A Framework for the Development of Online Virtual Labs for Engineering Education

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Abstract

Laboratory education plays a vital role in the education of engineers. Beyond concepts and principles, laboratories help students develop essential engineering skills such as problem-solving, designing, and troubleshooting. However, the use of laboratories in engineering education may be limited by a series of factors, including the cost of equipment, time, and infrastructure. To reduce the consequences of such limitations, educators are constantly looking for emerging technologies that make the lab more inclusive, creative, and effective. Among these technologies, virtual laboratories are becoming very popular in engineering education. This paper presents a conceptual and practical framework for developing virtual labs for engineering education. The framework combines a classical backward design approach with the concepts of virtual equipment and digital twins to create virtual versions of different hands-on experiments. In these virtual experiments, students can reproduce all the hands-on practices virtually and learn concepts, procedures, and attitudes toward experimentation. The authors will discuss the theoretical foundations of the framework and present examples of virtual labs already developed for mechanical, electrical, civil, and chemical engineering education. In addition, the authors will discuss the main concerns and difficulties in creating a virtual labs web platform used by more than 1,000,000 students.

1. Introduction

The use of virtual labs in education has its roots in the early days of computer-based simulation and modeling [1], [2]. In the 1990s, early virtual labs were used primarily as teaching tools to supplement traditional classroom instruction. These early virtual labs were limited in scope and functionality, but they gave students a new way to interact with and understand complex concepts. As technology advanced, virtual labs became more sophisticated and interactive, incorporating advanced animations, simulations, and visualizations to create immersive, hands-on-like learning experiences [3], [4]. Consequently, virtual labs are widely used in various educational settings, from primary and secondary schools to universities and professional training programs [5], [6]. They have become a valuable tool for educators, providing a flexible and accessible platform for delivering interactive and engaging educational content[7].

Research has documented the many advantages of virtual labs compared to traditional hands-on labs [5], [8], [9]. First, virtual labs usually require lower investment and fewer resources. Second, virtual labs can be accessed remotely. Third, virtual labs foster students' learning of concepts and principles through simulations and representations of abstract phenomena. Finally, virtual labs are usually flexible and allow students to change the values of the different variables and explore the experimental results faster than hands-on or remote experimentation.

Furthermore, many virtual labs focus on developing students' conceptual understanding of a particular phenomenon or theory. In most cases, characteristics associated with the equipment, the setup, the environment, and all the experimental procedures are neglected. This approach is appropriate in most science-based courses and usually results in equivalent learning gains compared to traditional hands-on labs. However, such an approach might hinder the development of essential skills associated with labs in engineering education. Among these skills, one might cite communication and collaboration, safety, designing experiments, and learning from failure. Furthermore, a common critique regarding virtual labs refers to the use of idealized data that usually does not reflect the uncertainties and nuances of the real world [10]. Also, these labs generally lack the sense of reality necessary to immerse students in more authentic experiences.

The use of virtual labs in engineering education has been particularly effective in helping students develop a deeper understanding of complex concepts and real-world applications [1], [11], [12]. For example, in electrical engineering, students can learn how to design and analyze electronic circuits and gain practical experience working with complex systems and processes using virtual labs that mimic oscilloscopes, multimeters, circuits, and errors [13]–[16]. Virtual labs may simulate real-world scenarios in mechanical engineering and allow students to design and test mechanical systems, such as engines and machines [17]–[20]. This approach provides opportunities for students to gain hands-on experience with the design and development of real-world products without the limitations and risks associated with traditional physical labs. The use of virtual labs has also been shown to positively impact student engagement and learning outcomes, with studies indicating that students who use virtual labs have a deeper understanding of concepts and perform better on exams compared to students who receive only traditional classroom instruction [21].

