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PAPER

Redesign of a Virtual Jet Pump Laboratory for Higher Process Engineering Education

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ABSTRACT

The digital transformation increasingly requires the development of competencies for learning and working in the context of Industry 4.0. To meet this need, a practical action research project was conducted to design and implement a virtual instructional laboratory for fluid mechanics in a higher process engineering education course. This paper provides a detailed overview of the key steps and outcomes of the project, including the design of a virtual jet pump experiment using a game engine, the implementation of a real-world scenario (RWS) that was developed with a special constructive alignment (CA) checklist for instructional design of laboratory learning, and the corresponding empirical investigation. The findings demonstrate that the integrated approach employed in this project can enhance learning outcomes related to competencies required in the Industry 4.0 work environment, despite the challenges encountered by students in mastering the RWS. This paper concludes by exploring some potential future directions for further work in the field.

KEYWORDS

virtual laboratories, practical action research, constructive alignment, process engineering education, learning and working 4.0

1 INTRODUCTION

Industry is currently undergoing a transformation process toward networked and digital working, necessitating a corresponding adaptation in higher engineering education [1]–[3]. This also applies to higher process engineering education. According to Wilk et al. [4], a notable disparity exists between process engineers' satisfaction levels with their university education, where 86% perceive it as good or very good, and digitisation, which has only 30% satisfaction. Moreover, prospective employees are expected to possess a diverse range of competencies, including self-organisation, socio-technical collaboration, design thinking, entrepreneurial thinking, and ethical behaviour [3], [5], [6]. This raises the question of whether online laboratories have the capacity to provide the essential infrastructure for fostering these skills [7].

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Laboratory experiments play a crucial role in fostering competency-oriented education for students in process engineering and various other engineering disciplines. Through practical application of theoretical principles, students can gain a profound comprehension of the interplay between theory and empirical research. This hands-on experience allows for an exploratory approach to learning [8].

However, Felder and Brent [9], [10] state that despite the potential for exploratory learning, many laboratory experiments still adhere to a prescriptive "cookbook" procedure. They argue that traditional instructional laboratories therefore fail to adequately replicate the authentic professional practice of research and development, where prescribed tasks or scripts are typically absent. On the contrary, they take the view that professional engineering practice is typically characterised by initially ambiguous problem definitions, uncertain solution approaches, and the expectation that tasks will be tackled with a high degree of autonomy and minimal managerial support.

Taking up this discrepancy between the common practice of efficiency-driven academic laboratory work and the actual requirements of laboratory work in the later professional world, the laboratory instructors of the Biochemical Engineering and Chemical Engineering undergraduate programmes at TU Dortmund University used the COVID-19 pandemic as an opportunity to carry out far-reaching technical and pedagogical revisions of their laboratory teaching [11]. Given that the traditional practical courses in fluid mechanics were not possible during the COVID-19 pandemic due to the strict hygiene regulations, instead of simply sending pre-produced laboratory videos and measurement tables to the students, as most colleagues had done, a virtual laboratory was established as an alternative. The creation of the virtual laboratory was also prompted by persistent discontent among certain laboratory instructors regarding the antiquated technical and pedagogical aspects of conventional laboratory experiments [12]. This leads to the following guiding research question: How can an outdated laboratory unit be technically and pedagogically revised to better integrate the competency requirements of Industry 4.0 for future employees?

Through a collaborative endeavour involving the laboratory instructors and experts in higher engineering education, an extensive redesign of the virtual laboratory was undertaken, employing a practical action research approach. According to Creswell and Guetterman, this iterative process encompasses research to "explore a practical problem with an aim toward developing a solution to a problem" [13].

A game engine was utilised for the technical overhaul, drawing upon previous projects to facilitate contemporary teaching-learning activities (TLAs). Consequently, a laboratory experiment was developed as a partially or fully immersive simulation in virtual reality (VR), thereby affording students the opportunity to engage in laboratory experiments remotely from their home offices. To enhance the pedagogical design, the conventional cookbook-style experiment instructions were replaced with a newly designed real-world scenario (RWS) [14] that pertains to the practical aspects of the field, specifically emulating a typical task found in a company's research and development department. To ensure the attainment of challenging deep-learning objectives through the newly developed RWS assignment, the research team employed a constructive alignment (CA) checklist [15] that was tailored for laboratory instruction. Subsequently, the redesigned laboratory experiment was implemented and assessed by instructors during regular class sessions, encompassing an analysis of both student performance and their individual experiences while engaging with the RWS [12].

This paper consists of the following sections: Section 2 reviews the relevant literature. Section 3 describes the practical research process, consisting of the technical redesign, the handling of the CA checklist, the scenario derived from it, and the evaluation design. This is followed in Sections 4 and 5 by the presentation and discussion of the evaluation results, respectively. This paper concludes in Section 6 with some potential improvements that can be implemented in the next deployment.

2 LITERATURE REVIEW

2.1 Virtual reality in education

As early as 1991, Bryson and Levit [16] pioneered the application of VR in the visualisation of fluid mechanics calculations. This involved the utilization of a head-mounted display (HMD) and a data glove, which allowed experts to visually examine fluid flows. However, recognising the challenges associated with comprehending fluid mechanics for non-experts, subsequent efforts focused on developing an intuitively accessible representation within the VR environment.

In the subsequent professionalization of the research field, commercial software designed for professionals became instrumental in flow computation and/or visualisation within the VR domain. Presently, immersive virtual worlds find applications in disciplines such as teaching architecture or civil engineering [17], [18], as well as in the field of fluid mechanics itself [19].

LaViola et al. [20] suggest that potential interaction features in immersive environments provide users with the opportunity for "hands-on" engagement with simulation results. By being immersed in the data or model, users can more readily grasp and interpret the outcomes of the simulation. Unlike non-immersive post-processing software, extensive training is not required, explanatory elements can be incorporated, and the scope of the provided data can be limited. The immersive nature of first-person perspective computer games can be leveraged to enhance direct exploration of the virtual world, offering users increased possibilities for interacting with simulation results.

According to Slater and Sanchez-Vives [21], the use of VR in education can lead to improved learning outcomes, particularly as the level of immersion increases. They argue that several advantages emerge in teaching and learning through VR, including the transfer of experiences into abstract spatial knowledge (1), promoting active engagement rather than passive observation (2), facilitating the comprehension of complex concepts through hands-on experiences (3), and transcending the limitations of reality (4). Ouyang et al. [22] developed an educational VR game for plant construction, while Massink [23] focused on fluid mechanical aspects of dike construction. Finally, a recent meta-analysis conducted by Di Natale et al. [24] demonstrates that:

> *IVR [immersive VR] can support a number of activities and experiences that in turn improve learning and motivate students to fulfil educational goals by eliciting their interest and engagement with the learning materials. The main advantage of IVR seems related to the possibility for users to have first-hand experiences that would not be possible in the real world, simultaneously offering unique opportunities for experiential and situated learning, as well as promoting students' motivation and engagement [24].*

The historical and technical development and use of virtual laboratories for STEM education in the secondary and tertiary sectors is discussed in detail in [7, 11, 25, 26].

