prioritize them. Furthermore, the students are more focused and actively use the extra offers during the semester (e.g., self-tests), moreover, they even asked for more tasks. It is also worth mentioning, that the investigation of the time invested does not distinguish the lecture (attendance) time from the lecture preparation time. However, for in-person lectures in presence, this separation can be made more easily. Students might not deduct the actual work on lectures and exercises from the preparation and follow-up time.

5.2 Reflection on findings of the study

The transformation of our courses' contents due to COVID-19 provided us the opportunity to overhaul conventional teaching methods. We managed to transform all course contents to online ones while providing additional teaching offers. Meanwhile, we faced challenges regarding the technical infrastructure and organizational aspects. **Comparison to previous** *[cp. Section 2 Background and Related Work]* show that we applied a similar approach to Ping et. Al [15], while providing evaluation information on the students' perception. Compared to Kolar et al. [16], our lecture views show

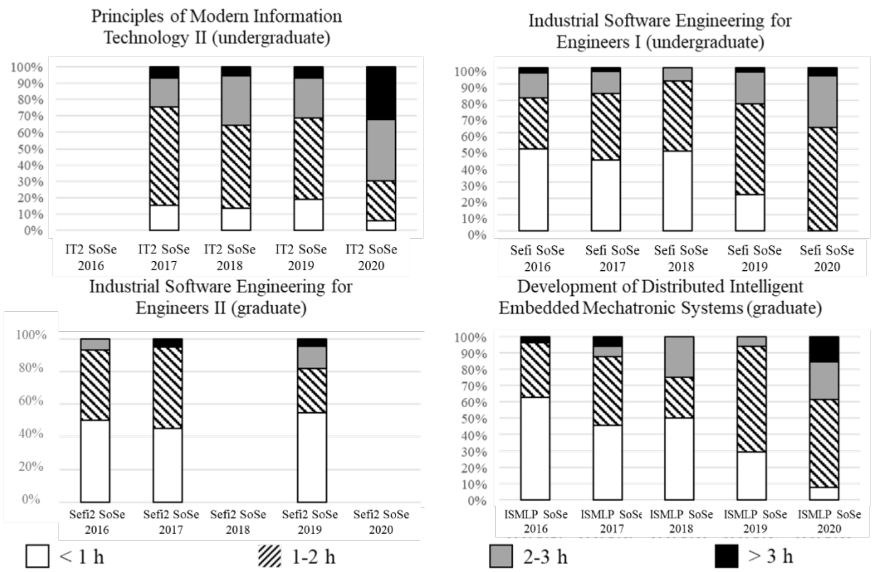

Fig. 7.. Comparison of the four selected courses over the past five years addressing time invested in preparation and follow-up of the lecture (7)

similar results. We could identify a visible peak one week before the final exam, a phenomenon called "last-minute cramming". Similarly to [17], students face challenges in practical exercises and group work, we suffered from problems in our practical courses. Comparing to Gaudiot et. al, [19] we extend the findings as the previous study listed some tools but did not compare them for different class sizes or teaching styles. Besides, no student feedback was considered within this study and the improvement in educational quality was neither verified with student feedback nor quantitative numbers in e.g. participation rates of students.

Technical infrastructure and e-tests *[cp. Section 3.3 Regular assessments (e-test) and Plant Exam; Section 4.3 Suggestions for Improvements]* were the major challenges we encountered during the design and implementation of our courses, e.g., different time zones, internet connection issues, large amounts of data, or creating a digital twin of an existing demonstrator plant. As stated above, the regular e-tests in *IT2* faced several technical issues due to the online format. Usually, a maximum of 64 students access the e-test and hence the Moodle platform combined with the Coderunner plugin at once, so that the server load is rather low. However, Coderunner could not deal with simultaneously requests of all 774 students. It responded with sporadic runtime errors and long loading times. As a result, students either did not compile their solutions, which makes them more error-prone, or they wasted time, so they were not able to finish the e-tests. Thus, the e-tests were later changed to an asynchronous and non-mandatory form. Also, solutions for a fair evaluation were elaborated, proposed, and negotiated with students and faculty. Yet, as the e-test results were slightly better than in previous years, the sudden switch to online

