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PAPER

Evaluating Effectiveness and Appeal of a Virtual Laboratory in an Undergraduate Fluid Mechanics Course

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ABSTRACT

This study investigates the integration of a smartphone-based virtual laboratory into a fourth-semester undergraduate fluid mechanics class on pump–piping systems. The virtual laboratory is designed according to constructive alignment and the SOLO taxonomy to foster deep learning. Students interact with realistic 3D system models, adjust component parameters, and receive real-time feedback based on physical simulations. To identify the effectiveness, a pre- and post-test with 26 paired responses showed a small overall improvement in general knowledge, with medium-to-large gains in specific methodological knowledge and self-assessed competence in handling real fluid systems. Student feedback was collected to assess the appeal of the teaching method. Students rate it highly positive (mean rating = 4.42/5), highlighting increased motivation, engagement, and active participation compared to conventional teaching. Future work will expand the app with additional levels targeting diverse learning objectives in fluid mechanics.

KEYWORDS

engineering education, fluid mechanics, virtual laboratory

1 INTRODUCTION

Fluid mechanics, along with mathematics and structural mechanics, are core scientific competencies in mechanical engineering and process engineering undergraduate studies. Due to many complex mathematical equations and physical models, the general students' interest in these subjects is often low. Many students get no access to the topic, and deep understanding of the teaching content is not achieved. Laboratory experiments can improve basic understanding through practical work. But these experiments in general show the following problems: Real experiments with fluid machinery involve safety risks, making a fully self-directed student laboratory almost impossible. Often, only one physical test rig is available, limiting

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students' access and requiring considerable teacher time to supervise all students. Because of high acquisition costs for fluid machinery, the variety of experiments is low, while most experiments take much time to prepare and execute. In addition, many flow effects are invisible and remain abstract, even in a physical experiment. The use of complex measuring devices also increases external and intrinsic cognitive load and reduces learning success [1].

Virtual laboratories avoid these problems since all students can carry them out on their own smartphones without high costs and safety risks. This supports the experience of autonomy and competence, which, according to self-determination theory, are the most important factors influencing high motivation [2]. Behr et al. demonstrated that the use of virtual laboratories in undergraduate fluid mechanics courses can promote deep learning and improve conceptual understanding. Their study on a virtual simulation of an extraction column illustrates how digital twins can provide safe, cost-effective, and scalable access to complex engineering processes [3].

2 FOUNDATIONS FOR EVALUATING TEACHING AND LEARNING QUALITY

Teaching and learning quality can be described with two dimensions introduced by Honebein and Reigeluth: effectiveness and appeal. Effectiveness means how much students actually learn and achieve the intended outcomes. Appeal describes how much they enjoy the learning experience and how motivated they feel. Looking at both aspects together makes it possible to evaluate not only the cognitive but also the emotional quality of instruction. This is especially important in engineering education, where students often struggle with interest and engagement [4].

Hattie's large-scale meta-analysis [5] also provides a useful benchmark for evaluating learning methods. By combining over 800 meta-analyses, he established Cohen's d as a standard measure of learning effects. Cohen's d is a dimensionless statistic that quantifies effect size in a standardized form, enabling comparisons across different measurements and scales [6]:

$$d = \frac{\overline{\underline{X}_{\text{Post}} - \underline{X}_{\text{Pre}}}}{\text{SD}\left(\underline{X}_{\text{Post}} - \underline{X}_{\text{Pre}}\right)}$$

The vectors $\underline{X}_{\text{Pre}}$ and $\underline{X}_{\text{Post}}$ contain the students' score for a single question on a pre- and post-test. The numerator represents the mean change in scores and the denominator contains the standard deviation (SD) of change in scores. Consequently, d is a dimensionless statistic that quantifies effect size in a standardized form, enabling comparisons across different measurements and scales. Cohen lists reference values for d to classify the effect size: $|d| \approx 0.2$ (small effect), $|d| \approx 0.5$ (medium effect) and $|d| \approx 0.8$ (large effect) [1]. Positive values of d indicates an improvement, whereas negative values correspondingly indicate a reduced effect. Hattie shows that the average effect size across all studies was $d_h = 0.4$, which is defined as the hinge point, that marks above-average effectiveness. His synthesis shows that digital approaches such as computer-assisted instruction or simulations typically produce moderate effects, with average effect sizes in the range of $d = 0.32 \ldots 0.37$. These results suggest that digital tools can support learning, but often need to be combined with well-structured instructional design to achieve stronger outcomes. Against this background, the effect sizes measured in our study allow for a direct comparison and position the virtual laboratory within the broader discussion of technology-enhanced teaching and learning [5].