While we agree with the importance and benefits of virtual labs, we contend that to achieve their full potential, these labs must be carefully designed and implemented. Indeed, a series of factors may affect the learning experiences derived from virtual lab activities, including, but not limited to, instructional designs, User Interface (UI) and User Experience (UX), and data generation process. In this paper, we propose and discuss a framework to support the development of virtual labs for diverse types of learners and, in particular, for engineering education students. We will address most of the factors that may affect the efficiency of a virtual lab, providing examples of several virtual labs already developed and used by a large number of students. Finally, we will bring insights from educators from several disciplines and higher education institutions who cooperated with us while creating those labs.

2. Best Practices for Designing Virtual Labs

The design and development of a virtual lab is a very iterative process involving several key factors, actors, and stakeholders. The following paragraphs will describe the key elements, providing conceptual and practical recommendations for improving students' learning experiences. Figure 1 illustrates the main steps in designing and deploying a virtual lab.

2.1 Instructional Design

The first factor to be considered when designing a virtual lab is related to the instructional design for the intended activities. A well-conceived instructional design considers the learning objectives, target audience, and desired outcomes of the lab activity and incorporates instructional strategies and tools that support student learning and development. Three key elements are fundamental for an effective design [22]: Content, Assessment, and Pedagogy.

By content, we mean defining clear learning objectives. By clearly articulating the learning objectives, instructional designers and educators can clearly understand what students are expected to learn and be able to do by the end of the course or program [23]–[25]. Another element, assessment, is crucial in the instructional design of virtual labs since it provides evidence of the instructional materials' effectiveness and helps identify areas for improvement. It allows for the evaluation of learning outcomes and the alignment of instructional goals with desired results. Additionally, assessment data can inform future instructional decisions and drive modifications to the instructional design for better student outcomes[26], [27].

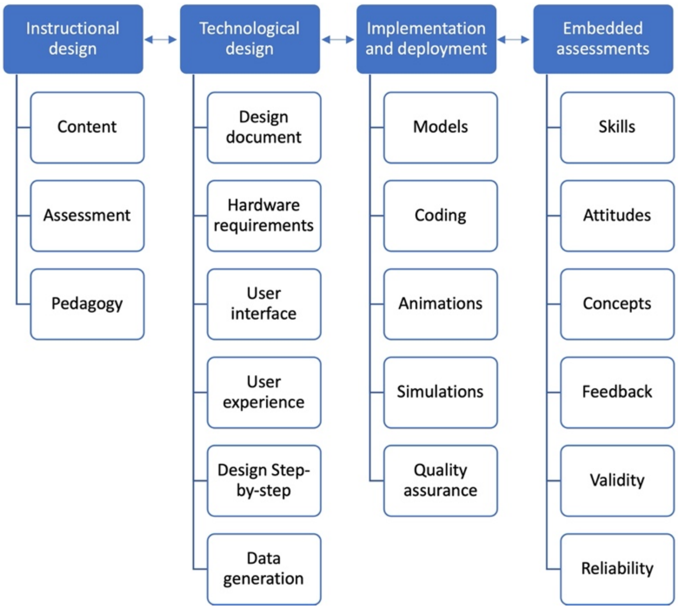

Figure 1 - Key steps in designing and deploying virtual labs

Finally, pedagogy determines how content is taught and learned. Effective pedagogy takes into account the characteristics of the learners, the content to be taught, and the desired learning outcomes to create instructional experiences that are engaging, meaningful, and relevant [28], [29]. Thus, the choice of pedagogical approaches can greatly impact student learning outcomes, so it is essential to make informed decisions when designing instructional materials. Content, assessment instruments, and pedagogy must be well-aligned to support the development of higher-order thinking skills and foster student motivation and engagement.

We noticed that laboratory activities conceived for real laboratories typically follow the traditional approach to laboratory instruction [30], which means well-structured activities where students must follow step-by-step instructions to conduct the experiments. Moreover, some instructors did not reflect on the learning objectives beyond developing practical engineering skills. Interestingly, when we engage with these instructors to reflect on the instructional designs for their lab activities, they used to start very cautiously. Still, after they see the translation of their actual practices into a virtual lab, they propose many new ideas to improve their labs. When these educators start designing a virtual lab, they bring all the existing constraints to the virtual lab. Then when they see that virtual labs have almost no limitations, they realize the power of these virtual labs as a technology-mediated learning tool.