2.2 Objectives of the instructional laboratory

To fully harness the unique potential of the laboratory as a learning environment and to effectively pursue competence-oriented learning objectives, it is essential to establish specific learning objectives that are explicitly tailored to the laboratory setting. Cunningham [27] highlighted this need in a seminal review paper, emphasising the importance of formulating dedicated learning objectives for laboratory experiences. However, as demonstrated by Hofstein and Lunetta [28], [29], Hofstein and Mamlok-Naaman [30], Feisel and Peterson [31], and Brinson [32], this requirement has often been overlooked in educational practice over the past few decades. Moreover, prevailing accreditation guidelines for engineering and science programmes have traditionally adopted generic formulations of learning objectives, reflecting their broad perspective on programme outcomes [8]. Consequently, the specific learning objectives that are uniquely suited for laboratory experiences have not received sufficient attention within these accreditation frameworks.

Due to the previous lack of adequately formulated learning objectives for laboratory instruction, a group of approximately 50 educators from US universities recognised this deficit and took action in 2002 [31]. They collaborated to develop a set of 13 fundamental objectives that were specifically tailored to engineering laboratory instruction. In 2005, these objectives were subsequently published by Feisel and Rosa [33] in the Journal of Engineering Education and have since become the most widely cited taxonomy of learning objectives for laboratory settings. Each objective consists of a title term that characterises the topic of the objective, followed by a concise explanatory statement that defines the specific learning activity associated with that topic. To maintain consistency and clarity, every objective begins with the introductory sentence, “After completing the laboratories in the engineering undergraduate curriculum, the student will be able to…,” which is followed by a brief explanatory statement that elaborates on the intended learning outcome. Following their initial publication, Felder and Brent [9], [10] presented a revised taxonomy for teaching STEM subjects. They also assert that this particular form of learning objectives is incompatible with the prevailing traditional teaching laboratory approach. Typically, these teaching laboratories involve experiments with clearly defined tasks for each laboratory session, culminating in relatively short laboratory reports.

Although these goals are referred to as “fundamental objectives”, they are nonetheless too broad when it comes to their application in the design of specific laboratory experiments. Feisel and Rosa [33] provide only general guidance on the use of their taxonomy, explaining that laboratory designers and educational researchers can identify the specific goals they wish to achieve through their work. But how does this work in practice?

2.3 Constructive alignment

The utilisation of CA in the design of teaching and learning activities (TLAs) and assessment tasks (ATs) has gained significant recognition in higher education for its effectiveness in directly addressing intended learning outcomes (ILOs) in ways that traditional instructional methods such as lectures, tutorials, and exams cannot achieve, as outlined by Biggs et al. [34]. As an approach rooted in outcome-based teaching and learning (OBTL), CA has experienced growing popularity in recent years as a framework for designing and evaluating teaching and learning experiences. Unlike conventional teaching approaches that primarily focus on knowledge transmission, CA places emphasis on guiding students towards the achievement of ILOs through aligned instructional activities [34].

2.4 Constructive alignment checklist to design laboratory intended learning outcomes

There is consequently a need to break down these 13 basic objectives for laboratory instruction into specific ILOs that are aligned with a particular subject laboratory experiment. To address this challenge, Tekkaya et al. [15] developed a checklist to design laboratory learning based on CA. This checklist integrates the 13 basic objectives proposed by [33]. The checklist aids in determining which of the 13 fundamental learning objectives should be addressed. Additionally, it facilitates the identification of any other ILOs that have not yet been addressed in the list. Moreover, as an extension of the original taxonomy, implementation levels range from Level 0 (not addressed) to Level 1 (rudimentarily implemented and achieved: the teacher demonstrates an experiment, the students remain passive), Level 2 (partially implemented and achieved: the instructor guides students to conduct an experiment), and Level 3 (fully implemented and achieved: students must complete the task independently). Following a deductive approach, six questions are answered for each learning objective and the result is reflected upon, as follows:

1. What are students able to do after the laboratory course in relation to objective #?
2. How, or through what specific actions, will students learn objective #?
3. At what level should they do this?
4. How does the teaching/learning activity relate to later professional life?
5. How will you recognise that the learning objective has been achieved through the TLAs?
6. How can this be checked in a competency-orientated way and integrated into an examination form?

For further details and a concrete outline of the CA checklists, see [15]. This allows a more precise determination of the degree of competence-promoting autonomy to be achieved in the learning process, be it in the pedagogical analysis and reflection of existing laboratory concepts or for the further and new development of pedagogical laboratory concepts.

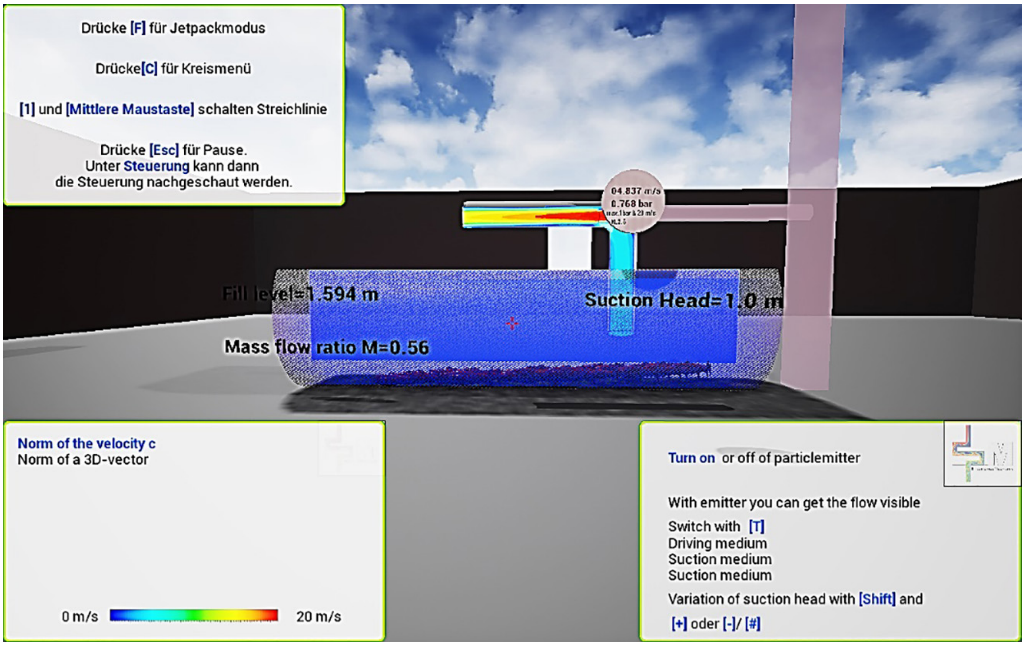
2.5 Real-world scenarios in education and training

According to Clark [14], an RWS is a simulated representation of typical workplace situations that enables students to confront real-life problems, apply guidelines and principles, and observe the outcomes of their actions and decisions in a safe and effective manner. The integration of an RWS in instruction has been shown to enhance student engagement and foster the development of practical skills during the learning process, as indicated by May et al. [35]. While RWSs are commonly employed in professional education, their potential for promoting academic learning, particularly in engineering laboratories for the cultivation of professional competencies, has also been recognised [36], [37].