Behr et al. identify constructive alignment (CA) [7]—with well aligned clear intended learning outcomes (ILO), teaching-learning activities (TLA), and learning outcome monitoring (LOM)—as a prerequisite for the effectiveness of virtual laboratories [3]. In this study, we apply the SOLO taxonomy (Structure of the Observed Learning Outcome) [8] as a framework for defining, analyzing, and categorizing student learning outcomes. Especially in the application of CA in the context of higher engineering education, proper definition of assessment tasks and ILO is important [9]. The SOLO taxonomy describes a hierarchy of cognitive understanding, ranging from surface understanding, where only one or a few aspects of a concept are grasped, to deep understanding, where the aspects are integrated into a coherent whole and can be generalized and applied to new contexts. These levels of understanding, summarized in Table 1 along with key verbs addressing the levels, serve as a structured framework to gauge the level and integration of students' understanding. To promote deep learning, the relational and extended abstract levels should be addressed. In addition, the learning outcomes can be classified into two types of knowledge: declarative knowledge, which refers to factual and conceptual understanding (knowing that something is the case), and functioning knowledge, which refers to the ability to apply knowledge in practice and solve problems (knowing how to do something) [8, 10].

Table 1. An example of verbs used for formulating ILOs and LOMs in different SOLO taxonomy levels of understanding, divided into declarative and functioning knowledge [8]

	Unistructural (SOLO 1)	Multistructural (SOLO 2)	Relational (SOLO 3)	Ext. Abstract (SOLO 4)
Declarative knowledge	identify, recite	describe, classify	analyze, conclude	generalize, hypothesize
Functioning knowledge	count, match	compute, illustrate	apply, construct	analyze and initiate countermeasures

3 EXERCISE DESCRIPTION

This study is based on an exercise in fluid mechanics for undergraduate students of mechanical engineering in the fourth semester. The topic treated by the exercise are pump-piping systems, the connection and interaction between common system components (e.g., pumps, pipes, valves, and tanks). As pictured in Figure 1, two different pump-piping systems are discussed.

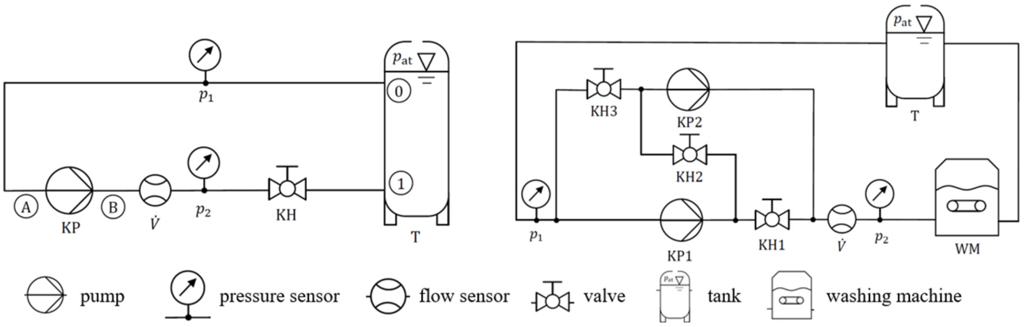

Fig. 1. Pump-piping systems 1 (left) and 2 (right).

System 1 is a simple cycle consisting of one pump, one valve, one tank, and pressure and volume flow gauges. This system is used to repeat and convey the basic knowledge of pump-piping-systems, which is discussed in detail. System 2 is more complex, and the single pump is replaced by two pumps and three valves that enable multiple pump configurations. Using a washing machine as a consumer, this system represents a realistic system for engineering problems. It is less discussed, and students must transfer knowledge by themselves to an advanced application.