The key outcomes of the instructional design phase are clear learning objectives, clear ways to assess students' learning, and possible pedagogical approaches. Regarding the latter, we must emphasize that virtual labs can be adopted with any pedagogical approach, including demonstrations, simulations, project- and problem-based learning, and inquiry-based learning. When you know in advance which approach you will use, a more tailored virtual lab can be developed.

2.2 Virtual Lab Design Document

Like a game design document [31], a virtual lab design document is a comprehensive plan for developing a virtual lab. It outlines the virtual lab's objectives, goals, and learning outcomes, as well as the instructional strategies and pedagogical approaches to be used. The document includes details on the content to be covered, the technology and tools to be used, the assessment methods and evaluation criteria, and the timeline and budget for development. In addition, this document must describe animations and simulations representing key concepts or principles to be addressed by the lab. Furthermore, details of the equipment, setting, procedures, and functionalities must be provided. A virtual lab design document serves as a roadmap for the development process, ensuring that the final product aligns with the instructional goals and meets the needs of the learners. It also provides a reference for stakeholders and team members to understand the virtual lab project's vision, scope, and direction.

A critical decision that must be taken at this stage is whether to employ virtual assistants or tutors to aid students during virtual lab sessions. Virtual assistants can assist students by guiding them on procedures or step-by-step actions and functioning as mentors, encouraging students to reflect on phenomena and activities or even prompting them with questions to enhance cognitive and metacognitive strategies. The extent to which virtual assistants support students may vary depending on the student's level of proficiency and the pedagogical approach utilized.

2.3 Hardware Requirements

Beyond the conceptual elements described above, a virtual lab design document must indicate the hardware requirements for the applications. Hardware specifications play a crucial role in determining the lab's performance, compatibility, and overall user experience. If the hardware requirements are unmet, the lab may run slowly, suffer from technical issues, or be unusable. By providing precise hardware requirements, designers can reduce the likelihood of negative feedback, technical support requests, and returns due to compatibility issues. In our case, we developed virtual labs for students from several backgrounds and economic levels. Thus, considering that low socio-economic students usually have low-capability hardware, we must carefully consider the characteristics of the labs to attend to the learning objectives without compromising the students' learning experiences.

2.4 User Interface and User Experience

User Experience (UX) refers to a person's overall experience when interacting with a product, such as a website, mobile app, virtual lab, or game [32]. It covers all aspects of the interaction, including design, usability, accessibility, and emotions. The goal of UX design is to create a product that is functional, efficient, enjoyable, and satisfying to use. User Interface (UI) refers to the graphical layout of an application and the way it interacts with users. It includes the visual design, layout, and flow of the application, as well as the controls and feedback provided to the user [33]. The goal of UI design is to create an intuitive, efficient, and visually appealing interface, making it easy for users to perform tasks and access information. Indeed, the use of best practices and principles for good user experience and the user interface is a critical factor for the success of virtual labs. Interestingly, this continuous process requires constant interaction with students and educators to improve their experiences based on their feedback.

2.5 Design Step-by-Step

As we said, creating a virtual lab may involve many actors and stakeholders, including instructional designers, lab writers, graphic designers, 3d modelers, programmers, testers, instructors, and students as the final users. That said, the person in charge of developing the lab scripts has, like a movie screenwriter, to carefully think of a step-by-step process providing, in minimum detail, how the lab will work and what must be done by each actor.

A design step-by-step refers to a systematic and structured approach to design, where each step in the process builds on the previous one. The purpose of this step-by-step process is to ensure that the design is thorough, effective, and meets the needs of the stakeholders. It helps designers to reduce the likelihood of overlooking essential considerations and increase the chances of creating a successful design.