3 PRACTICAL ACTION RESEARCH

3.1 Technical redesign: Employing a game engine to develop an immersive virtual reality laboratory

The immersive VR laboratory was constructed using Unreal Engine 4, a programming and runtime environment renowned for its proficiency in generating professional real-time 3D games [38]. The laboratory can be accessed from a first-person perspective, optionally utilising a HMD from the comfort of one's home. Additionally, free movement within the virtual space is enabled through a flight mode, as illustrated in Figure 1. The experiment focuses on fluid dynamics, which involves computationally intensive flow calculations that are not feasible to perform in real-time on home computers. Nevertheless, to ensure broad accessibility of the laboratory experiment for as many students as possible, the foundational data for all flows was pre-generated using the commercial computational fluid dynamics (CFD) software Ansys CFX [39]. The computed data was subsequently integrated into the Unreal Engine 4 using a standardised framework [40]. The resulting visualisation of flow physics is depicted in Figure 2. By employing simplified graphical programming through level blueprints, various options were developed for intervening in the experiment's events. The compiled program can be utilised as standalone software and is accessible to students through the practical platform supported by Moodle. For further details, see [12, 19, 40, 41].



Drücke **[F]** für Jetpackmodus

Drücke**[C]** für Kreismenü

[1] und **[Mittlere Maustaste]** schalten Streichlinie

Drücke **[Esc]** für Pause.
Unter **Steuerung** kann dann
die Steuerung nachgeschaut werden.

Norm of the velocity c
Norm of a 3D-vector

Turn on or off of particlemitter

With emitter you can get the flow visible

Switch with **[T]**
Driving medium
Suction medium
Suction medium

Variation of suction head with **[Shift]** and
[+] oder **[-]**/ **[#]**

Fig. 1. Flight mode in the jet-pump laboratory with a schematic sensor and a school of fish at the bottom of the tank

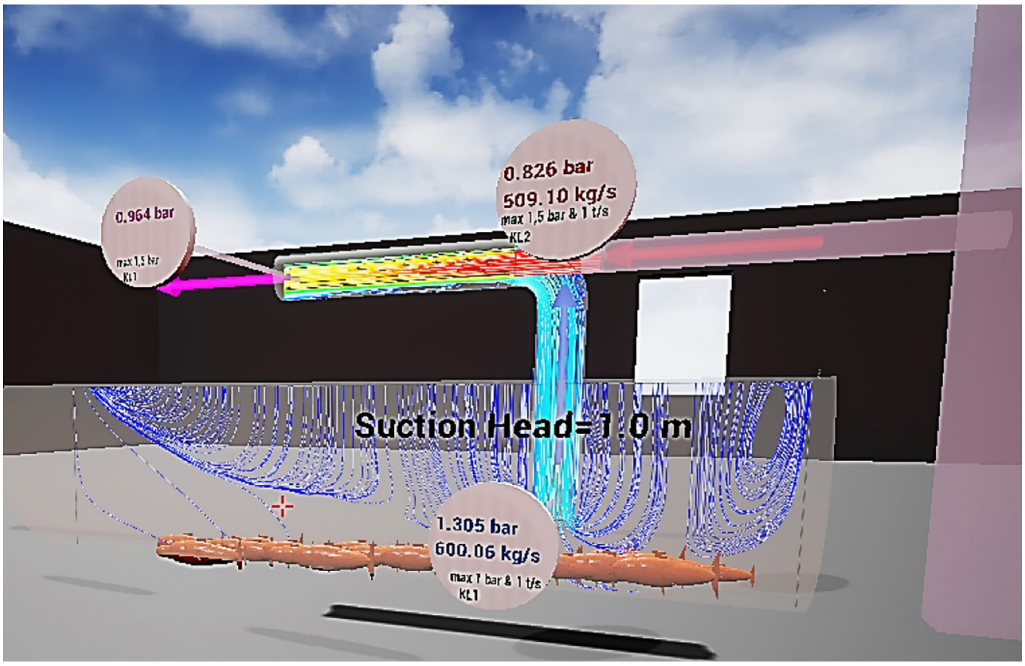


Fig. 2. Jet pump with streamlines: suction height 1.0 m and a school of fish at the bottom of the tank

Considering the limited time available for preparation and development of the RWS, the emphasis of the project team was placed on instructional design rather than technical optimisation of the VR environment or resolving all possible bugs.

3.2 Pedagogical redesigning 1: Employing the constructive alignment checklist to analyse, reflect, and improve existing ILOs

As stated in the module handbook, the laboratory experiments should align with faculty-wide guidelines that promote exploratory learning, reinforce course content, and ideally prepare students for examinations [42]. According to [9], the 13 objectives outlined by [33] are well suited for addressing the requirements of professional life, which is why the extended CA checklist was employed to optimise the experiment. In this process, three staff members individually utilised the CA checklist and subsequently engaged in discussions to consolidate and summarise their findings. The application of the CA checklist proved instrumental in identifying important aspects of the laboratory experiment and generating numerous creative ideas for the instructional designers.

Furthermore, it is crucial to promote competencies essential for the contemporary working world, such as self-organisation, creativity, and ethical behaviour [43], [44]. In light of this, the laboratory developer team supplemented the original 13 aspects of the CA checklist with four additional explicit learning objectives, aiming to achieve the overall objectives of the laboratory experiment. These additional objectives are promoting exploratory learning (#14), integrating laboratory work with lecture content (#15), conducting literature research (#16), and fostering learning in the context of the working world 4.0 (#17). Table 1 provides a comparison of the content of the laboratory experiments before and after applying the CA checklist, displaying the 17 addressed goals along with the assessed level of implementation. Even though the laboratory instructors only used keywords and sometimes made mistakes, it still served as a valuable tool for transformative reflection and pedagogical redesign within the team.

Table 1. Comparison of the results of the experimental design before and after the application of the CA list