teaching and the measures taken seem not to affect the students' performance severely.
Loss of experience compared to in-person education *[cp. Section 3.3 Practical Courses and Plant Exam; cp. Section 4.3 Suggestions for Improvements]* Although we encouraged students to work and communicate online in groups via web-conferences, they rather worked independently. Since most of the lecture content is recorded online, it is more anonymous. This contradicts the students wish to attend a live lecture and engage in conversation. As one of the results of the quantitative evaluation statics show, the coherent explanation of the lecturer/instructor and the ability of the student to explain key concepts in reply are important to undergraduate students, for both online and in-person lectures. The direct link indicates a need for a stronger exchange between students and lecturers to improve the explanation of the course contents deliberately.
Practical Courses with digital twins *[cp. Section 3.3 Practical Courses, Plant Exam]* enable students to work on complex use cases and to apply theoretic knowledge in practice despite the online format. The evaluation results showed that digital twins are beneficial and well appreciated by the students. However, the practical courses and the plant exam in person have a clearly higher didactic effect for the students, since they directly encounter actuators and sensors of a real plant as well as can understand the temporal sequences and dependencies in automated production plants. They learn about the links between software and hardware, as well as between mechanics and electronics, which are important for mech. eng.. Besides comprehensible interactions between individual components, they identify special cases such as non-deterministic behavior or physical effects, which are crucial but unfortunately can hardly be represented in such a way in a simulation. The joint commissioning of the plant by several students with different previous knowledge of the parts of the plant also trains communication and coordination in the team in addition to technical skills.
Self-tests *[cp. Section 3.3 Teaching Procedure and Strategy; Section 4.1 Self-Test]* Self-tests and the follow-up discussion on faults that students typically make in their solutions, were especially helpful by students of all courses. In small courses, we were able to correct all solutions handed-in weekly so that each student received individual feedback. For big course sizes, only samples could be taken and discussed. We introduced a peer review system among the students. Although only one-third of the students actively used the peer review, they highlighted the learning effect as significantly better because of the threefold structure of working out one's own solution, reviewing a peer's solution based on the discussion on typical faults of the lecturer, and then reflecting again on one's own solution.

5.3 Threats to validity

External validity refers to the potential for readers to generalize the results and extrapolate from them for their own use. This paper describes the educational process and implementation in several mech. eng. courses of a German university. Based on these experiences we present a collection of functions in a comparable table with advantages, disadvantages, and student feedback from three sources. Furthermore, quantitative data of four courses over the past five years are elaborated to evaluate the study outcomes. Although the perceived challenges and methods reflect own experiences, and are evaluated with courses of one institute, measures and tools applied and the challenges encountered, especially the self-test and digital twin concept, can be adapted to the teaching design of other institutions of mech. eng. in higher education. Internal validity refers to the accuracy of inferences, e.g., if one factor affects another. We carefully selected multiple sources to evaluate the students' learning behavior (cp. Chapters 4.1-4.3). The evaluation groups may show overlaps, yet the core feedback is included and reflected. Reliability is concerned with to what extent specific researchers influence the data, the analysis, and the results. Deliberately, we used anonymous statistics for which participation was voluntary. Further, different lecture responsibles were involved, so the contents of this paper represent the general procedure and teaching of the institute.

6 Conclusion and Outlook

In mechanical engineering, students' learning success greatly correlates to the application and implementation of the engineering theory in practical settings. During COVID-19, we transformed in-class courses with up to 700 students to online ones, implementing and offering many additional interactive formats and supportive material. Further, working with demonstrator plants forced us to include digital twin technologies to simulate the response of a real plant. Depending on the desired concept, functions required, and the group size, lecturers can assess and adapt the presented tools and teaching concepts for future digital teaching in engineering.
Two measures taken are to be highlighted: The self-tests and the digital twins for plant programming. The method to provide self-tests for the students, to peer-review them and to discuss typical faults in student solutions was well-received and the evaluation showed that students rated them as especially helpful as clear guidance during online self-study. The digital twins of the demonstrator plants in practical blocks enabled students to apply their theoretical knowledge to complex examples. As during the pandemic, in-class experience on real plants is permitted, students get to know the plants remotely. Yet, the digital twins could not teach all aspects that are crucial for engineering students such as software-hardware-interdependence or non-deterministic plant behavior, as this can be hardly simulated.
For the winter term, online teaching is still mandatory. The concept presented is reused with some adjustments based on the findings presented. Instead of pre-recorded lectures, we will lecture live via Zoom as scheduled in the timetable to enhance personal contact and guidance. Online questionnaires during the lecture reveal problems and misunderstandings of parts of the lecture. Thus, the immediate reaction by the lecturer is feasible similar to face-to-face teaching. These lectures will be recorded and provided via Moodle. E-tests will take place asynchronously, more similar to self-tests, to address the challenges of the infrastructure and to minimize technical issues. The main challenge to us in the winter term still is to support students' cooperation and continuous learning process, as already well known since long from distance learning.

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