2.6 Data Generation

To be effective, virtual labs in engineering education must generate data as closely as possible to the data students find in real or physical labs. To this aim, two main approaches can be used, each with pros and cons. A theory-driven data generation process creates data based on existing theories, hypotheses, or models. We incorporate in the lab the mathematical behavior of the system given the variables of the theoretical model. This approach works well in science-based labs where the main goal is to show or demonstrate how a principle or concept works and help students develop conceptual understanding. One known disadvantage of this approach is that it cannot reproduce the uncertainties and adversities that may occur in real engineering life. To minimize this drawback, we usually add some randomness in the model to create a sense of variability in the results.

Another approach to data generation is what we call the experiment-driven method. In an experiment-driven data generation process, the system's variables are manipulated to generate different outputs, which will be processed and used in the virtual labs. In other words, we conduct several experiments to generate data that can be used in the virtual labs to test hypotheses, models, or theories about the relationship between the variables. The main benefit of this approach is that students will work with real data, reproducing the characteristics of the actual system used in real labs. We usually use this approach for engineering virtual labs to foster the development of critical engineering skills such as problem-solving, analysis of stochastic data, measurement, and instrumentation, among others [24].

3. Implementing and Deploying Virtual Labs

The factors discussed above are fundamental for the success of a virtual engineering lab. Interestingly, these factors must be discussed and planned before writing any line of code or sketching any model. We will present factors that must be considered when implementing the virtual lab on a computer, including models, coding, animations, and simulations.

3.1 Models

Game apps commonly use geometric models to represent 3D objects and scenes. Some standard geometric models used in virtual lab development include polygonal, NURBS, implicit, and procedural models. These models are used for various purposes in the development phase, including rendering objects, defining object behavior, creating realistic environments, and more. The choice of the model must consider how natural the things should be, how students will interact with these objects, and the performance requirements defined in the virtual lab design document. Indeed, models play two essential roles in virtual labs. First, they create a sense of immersion that improves learning [34]. Thus, as closer to the actual objects these models are, the more immersive the virtual environment of the lab. Second, choosing a geometric model for a virtual lab may impact the lab's performance. This impact happens because more complex models require more processing power to render. More extensive models require more memory to store, which can impact the overall performance of the labs, especially on mobile devices with limited memory. The speed at which a model can be rendered can affect the overall performance of the lab. Finally, complex models may impact the ability to interact with the lab in real time, compromising students' learning experiences. Thus, to ensure optimal performance, it is essential to carefully consider the implications of different models and choose the one best suited for the lab's specific needs. This process may involve making trade-offs between detail and performance or using optimization techniques to minimize the impact on performance.

3.2 Coding

Coding refers to the process of writing computer programs, or code, that can be executed by a computer to perform specific tasks. Coding involves using a programming language to write instructions that a computer can understand and carry out. The resulting code can create software applications, automate tasks, and control various devices.

The success of a virtual lab is highly impacted by the coding strategy adopted. As many developers learn to code very unstructured way, they usually rely on very naïve approaches that result in an apparent good virtual lab but with dirty code. That means they are beautiful on the outside and ugly on the inside. This fact compromises future upgrades and improvements in the labs, given difficulties in understanding the actual code of the lab. Thus, best practices in software development must be followed, including using object-oriented methodologies, using comments to explain each section of code, and creating testing strategies during the coding process [35], [36].

Also, object-oriented programming approaches are highly recommended when one wants to develop more and different labs. Thinking about reusability is fundamental in such cases, and well-written codes certainly add to the performance and rate of development.

3.3 Animations

Animations can be a valuable tool in education, as they can help to explain complex concepts visually and interactively. Animations can bring abstract concepts to life, such as the inner activities in a nuclear reactor or the electrical current in a wire. Animations make the learning experience more engaging and help students retain the information better [37]. In addition, they can also be used to simulate real-life situations and scenarios, allowing students to experiment with different scenarios and observe the results. The use of animations is very tied to the desired learning outcomes. Whenever an abstract phenomenon or principle has to be learned, using animations helps students to grasp that concept better. So, animations are very useful in developing conceptual understanding. In addition, in situations where a procedure must be learned, an animation may help students to see how the process occurs and learn how to proceed with an actual problem.