F&R 2005 ILOs	Before CA Checklist	After CA Checklist
#1 Instrumentation	Level 3: To work independently with laboratory equipment; to measure pressure, mass flow, and time; to use software tools such as MS-Excel.	Level 3: To specify measuring devices, to analyse noise, based on accuracy class, to analyse systematic and random errors; to deploy real measuring devices outside digital twin, such as a stopwatch on a smartphone, software tools; to organize and manage meetings via Zoom; to prepare and present results in the final exam with PPT.
#2 Models	Level 1: To follow the given script, containing a derivation of the dimensionless pump characteristic curve.	Level 3: No script is given any longer; to autonomously create a model, to compare the model with measurement and to recognize and discuss limitations of model; to use fluid mechanics tools (e.g., current filament, integral momentum, continuity).
#3 Experimentation	Level 2: To plan an experiment including time and work management; to investigate parameters; to vary suction height.	Level 2: To plan an experiment including time and work management; to discuss the measuring equipment: to make changes to the experimental set-up with regard to measured variables, location, and system.
#4 Data Analysis	Level 1: To read pressure and speed on the gauges.	Level 3: To analyse (e.g., noise) and interpret data (e.g., accuracy classes); to compare field sizes using colour scales; to compare model and experimental results; to explain and interpret deviations; to estimate and distinguish between limits of model and digital twin (e.g., unconsidered physics or bugs in the program).
#5 Design	Level 0: Not addressed.	Level 2: To design a model for the jet-pump (see #2); to identify, to estimate, and to extend specifications or model limits, if necessary.
#6 Learning from Failure	Level 0: Not addressed.	Level 2: To deal with unexpected results from faulty devices due to built-in bugs; to recognize and to interpret if it is real physics or a bug in the system.
#7 Creativity	Level 0: Not addressed.	Level 3: To find other creative solutions instead of pumping the tank empty, and thus killing fish, (e.g., to calculate measuring points via extrapolation). Do students specify extrapolation or is it concealed? Other ideas: To use external measuring devices for time measurement; to find and to interpret errors; to freely create a model; to discuss measuring devices.
#8 Psychomotor	Level 1: To work on the digital twin with technical assistance.	Level 3: To select and to apply literature; to measure time with external stopwatch.
#9 Safety	Level 0: Not addressed.	Level 3: To consider environmental aspect (let fish live); to analyse technological risks (lack of digital empathy); to critically weigh and reflect on operating in digital environments; to detect cavitation in order to avoid pump damage.
#10 Communication	Level 1: To communicate in the laboratory; to present results in technical language.	Level 2: To communicate competently and appropriately (e.g., to reduce to essentials); to explain to non-specialists; to manage regular internal meetings.
#11 Teamwork	Level 1: To work together in the laboratory; reality: only one student works on the evaluation of an experiment.	Level 3: To work collaboratively as a team with team leader and team members; to assess and allocate work packages and tasks within the group; to stick to deadlines.

(Continued)

Table 1. Comparison of the results of the experimental design before and after the application of the CA list *(Continued)*

F&R 2005 ILOs	Before CA Checklist	After CA Checklist
#12 Ethics in the Laboratory	Level 0: Not addressed; comment: cheating such as copying from other groups is unethical.	Level 3: To avoid an uncritical fulfilling of a given work order from above at any cost (in this case, to kill fish); to take responsibility in an unexpected situation, instead to reflect on this behaviour by answering questions in the learning and content management system and to discuss it during the colloquium.
#13 Sensory Awareness	Level 1: To evaluate optically quantities on the basis of displayed scalar fields.	Between Level 1 and 2: To assess non-physical behaviour by technical assistance on digital twin (bugs) (#6); to perceive cavitation noise.
#14 Explorative Learning	Level 0: Prescriptive manual.	Level 3: To discover inserted content such as cavitation, scalar fields: k-epsilon, velocity contributions, pressures, turbulence energies; no detailed work instructions are given; no script with step-by-step instructions.
#15 Linking Laboratory Work with Lecture Content	Level 1: To apply fluid mechanics tools evident in the script relevant for maximum suction height.	Level 3: To independently apply fluid mechanics tools to create models; to apply physical understanding of flows to analyse and interpret results.
#16 Conducting Literature Research	Level 0: Not addressed due to a given script.	Level 3: To independently carry out all relevant steps of a literature research on the functioning of the jet pump and the dimensionless characteristic curve.
#17 Learning in the Mode of the Working World 4.0	Level 3: To interact and to learn with a digital twin of a real jet-pump and technical assistance in VR; to control it directly from the PC.	Level 3: To interact and to learn with a digital twin of a real jet-pump and technical assistance in VR; to control it directly from the PC.
Average	Level 0.9	Level 2.7

Through the utilisation of the CA checklist and the improvement of the quality of the ILOs, the potential average implementation level increased from 0.9 to 2.7. This indicates the importance of enabling students to conduct the experiment with a high degree of independence (Level 3). In addition, the group discussion in the team on question 4 of the CA checklist on the relationship of the activities for all objectives depicted in [33] and the additional goals to the later professional world (how does the teaching/learning activity relate to later professional life?) led to the conclusion that the implementation should best take place in an RWS in order to best map technical and interdisciplinary ILOs of an increasingly digitalised working world 4.0.

3.3 Pedagogical redesigning 2: Developing a real-world scenario to emulate typical conditions of a professional laboratory workplace

The redesign of the working instruction for the RWS is based on pedagogical principles derived from professional training, where situations of significance to professional practice serve as reference points. The RWS integrates the laboratory experiment within a simulated typical professional assignment and situation, with instructional optimisation achieved through the utilisation of the CA checklist for reflection and (re)design of laboratory work. To align the laboratory experiment with the demands of professional work, the RWS takes the following form. Students play the role of employees who receive a work assignment from a fictional boss via email. The assignment is formulated in a vague and initially incomplete manner, presenting an “incomplete problem” definition. The original was in German and has been translated. All personal names and company names used are fictitious. The written assignment for the students is as follows:

> *Hello Mr./Mrs. XYZ,*
>
> *In four weeks, we have to present the performance (dimensionless characteristic curve, efficiency, etc.) of the newly developed jet pump to the management. I know that you and your team have just joined us, so it is an ideal task for you to prepare the presentation for the management. Think about the composition of the board!*
>
> *The pump is set up in the I4.0 lab. The link to it is given below; you need to go to the injector pump section or similar so you can then study the pump in the comfort of your home office by controlling it via the virtual lab. Get familiar with it if you want to stay with us. You will use this more often!*
>
> *Remember that the digital twin is the real-time digitised image of the lab and controls the real pump, so don’t break it!!!!!! While you are working at it, check again to see if the digital twin is working properly. Take this opportunity to check whether you notice any discrepancies and note them. We want to address this in the presentation so that it doesn’t happen again in the future.*
>
> *Since you studied in Dortmund, you know a lot about fluids. If you are clever, you will be the first (and hopefully the only one) who will have to deal with the pump. Therefore, model the pump and compare the model with the measured data from the digital twin to save this work in the future. By the way, the lab technicians still need the information about how long the pump needs to empty the tank.*
>
> *I need a brief response by 6:00 pm this evening with the stage goals and deadlines for the presentation on 8/17/2020. Please let me know briefly when you have achieved each goal so we don’t embarrass ourselves at the presentation.*
>
> *The link to the digital twin is here: https://moodle.tu-dortmund.de/pluginfile.php/1279858/mod_folder/content/0/Injektorpumpe.zip?forcedownload=1*
>
> *PW:WirLiebenPumpen*
>
> *You may need the construction sketch. It’s attached.*
>
> *Kind regards,*
> *Dean Brandner*
> *Super-PumpenService GmbH · Nibelungenstraße 57 · D-Ottweiler*
> *Managing Directors: Dr. Thalos Monetos (Vorsitzender), Waldemark Romanesco, Dr. Josephko Trockenflechter*
> *Registered office of the company: Mannheim an der Lippe · Not registered at Duisburg local court.*

A “model” that represents the performance of the jet pump needs to be developed and compared to the measured values of the digital twin. Additionally, the time required to empty the tank needs to be measured, taking into consideration the presence of the fish swimming at the bottom of the tank to address ethical considerations. The students are encouraged to identify and investigate any errors or bugs in the digital twin, as depicted in Figure 3, demonstrating their creativity. The modelling task has already been partially addressed in an exercise related to integral momentum balance.