Table 2. Exercise tasks on the worksheet

Task	Description	SOLO	Knowledge
1.1	*Identify* and *match* symbols or quantities in the pump supply curve; formulate the corresponding equation.	1	Declarative
1.2	*Identify* and *match* quantities in the system demand curve; formulate the corresponding equation.	1	Declarative
1.3	*Analyse* the pump supply and system demand curves; *conclude* the operating point by determining the intersection graphically.	3	Declarative
1.4	*Apply* and *compute* the specific work of an incompressible fluid; use the appropriate formula.	2	Functioning
1.5	*Plan, conduct* and *construct* pump characteristic curves at different rotational speeds using the **Virtual Laboratory**.	4	Functioning
2.1	*Analyse* the requirements of two washing programs and conclude the appropriate pump configuration (series/parallel).	3	Declarative
2.2	*Plan, conduct* and *construct* the system demand curve of the washing machine using the **Virtual Laboratory**.	4	Functioning

Table 2 presents the tasks addressed in this exercise for System 1 (1.1–1.5) and System 2 (2.1–2.2), along with the intended SOLO level and type of *knowledge* (refer to Table 1). Tasks 1.1–1.4 and 2.1 were designed for a conventional, teacher-centered exercise format. Tasks 1.5 and 2.2 are designed to be student-centered and use the smartphone app as a virtual laboratory, requiring students to work independently.

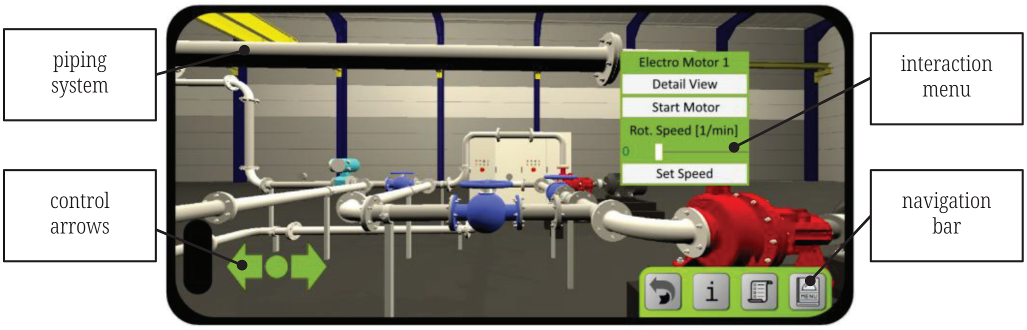

Fig. 2. In-game-view of level 2

Figure 2 shows an in-game-view (ego-perspective) of the smartphone app for the virtual laboratory, developed with Unity Engine [11]. The app includes two levels for tasks 1.5 and 2.2 correspondingly. It displays 3D representations of the 2D circuit diagrams of the worksheet (see Figure 1), which is also presented to the students during the TLA. All relevant system components (pumps, motors, valves, and consumer machines) are interactable and allow an adjustment of component parameters (rotational speed, valve position). Based on the chosen system parameters, a physical analytical model calculates all relevant fluid quantities in real-time in the background. Consequently, interacting with pressure and volume flow gauges gives real-time feedback about the flow variables. Via control arrows in the heads-up display, the user can navigate around the 3D pump-pipe system and access all system components. Interacting with valves, starting the consumer machine and adjusting motor speed gives audio feedback using real sounds. All in all, the virtual laboratory imitates a real physical system in the relevant areas. In addition, the app includes a quest system that offers some hints to the students and gives feedback for solved subtasks.