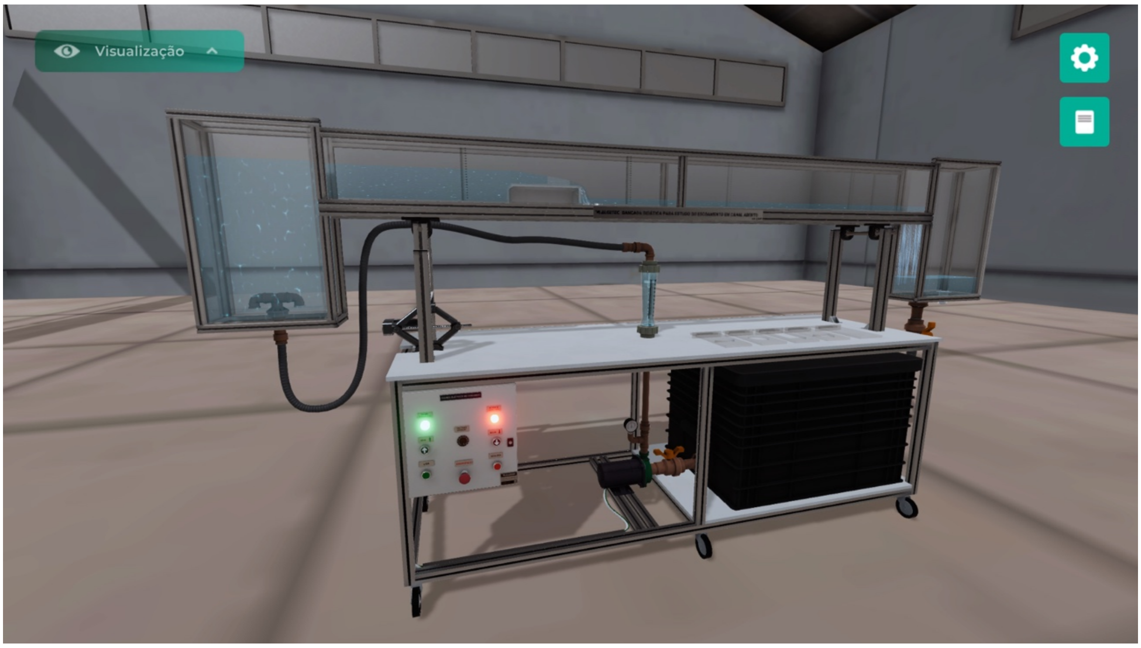

Figure 2 - Animation in an open channel flow virtual lab

3.4 Simulations

Simulations mimic real-world systems or processes [38]. They are used in various fields, including education, to foster learning and engineering applications to allow a deep understanding of different systems [9]. One of the main benefits of using simulations in education is that they provide a safe and controlled environment for students to experiment with complex systems and processes [39]–[41]. Simulations can also help students develop problem-solving skills. By interacting with a simulation, students can observe the results of their actions and make adjustments to find the best solution to a problem. This can help them build their critical thinking and decision-making skills [42].