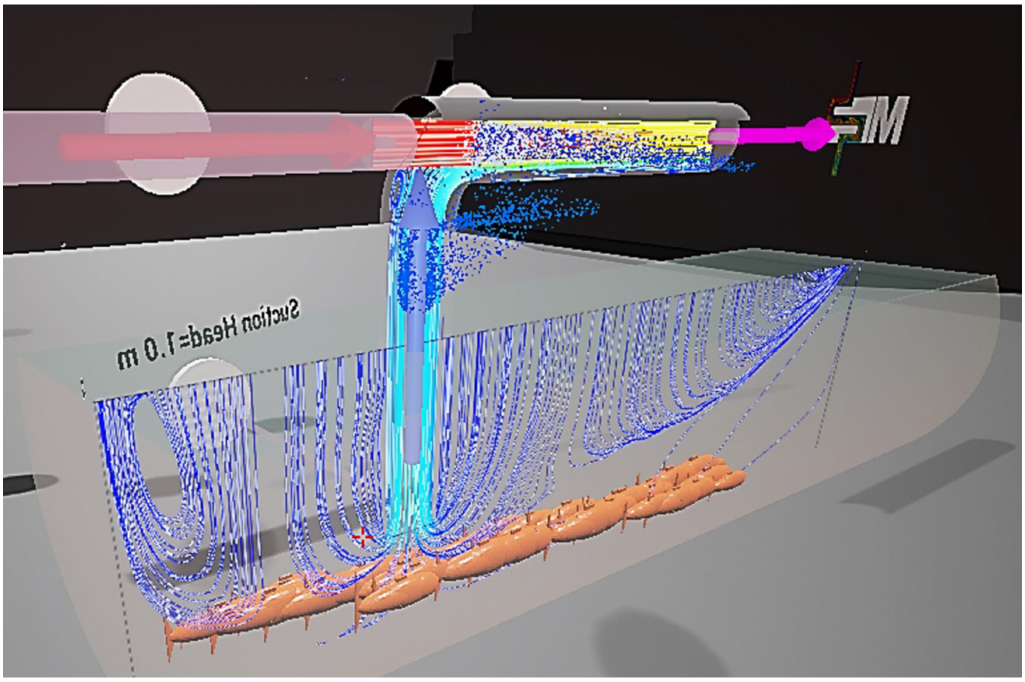


Fig. 3. Jet-pump with streamlines and particles (blue) leaving the pump through the casing (elbow) and not following the streamlines (bug)

The obtained results are required to be presented to the management, including non-technical individuals, as stated in the email disclaimer. This implies the need for simple and easily understandable explanations, despite the technical nature of the content. The email provides specific instructions to the responsible employee, including a deadline for completion and a technical drawing that may have unclear approaches to the solution. One student is selected as the team leader, whose main responsibility is to facilitate communication between the team and the manager. This arrangement aims to provide the students with experience in managing such dynamics and to demonstrate that team leaders do not necessarily have to be the most skilled members. The selection of both male and female students as team leaders is done equally.

Intentional spelling errors and incomplete sentences are used to represent a manager with a demanding demeanour, who prioritises results over the process (e.g., “not much support from management level”). The supervisor’s character traits are assigned to add realism to the real-world scenario.

The work assignment may include the following subtasks that the students need to identify, bring into meaningful order, and carry out with maximum possible autonomy:

- To familiarise oneself with the VR environment (VR)
- To create a mathematical-physical model (task provided, but not the method; non-VR)
- To conduct calculations using the developed model (not specified; non-VR)
- To perform a literature search (not specified; non-VR)
- To formulate an equation to determine the dimensionless characteristic curve from collected data (task given, but not the method; non-VR)
- To design the experiment (not specified; non-VR)
- To operate the test rig (VR)

- To conduct measurements (not explicitly stated; VR)
- To identify and report any bugs or errors (specifics of the bugs not provided; VR)
- To analyse, present, and discuss the obtained results (explicitly stated)
- To effectively communicate with the fictional boss (non-VR)
- To create and to deliver a presentation (non-VR, explicitly stated)

To successfully complete the work assignment, students are required to effectively coordinate their efforts, assess the workload, sequence the tasks, delegate responsibilities, and establish deadlines. Recognising that these aspects may pose challenges for students at this stage of their education, it is recommended that they communicate their progress and deadlines to the supervisor, who can provide support if needed.

3.4 Evaluation design

The laboratory experiment was conducted as part of the Fluid Mechanics 1 course, which is a fundamental course offered in the third semester of the Biochemical Engineering and Chemical Engineering undergraduate programmes at TU Dortmund University. Prior to the COVID-19 pandemic, these programmes had already conducted several in-person laboratory experiments. However, due to the pandemic, the organisation of all laboratory activities moved online using the university's central learning and content management system (LCMS), which facilitated the integration of various resources, such as data, programmes, video chats, and tests. Students worked collaboratively in groups of two to three members.

A total of 84 students participated in the experiment, 55 males and 29 females. Students were divided into 31 groups for the laboratory work.

In order to evaluate the laboratory experiment, a mixed methods approach was employed to gather comprehensive information. The evaluation consisted of the following components:

1. **Self-assessments via Moodle:** Students were provided with a standardised questionnaire that contained both closed and open-ended questions. The purpose of the questionnaire was to capture the students' perceptions of the laboratory experiment. This self-assessment allowed students to reflect on their experience and provide feedback.
2. **Oral presentations and colloquium:** Students had to present their results in the form of an oral presentation. These presentations were conducted in a colloquium, in which group discussions were integrated. During these discussions, the results of the self-assessment were jointly analysed and reflected upon by the students.
3. **Oral discussions with instructors:** The instructors conducted an oral discussion with each group in which they asked standardised questions. The purpose of these discussions was to evaluate the extent to which the students achieved the ILOs of the real-world scenario.
4. **Question in a written examination:** To evaluate the lasting effects of learning, a concise set of four questions was incorporated into the fluid mechanics exam, which took place six to eight weeks following the completion of the laboratory experiment.
5. **Regular group discussions:** These discussions were held in the interdisciplinary working group to ensure the transformative reflection necessary for the revision of the laboratory.

The students' data were collected using the qualitative and quantitative survey options of the LCMS. In addition, memory logs of the interactions between students and teachers during the colloquium were compiled. The working group discussions in the team and the decisions made for the next steps and future adjustments were recorded in written minutes. The analyses were carried out using qualitative data analysis and statistical evaluation methods [13].

4 EVALUATION RESULTS

All groups successfully met the minimum standard established, indicating that they achieved the ILO associated with working with incomplete problem definitions as identified by [9, 10]. Additionally, it was observed that all groups made multiple permissible corrections, in accordance with the laboratory course regulations. This pattern of making corrections aligns with the general trend observed in other experiments, where approximately 80% to 90% of groups exhibit similar behaviour.