4 STUDY PROCEDURE

A virtual laboratory is implemented as part of an exercise and its effectiveness is evaluated. The exercise is integrated into the basic lecture on fluid mechanics for fourth-semester bachelor's students in mechanical engineering. The exercise focuses on pump–piping systems and was structured into four consecutive parts:

1. **Teacher-centered instruction (30 min):** The session began with a teacher-led segment designed to activate prior knowledge and consolidate key concepts from the lecture. This was achieved through targeted questioning and the guided solution of calculation tasks 1.1–1.4 and 2.1, encouraging student participation and fostering discussion.
2. **Pre-Test (10 min):** Students then completed an online test aimed at assessing their initial knowledge level prior to interacting with the virtual laboratory. The test was accessible via smartphone and provided a baseline for later comparison.
3. **App-based virtual laboratory activity (40 min):** In the main part of the exercise, students downloaded and installed the dedicated smartphone application for the virtual laboratory. For participants without a compatible device, enough preconfigured smartphones were made available. Using the app, students completed Tasks 1.5 and 2.2, engaging in interactive simulations of pump-piping systems and applying their theoretical knowledge in a practical, virtual environment.
4. **Post-Test (10 min):** To evaluate learning gains, students completed the same online test as in the pre-test phase. The results were compared to determine changes in knowledge and understanding after using the virtual laboratory.

The Pre-Test was deliberately positioned between the introductory segment and the virtual laboratory activity in order to assess students' knowledge gains only through the use of the app. Beyond this primary objective, the arrangement also enabled the instructor to observe differences in student behavior across the two teaching formats. Due to the small sample size and the integration of the exercise into regular teaching, it was not possible to apply a Solomon four-group design [12]. As a result, the outcomes might be affected by priming effects [13], although the pre- and post-test design still provides useful indications of learning gains.

5 TEST METHODOLOGY

To measure students' learning gains, an online test was developed that covers all levels of the SOLO taxonomy and addresses both declarative and functioning knowledge. Nine core questions primarily target the relational and extended abstract levels, with a particular focus on functioning knowledge. Table 3 provides an overview of the core questions included in the pre- and post-test. All questions can be answered based on the lecture content and the teacher-led instruction at the beginning of the exercise. The first eight questions address general knowledge of pump-piping systems, while the final core question focuses specifically on the methodology applied in the virtual laboratory using the smartphone. Each question was valued at a maximum of one point.

Table 3. Core questions of the pre- and post-test with respective SOLO-taxonomy level, addressed knowledge and format in which the question was posed to the students

Question	Description	SOLO	Knowledge	Format
1	*Identify* and *match* symbols to different system components.	1	declarative	multiple choice
2	*Classify* sensors for a measuring task.	2	functioning	multiple choice
3	*Analyse* characteristic pump curves and *conclude* accordingly.	3	functioning	multiple choice
4	*Apply* the correct ball valve position for a series connection and *construct* the corresponding setup.	3	functioning	multiple choice
5	*Apply* the correct ball valve position for a parallel connection and *construct* the corresponding setup.	3	functioning	multiple choice
6	*Analyse* statements on parallel and series connections and *conclude* which are correct.	3	declarative	multiple choice
7	*Analyse* characteristic pump curves and *conclude* which statement is correct.	3	functioning	multiple choice
8	*Generalize* the effects of changes in the operating point and characteristic curve, and *hypothesize* the underlying reasons.	4	functioning	free text
9	*Analyse* and *initiate* the procedure to determine a supply curve, and *construct* the corresponding setup.	4	functioning	free text

In addition to the core questions, the pre- and post-tests includes two supplementary items to capture students' self-assessment of their own capabilities as listed in Table 4. Students can rate themselves on a scale from 1 (no capability) to 5 (high capability).

Table 4. Self-assessment questions of the pre- and post-test

Question	Description	Format
10	Confidence in applying lecture content on pump–piping systems to a real, physical system	rating
11	Confidence in identifying and naming individual components on a real, physical system	rating

In the end of the post-test the students were asked to rate and evaluate the virtual laboratory and digital tools for higher education as listed in Table 5 in order to assess the appeal of the virtual laboratory. Students can rate on a scale from 1 (bad) to 5 (good).