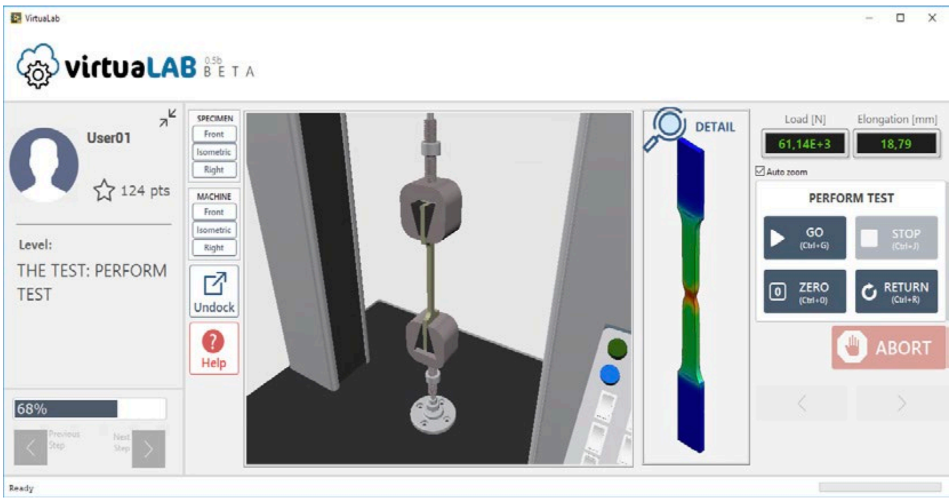

Figure 3 - Simulation of a specimen under tension

Simulations can be used in virtual labs to create a more engaging and interactive learning experience than traditional methods, such as lectures and textbooks. By allowing students to interact with the material in a hands-on way, simulations can increase their motivation and interest in the subject. Both simulations and animations help create meaningful learning experiences. Using one or another, or both depends on the desired learning outcomes.

3.5 Quality Assurance

Quality assurance (QA) helps developers to ensure that the final product meets the needs and expectations of users [43]. It is a critical step in any software development process. In this step, we can: Identify and fix errors; improve user experience; improve reliability; and comply with standards.

In our development process, a dedicated team checks all possible sources of errors and issues that may compromise the user learning experience. For example, user interface and user experience specialists check the prototypes every time a new version is implemented to identify bugs, usability, accessibility, and potential issues that may cause students discomfort. Another team controls the code to verify if it meets the desired standards. Furthermore, a validation team checks the compliance of the data with theoretical and empirical sources. Everything must be tested and eventual problems fixed. Finally, a beta version of the virtual lab is released for faculty and students before launching a definitive version to students. During this process, whenever a problem is detected, it triggers immediate feedback to the development team to fix the issue.

4. Assessment Instruments

Assessment instruments are tools or methods used to measure and evaluate a person's knowledge, skills, attitudes, or other attributes related to learning [28], [44]. They help educators in several ways: measuring learning outcomes; identifying areas of improvement; providing feedback; and ensuring accountability of the virtual labs. These instruments should align well with the desired learning outcomes, as defined in the instructional design phase [22]. In addition, assessment instruments must be designed to be valid and reliable, to measure what they are intended to measure accurately, and consistently yield similar results over time [44].

Although we have developed more than 800 new virtual labs, including social sciences, health, law, and art education labs, we still need to develop sound assessment instruments for our online labs. Today, whenever possible, we use a pre-and-post approach, using questions from Concept Inventories (CIs) related to each specific lab [26], [45], [46]. When we do not find any concept inventory, we develop the questions based on the teachers' experience. Further studies need to be conducted to design new instruments to measure all the different aspects of students' learning experiences, including learning gains, learners' user experience, and the usability of the tools.

A study is underway to examine the efficacy of various labs concerning learning efficiency, motivation, and pedagogical approaches. The authors are leading this investigation in partnership with The Institute for the Future of Education at Tecnológico Monterrey [47].

5. Practical Implementations

We developed a web-based platform easily integrated into different learning management systems to support the use and scalability of the virtual labs discussed in this paper. This platform provides tools for students and faculty to receive feedback from the activities (see figure 5). First, we introduce the labs giving students an overview of the practice and its learning outcomes and connecting these outcomes to real-world situations possibly faced in the future. That is what we call Lab Context. Then, we provide a brief theoretical summary to help students to recall essential information about the practice. This is the Recall stage. We have a first assessment in the form of a conceptual pre-test, usually based on concept inventory questions. This stage is called the Conceptual Understanding Assessment. Next, we bring a roadmap of the practice and detail the procedures to be followed. In this stage, we also provide helpful information such as frequently asked questions, tutorials, and a link for the support staff. After all these stages, we allow students to access the virtual lab and run the experiments. We call this stage the Practice stage. The practices are usually designed to last 15 minutes. However, students can tinker for more time, as they have opportunities to try different approaches to the lab. All virtual labs were designed to support those tinkering activities by allowing procedure variations, sometimes leading to wrong results. Thus, trial-and-error is not only allowed but stimulated. Finally, we have a final assessment as a post-test. This time, the questions aimed at assessing the learning outcomes of the activity.