All groups successfully expanded the pump model by incorporating additional effects, such as inertial losses, and determined the pump's own loss coefficient using the measurements obtained from the digital twin. Furthermore, some groups unexpectedly discovered alternative solutions, demonstrating their ability to engage in creative problem solving.

Approximately 35% of the groups conducted more comprehensive modelling of the pump, delving deeper into its characteristics. All groups, without any assistance, successfully carried out the time measurement task using an external real-world measuring device. The majority of groups accurately identified the cavitation noises and correctly interpreted them as such, while a few groups provided creative explanations, such as attributing the noise to friction or vibration in the suction pipe.

About 70% of the groups acknowledged the presence of fish in the tank and recognised the need to ensure their protection. Many groups proposed solutions such as installing a fish guard on the pump intake or increasing the cross-section of the intake line to reduce the impact on the fish. However, it is important to note that the students were surprisingly not able to predict the actual consequences of their proposed actions. Regardless of the presence of a fish guard or cross-section expansion, draining the tank would ultimately result in the suffocation of the fish, who require water to survive.

To assess long-term learning outcomes, a short four-item question was included in the fluid mechanics examination that was administered 6 to 8 weeks after the laboratory experiment. The question was related to a specific aspect of the experiment, namely the calculation of the maximum suction head of a pump. This content was also covered in the exercise of the course fluid mechanics. Of the 93 students who answered this question in the examination, 20 of them had participated in the laboratory. The average score obtained by students who attended the practical course was 1.65, which was more than twice as high as the average score of the other students (0.73). A two-sided t-test was conducted, resulting in a p-value of $p = 0.006$. This indicates that the observed difference is unlikely to be a random occurrence and suggests that the laboratory experiment has contributed to the long-term consolidation of the ILOs. However, it should be noted that not all of the students were able to make the connection between the experiment and the examination question. This variation in outcomes is expected in the context of exploratory learning because not all students can explore every aspect fully.

The students were asked to assess the importance of key skills in their future professional work, in analogy to German school grades between 1: very important and 6: completely unimportant. The findings are presented in Table 2, ordered in descending importance based on the results from all of the respondents. The results reveal some interesting patterns. Skills related to the interpretation of scientific results (1.56) and the students' perceived aspects of project work, such as time management (1.62) and team management (1.63), are particularly important. However, there are contradictory statements towards the bottom of the list. While the significance of following cookbook-like instructions for completing tasks was rated significantly lower (2.93) compared to working freely (2.04), the importance of creativity was not anticipated to be high (2.25) either.

Interestingly, working with a digital twin was considered somewhat more important (2.31) than manually operating experimental equipment or measurement systems (2.63). This suggests that students recognise the value of both real laboratory experiments and those conducted on a digital twin. Additionally, the skill of conducting literature searches (1.79), which was added to the CA checklist, was perceived as significantly more important than working on a digital twin (2.31). These findings highlight the students' perspectives of the importance of various skills for their future professional endeavours and provide insights into their preferences and priorities.

Table 2. Comparison of the evaluated average of importance of key skills in future professional activities, in analogy to German school grades between 1: very important and 6: completely unimportant

How Important do you Evaluate the Following Key Skills?	
Scientific interpretation of results	1.56
Time management	1.62
Team management	1.63
Modelling	1.73
Literature search (publications, patents, freely available data, etc.)	1.79
Finding errors or bugs	1.85
Comparison of model with measurement data or similar	1.88
Presentation of project results	2.01
Compliance (ethically correct behaviour)	2.02
Free work for work order fulfilment (open work order)	2.04
Creativity	2.25
Working on the digital twin (Industry 4.0)	2.31
Manual operation of equipment or measuring systems (engineer, not technician)	2.63
Work according to step-by-step instructions (descriptive work instructions)	2.93

The evaluation of the work instruction and the overall RWS aligns with the assertions made by [9, 10], who emphasise that engineering work is characterised by initially incomplete problem definitions, unclear approaches to solutions, and the expectation of independent completion of tasks with limited support from management. However, conventional instructional laboratory tests often fail to reflect these realities. In the case of the RWS, the specific and imprecise work assignment delivered via email received poor ratings, as depicted in Figure 4.

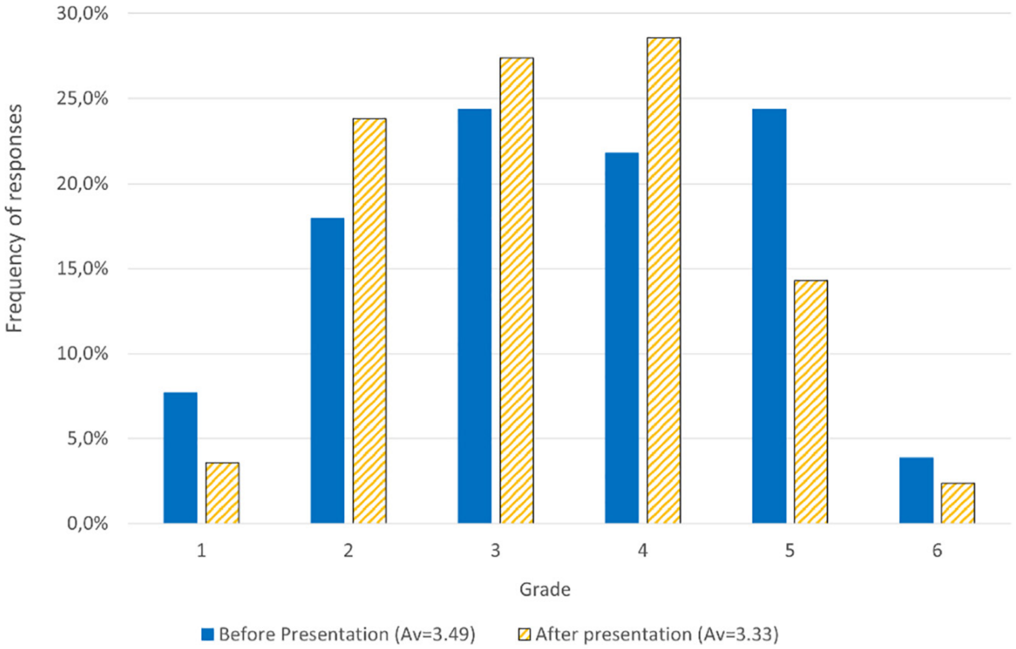


Fig. 4. Evaluation of the given open instructions into the problem before and after the discussion

The initial mean value was 3.49, which only slightly improved to 3.33 after the discussion. Approximately half of the students expressed dissatisfaction with the assignment, stating that it lacked clarity in many areas and that more specific objectives should have been provided. It is worth noting that despite the general understanding of the overall requirements, around 30 students independently highlighted that the assignment was unrealistically open-ended and incomplete. This perceived lack of structure made the task solution unnecessarily challenging and, in some cases, even intimidating. In light of these findings, students generally expressed the need for explicit goal-setting and clear requirements in order to enhance their understanding and performance. The students also voiced their criticism of the communication style, which was initially limited to email exchanges. They found this approach unrealistic because it hindered the clarification of any questions or concerns, they had upon receiving the task. Additionally, the level of support from the management was perceived as inadequate.