Table 5. Evaluation questions for the virtual laboratory app (only post-test)

Question	Description	Format
12	Usefulness of digital tools, such as the app, in higher education teaching	rating
13	Feedback on the app: strengths, weaknesses, detected errors, and suggestions for improvement and integration into teaching	free text

6 TEST EVALUATION

A total of 31 students participated in the virtual laboratory and completed the pre- and post-tests. Of these, only 26 provided complete responses and were therefore included in the paired-sample analysis. Figure 3 presents the average scores for the nine core questions as well as for the two questions assessing students' self-evaluation.

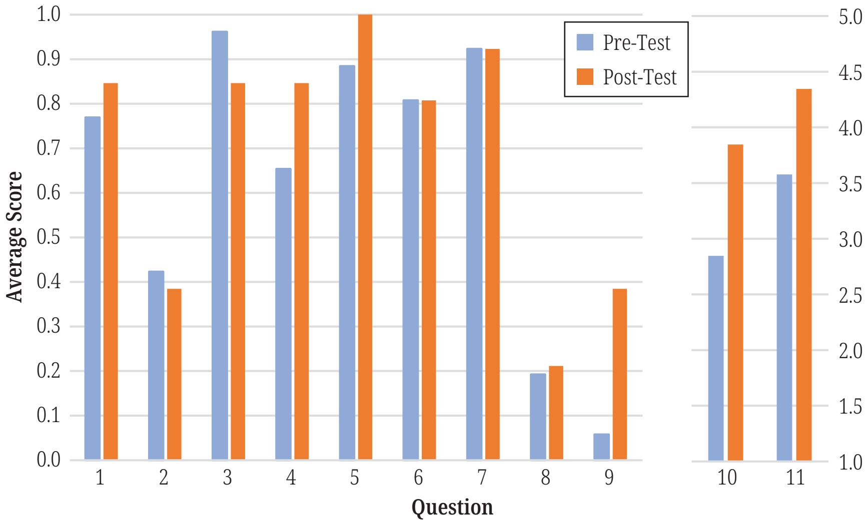

Fig. 3. Average results of the pre- and post-tests (sample size 26)

Table 6. Effect sizes *d* and *p*-values for each question in the pre- and post-test

Question	1	2	3	4	5	6	7	8	9	10	11
d	0.28	–0.06	–0.35	0.39	0.35	0.00	0.00	0.09	0.67	1.58	0.81
p	0.161	0.770	0.083	0.057	0.083	1.000	1.000	0.664	0.002	0.0000	0.0004

In Table 6 the evaluated *d*- and *p*-values for core questions (1–9) and two self-assessment questions (10–11) are listed. The *p*-values were calculated using a paired *t*-test, they indicate the statistical significance [14]. Questions 1–8 show no statistical significance ($p > 0.05$) whereas questions 9-11 have a high ($p < 0.01$) and very high significance ($p < 0.001$). The effect size *d* can be interpreted independently of statistical significance, and thus remains informative even when results are not significant. For questions 2, 6, 7, and 8 no relevant effect size can be noticed. Question 3 shows a small-medium reduction in score, whereas questions 1, 4, and 5 show a small-medium positive effect. Question 9 has a medium-large improvement in score. Question 10 and 11 indicates a large positive effect in self-assessment.

All in all, the results indicate a medium positive average significant effect on students' general knowledge on pump-piping systems ($\bar{d} = 0.45 > d_h = 0.4$, $\bar{p} = 0.032 < 0.05$) based on the nine core questions. The result of Question 9 ($d = 0.67$ $d_h = 0.4$) shows, that using the smartphone application significantly improves students' functioning knowledge on the specific methodology applied in the virtual laboratory. This indicates that students were able to integrate and generalize their knowledge, which corresponds to the extended abstract level of the SOLO taxonomy. In addition, the students' self-assessment about dealing with real fluid systems is significantly increased.