Figure 4- Learning Management System

In the following sections, we will shortly present and discuss some of the more than 250 engineering and science virtual labs already available online for students in several institutions in Latino America and the USA.

Example 1 – Fluid Mechanics (Mechanical Engineering)

Figure 5 shows the actual apparatus and a fluid mechanic's virtual lab. In this lab, students can explore several concepts and principles from fluid mechanics, including but not limited to losses in pipes and accessories, pump arrangement, and Reynolds experiment. The virtual lab is a digital version of the actual lab. Almost all experiments students can run in the existing apparatus can also be conducted in the virtual version. A panel on the superior left side of the screen allow students to switch between the different view of the system quickly. To run a virtual experiment, students must set up the system first, then turn on the pumps and adjust the flow using the inverter dial. The water flow is measured through a rotameter and pressure drop using a u-tube differential manometer.

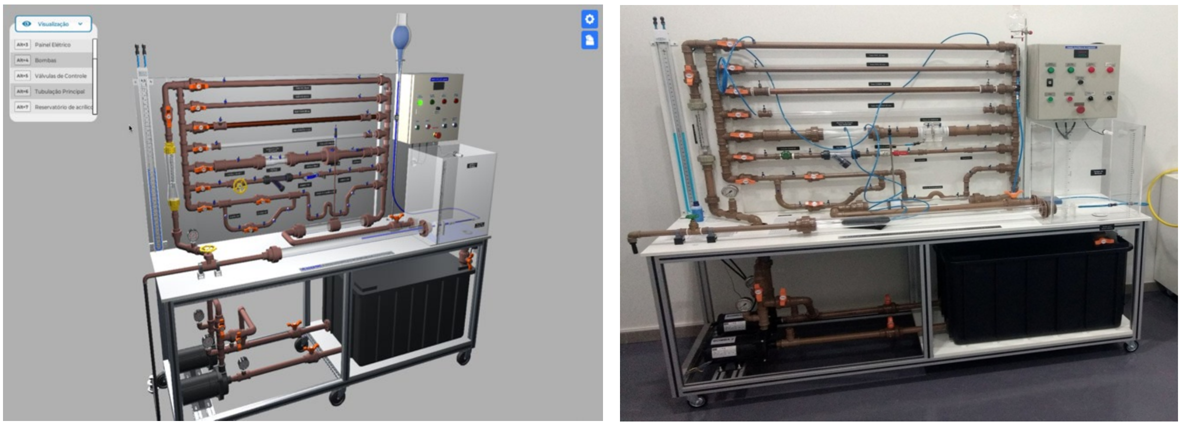

Figure 5 - Universal fluid mechanics apparatus.

Example 2 – Industrial Electrical Installations(Electrical Engineering)

This virtual lab mimics the experimental apparatus shown in figure 6 b). In this case, students have a set of different circuits to set up and measure electrical variables. To make the system work, students must connect cables, components correctly, and the power supply. The focus of this experiment is to provide hands-on opportunities for students to practice electrical circuits used in industry.

Figure 6 - Industrial Installations Apparatus. a) Virtual lab; b) Actual lab

Example 3 – Civil Engineering - Slump Test

The slump test measures the consistency and workability of freshly mixed concrete. The test involves filling a cylindrical mold with freshly mixed concrete, then removing the mold and measuring the amount of slump or settlement of the concrete. The test result indicates the workability and consistency of the concrete mixture, which is vital for ensuring the quality and durability of the final concrete structure. In the virtual lab depicted in figure 7, students must follow the guidelines of a standardized procedure to conduct the experiment and make the necessary measurements.