Alongside the issue of assignment precision, students also highlighted their difficulty in navigating unclear solution paths at this stage of their training. Some students had anticipated being able to solve the task independently using the knowledge acquired from lectures. They expressed a desire for a hint indicating the need to conduct literature research. Furthermore, there were explicit mentions of the excessive demand associated with the literature research (mentioned by 15 students) and the creation of the model due to a lack of sufficient background or clarity about the objectives. According to the students, a potential solution to address these concerns would involve initiating a brief discussion at the outset of the laboratory experiment, allowing for the direct clarification of ambiguities. However, such a clarification process would deviate from the intended emulation of professional practice that the instructors aimed to achieve.

Despite, or perhaps precisely because of, the complaints regarding the work assignment, the students acknowledged a greater practical relevance in the experiment and the RWS compared to the conventional instructional laboratories that lacked both an RWS framework and a CA checklist, as demonstrated in Figure 5. The conventional laboratory experiments received an average practical relevance rating of 2.60. In comparison, the initial rating for the practical relevance of this particular experiment was only slightly higher at 2.45 before the discussion took place. However, following the explanation of the learning objectives during the discussion, the perceived practical relevance significantly improved to 2.08. This increase can be attributed to the fact that after the disclosure of the learning objectives (such as project work, literature search, and unclear tasks), the students were able to attain a clearer understanding of their own learning achievements, which were also more comprehensive in nature compared to those in the usual experiments.

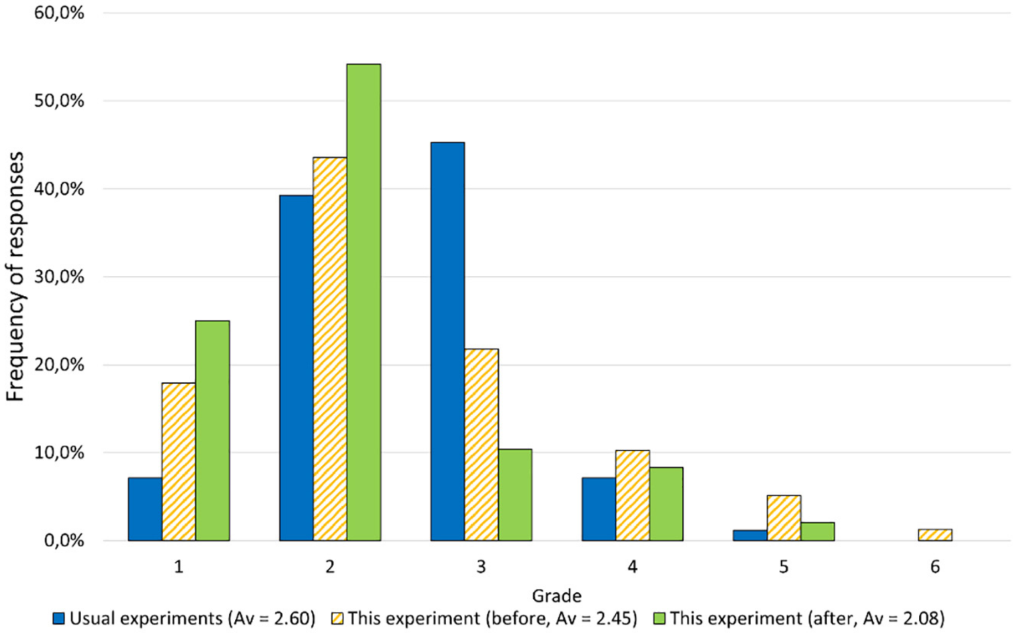


Fig. 5. Survey results (84 participants) of future professional activities with one: very good and six: very bad

Unprompted, several students highlighted certain aspects of the experiment that they felt particularly reflected professional practice. Specifically, 17 students emphasised the importance of effective communication and mentioned the target group-appropriate presentation in front of the board. Additionally, 11 students appreciated the requirement for creativity stemming from the independent goal setting, recognising its relevance in RWSs. Furthermore, five students acknowledged that the experience of team management during the experiment aligned with professional expectations. Moreover, a majority of students recognised the value of the flexible time allocation and the in-depth exploration of the subject matter, perceiving them as valuable preparations for future project work and a deeper understanding of the field.

Figure 6 illustrates the results of the evaluation regarding the learning effect of different laboratory experiments. The conventional experiments receive an average rating of 2.38, while the redesigned laboratory experiment receives a lower average rating of 2.00. However, it is important to note that the learning effect of the redesigned experiment is still perceived as greater than that of the conventional experiments, with a shift towards the two highest ratings.

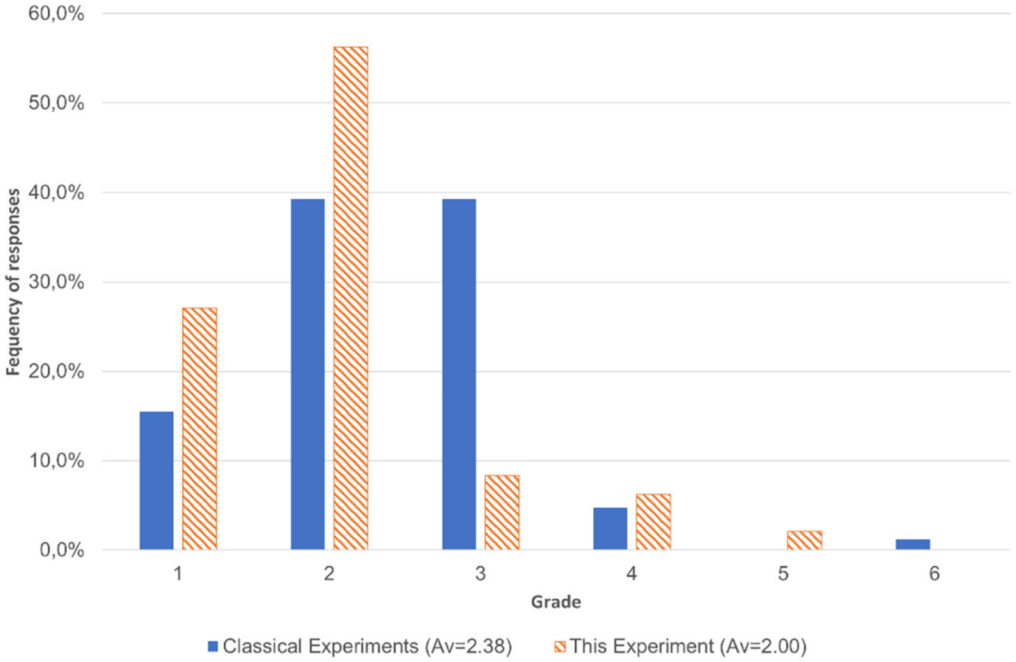


Fig. 6. Comparison of the learning effect of the classical and the redesigned experiment

According to the students' assessment, this discrepancy can be attributed to several factors. First, unlike traditional experiments in which reading material is provided and then repeated, the redesigned experiment requires active and independent exploration of a particular topic. This approach promotes a deeper level of engagement and understanding. Second, the relatively long duration of four weeks, which can be flexibly designed by the students themselves, plays an important role. This longer timeframe allows students to devote more time and effort to the task than the usual half-day duration of traditional experiments.