The overall student feedback was highly positive. The provided smartphone app, as well as the usefulness of digital tools in higher education (Question 12), received an average rating of 4.42 on a scale from 1 (useless) to 5 (useful). Furthermore, the free text responses to Question 13 show that students generally found the virtual laboratory engaging, visually clear, and helpful for understanding theoretical concepts through practical examples, with realistic 3D representations of components. Common suggestions for improvement included adding a top-down view, clearer visual or interactive feedback when values or settings are changed, and simplifying the control and adjustment of elements. Some participants noted minor technical issues (bugs, quest tracking errors, limited movements) and suggested enhancing accessibility, cross-platform compatibility, and updating the interface for smoother operation. This overall feedback shows that the use of the virtual laboratory increased the appeal of the learning setting. In the sense of Honebein and Reigeluth, appeal reflects how much students enjoy and value the learning process [4]. The high ratings and positive comments therefore indicate not only effectiveness but also higher motivation and acceptance.

7 TEACHER'S OBSERVATIONS

This study employed two distinct teaching approaches. In the introductory part, a conventional, teacher-led approach was used: the tasks were presented, discussed with the students, and concluded by showing the solution. As in many previous exercises, student feedback during the discussion was limited, with only a few students actively participating. The second part involved the use of the smartphone app for a virtual laboratory activity. In contrast to the first part, all students participated with interest and worked on the exercise independently. Interaction was significantly higher, with students engaging in discussions with their peers and actively asking the teacher questions—both on technical topics and on the teaching content.

Overall, from the teacher's perspective, the use of the smartphone app transformed student behavior from passive to active participation. Student motivation increased from the teacher's perspective, the barrier to teacher–student interaction was lowered, and access to the students was facilitated. These observations also indicate an increase in the appeal of the teaching setting, as students showed greater enjoyment and engagement in the learning process.

8 SUMMARY AND OUTLOOK

In this study, a virtual laboratory for pump-piping systems was integrated as a smartphone application into a fluid mechanics undergraduate class. After conventional teacher-led instruction, students worked independently with their smartphones. Students showed high acceptance of using digital tools in higher education. Based on a pre- and post-test, a medium increase of students' general knowledge about pump-piping systems was determined. But specific learning objectives that were applied in the smartphone app and students' self-assessment are significantly higher after the virtual laboratory. From the teacher's perspective, a highly positive effect regarding students' learning motivation, active participation, and communication was observed. In summary, the virtual laboratory in the undergraduate fluid mechanics class received highly positive evaluations.

In comparison to other teaching methods reported by Hattie, the effectiveness of the virtual laboratory can be classified as moderate. The overall effect across the nine core questions was medium high ($\bar{d} = 0.45$), which is above Hattie's hinge point ($d_h = 0.4$) for above-average learning effects. At the same time, specific objectives directly supported by the app reached medium to large effects ($d = 0.67$), comparable to approaches like mastery learning ($d = 0.57$), direct instruction ($d = 0.59$) or individual feedback ($d = 0.72$). In contrast, technology-based approaches in Hattie's synthesis, such as simulations or computer-assisted instruction, typically showed only moderate effects ($d = 0.32 \ldots 0.37$). This indicates that the virtual laboratory outperforms average technology-based interventions and approaches the effectiveness of more guided instructional methods. In addition, the high student ratings and positive feedback demonstrate a clear increase in appeal in the sense of Honebein and Reigeluth, highlighting the motivational value of the virtual laboratory.

Until now, only two levels were introduced to the teaching context. Together with students' feedback for further improvement of the app, more levels for various topics in fluid mechanics will be provided and evaluated. The core learning objectives of the lecture and typical problem topics of the students will be specifically integrated into the app. By progressively expanding the range of scenarios, the virtual laboratory aims to address diverse learning needs, enhance conceptual understanding, and foster greater engagement with complex fluid mechanics concepts. In addition, effectiveness will be further enhanced by incorporating approaches such as mastery learning, direct instruction, and individual feedback into the smartphone app.

9 ACKNOWLEDGEMENTS

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10 ETHICS STATEMENT

The approval was granted by the Ethics Committee of TU Dortmund University (No. GEKTUDO2023-46). Informed consent was obtained electronically before students participated in the online pre- and post-test. Students were informed about the study's objectives, the voluntary nature of participation, and data protection measures. They could discontinue participation at any time without negative consequences.

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