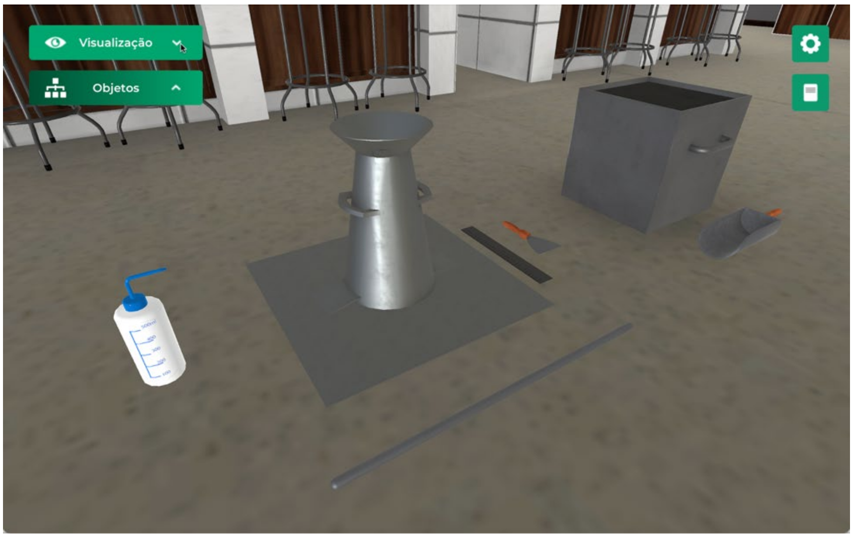

Figure 7 - Slump Test Virtual Lab

Example 4 – Chemical Reactors (Chemical Engineering)

In this virtual lab, students can explore the elements of a chemical reaction in a tubular reactor and in mixed reactors, evaluating the differences between theory and practice in determining the residence time distribution (RTD) in a continuous tubular reactor operating with packing (PBR) or without packing (PFR), and in continuously mixed reactors (CSTR), in addition to determining the batch reaction parameters of sodium hydroxide with ethyl acetate, analyzing the behavior of this reaction in the reactors studied during the determination of residence time.

Figure 8 - Chemical Reactors

6. Feedback from faculty and students

Despite ongoing efforts to evaluate the effectiveness of the previously mentioned laboratories, we have already undertaken qualitative and quantitative investigations into the opinions of faculty members regarding them. The Net Promoter Score (NPS) survey presented in Figure 9 demonstrates a high degree of contentment among 90 faculty members from 18 higher education establishments. It is worth noting that this outcome does not pertain to any individual virtual laboratory but instead reflects the collective satisfaction with the virtual engineering laboratories implemented in each respective institution.

Figure 9 - Level of contentment among faculty members with the use of virtual labs

It is important to emphasize the fundamental role of instructors in creating meaningful virtual laboratories. Instructors maintain regular communication with students during laboratory activities, enabling them to provide valuable insights into students' challenges and difficulties throughout the exercises. Moreover, instructors possess extensive knowledge of laboratory procedures and expected outcomes and are adept at identifying common areas where students may encounter difficulties. However, instructors may face limitations such as inadequate resources and personnel, impeding their ability to implement improvements. Thus, involving instructors in the design and implementation of virtual laboratories can enhance the authenticity of the labs and bring valuable information about students' learning processes.

7. Conclusions

Virtual laboratories are a powerful tool in engineering education. However, to achieve their potential, these labs must undergo a meticulous development process, which necessitates the support and cooperation of a diverse group of professionals. One pivotal aspect in creating these labs is instructional design, which also holds significance in physical labs. Once the instructional design is established, all components must be deliberately crafted to reinforce the intended learning outcomes. Conversely, attention must be given to the characteristics of potential users, as overly realistic models or complex simulations may necessitate advanced hardware that some students do not possess. Consequently, a trade-off exists between performance and realism.

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