5 DISCUSSION

The virtual experiment provided a valuable alternative for conducting laboratory experiments. Unlike remote laboratory experiments, the stand-alone nature of the program ensured that there were no limitations or constraints due to limited equipment availability, such as those caused by reservation systems and temporary hardware failures. This flexibility allowed both the students and their supervisors to manage their time more freely since there was no need for equipment instruction or preliminary examinations. Although the digital experiment lacked the typical hands-on experience with equipment, the freedom to design the experiment provided a compensatory advantage, allowing for innovative approaches and problem-solving strategies.

The virtual experiment offers the advantage of being customisable to specific themes, is unaffected by equipment and material costs, and is unrestricted by physical limitations, such as unexpected behaviour or design constraints (e.g., holes in the pump housing). It also allows students to gain experience in working with Industry 4.0 equipment. However, it should be noted that while VR experiments complement real experiments by incorporating crucial features, they cannot fully replace them. Real experiments still provide unique "hands-on" experiences and related ILOs that still cannot be replicated in a virtual environment [8].

The laboratory instructors who were directly involved in developing the laboratory experiment perceived the CA checklist as a valuable tool for enhancing both real and virtual laboratory experiments. However, they initially found the announcement of the learning objectives before the start of the experiment contradictory to intentionally incomplete work assignments. The pedagogical language used in the checklist was unfamiliar to these subject specialists, leading to some initial hesitation and confusion ("it all sounds the same"). Despite this, the checklist format proved to be effective because it provided a concise and comprehensible framework, supplemented with examples, making it easier to understand and apply. Going through each checklist item prompted reflection on the experiment's completeness, content quality, and alignment with the intended learning objectives. The checklist facilitated the identification of the actual ILOs and helped to focus the laboratory experiment accordingly. It also highlighted any overlooked or superficially addressed areas of learning objectives. In particular, in the creation of a digital experiment, the CA checklist proved invaluable in recognising the limitations of the digital format compared to real equipment and finding ways to mitigate those limitations. The use of a "0, 1, 2, 3" formulation for implementation steps provided valuable insights into potential improvements, such as introducing cavitation noises for acoustic sensing.

In conclusion, incorporating the CA checklist into the experiment creation process has highlighted the shortcomings and limitations of the previous experiments, as evidenced by the students' feedback. It has also been instrumental in identifying crucial aspects that were previously overlooked and has sparked numerous creative ideas among the experiment creators. The utilisation of the CA checklist has significantly raised the average implementation level from 0.9 to 2.7, indicating a substantial improvement in the quality and effectiveness of the experiments.

The primary finding of this study emphasises the creation and handling of engineering-related theoretical models. Essential skills necessary for the course, such as selecting appropriate modelling tools and applying them effectively, were successfully incorporated.

The introduction of the RWS had a mixed impact on the students. For some, the simulated work assignment posed challenges. In particular, difficulties arose when independently organising and setting deadlines because this competency had not been emphasised in the previous coursework. Eleven out of the 31 participating groups encountered these challenges. Additionally, the lack of prior experience with literature searches at their level of study posed another obstacle. Consequently, the students required assistance in this aspect, including guidance on research strategies, such as searching for specialised literature in English or using synonyms. In total, 19 out of the 31 groups needed support in this regard.

The RWS also facilitated the use of simple and concise language in the presentation, avoiding unnecessary technical jargon. This skill is often lacking in subsequent written assignments. The unfamiliar task and approach presented in the RWS seemed to engage the students more effectively because they demonstrated increased attentiveness and interest. Moreover, the RWS framework simplified the process of creating a work assignment that aligns with the realistic expectations of the engineering profession, as advocated by [9], [10]. This preparation equips students with relevant skills for their future careers as engineers.

Furthermore, the investigation of how students dealt with unexpected outcomes was facilitated by deliberately introducing faulty representations and observing whether they were corrected. One specific measure used to evaluate their performance was the determination of the empty suction time, which provided insights into whether the students emptied the tank, resulting in the unfortunate demise of the fish, or if they extrapolated the final data points instead. It was only through this particular experiment that students were confronted with an ethical dilemma. While it may be easy to disregard the well-being of digital fish, the situation changes when these digital representations correspond to real fish in the digital twin.

The instructors' communication of expectations (e.g., goals, milestones and meeting deadlines) was generally effective. Meaningful milestones were typically employed and realistic deadlines were set. However, the initial groups faced challenges in developing a structured approach due to the open-ended nature of the task. Fortunately, as the groups started to communicate with one another, inadequate structuring became less frequent over time. This improvement was evident through explicit questions raised during the colloquium. Approximately 50% of the groups encountered a specific issue where they prioritised recording measured values without conducting a suitable literature search as the first step. Recognising that a literature search is essential for meaningful task processing and that arbitrary data collection lacks completeness, the instructors' interventions were necessary in such cases. This highlights the difficulty that some students face at this stage of their training in independently setting intermediate goals. It also supports the assertion of [9], [10] that students often expect to solve subtasks independently without recognising the need for a comprehensive approach.

6 CONCLUDING REFLECTIONS FOR FURTHER REDESIGN

The developed laboratory experiment will be retained for future use, with the potential for further improvements to enhance ILOs. One aspect that can be enhanced is the pre-organisation of the experiment. Many students expressed confusion and raised numerous organisational questions because it was their first time encountering a laboratory experiment without a script. To address this problem, it is advisable to explicitly communicate, prior to the start of the practical sessions in the semester, that no preparation is required for the experiment and that the necessary working documents will be provided on the day of the experiment. This recommendation holds particular value for students who have limited experience with non-traditional laboratory experiments.

As a technical design consideration, it is not necessary to invest significant effort in identifying every error in the code or representations. Such an endeavour would not only be highly time-consuming but would also detract students from an important aspect, which is the exploration and interpretation of errors within the digital twin.

Many students express a desire for a more clearly structured and defined work assignment. However, this desire conflicts with the objective of creating a high level of realism, which would impede the opportunity to challenge the students' creativity. It is important to maintain an intentionally incomplete and ambiguous work order, as well as unclear paths to resolution, in order to uphold the realism advocated by [9], [10].

Concerning inter-group work, it is necessary to make some alterations to the work assignment each year to prevent students from simply copying the previous year's work. This is particularly straightforward in the VR experiment, which offers ample exploratory content.

The utilisation of the CA checklist is highly recommended for enhancing virtual experiments. It is advisable to thoroughly work through the complete checklist and review the attainment of ILOs for each item to improve the instructional quality of the laboratory experiment in subsequent years. This process can help identify any unexpected learning objectives that were not successfully achieved, such as the accurate application of measuring instrument accuracy classes.

To facilitate the practical application of the CA checklist, the availability of a database containing implementation examples would be beneficial. Furthermore, specific refinements should be considered to tailor the CA checklist specifically for VR laboratory testing.

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