Defining User-centric Requirements for Virtual Laboratories: A Mixed-methods Study on XR in Engineering Education

Heiko Fechtner *, Nicole Klewicz, Josephine Martini, and Benedikt Schmuelling

Institute of Electric Mobility and Energy Storage Systems, University of Wuppertal, Wuppertal, Germany
Email: fechtner@uni-wuppertal.de (H.F.); klewicz@uni-wuppertal.de (N.K.); josephine.martini@uni-wuppertal.de (J.M.); schmuelling@uni-wuppertal.de (B.S.)
*Corresponding author
Manuscript received February 9, 2026; revised March 2, 2026; accepted May 9, 2026; published September 10, 2026

Abstract—**In recent years, the use of virtual laboratories has become increasingly vital in engineering education. For the effective implementation of virtual laboratories, the identification of complex student needs is essential. The adoption of Extended Reality (XR) at universities has increased significantly. Nevertheless, specific design guidelines for engineering environments with high risk like virtual battery laboratories remain scarce. This study identifies key user-centric requirements through a four-phase mixed-methods design. In the first part of our research, the theoretical foundation is established by a systematic literature review of recent publications and existing state-of-the-art overviews. In addition, a quantitative survey with 106 engineering students, which was carried out in October 2025, assessed broad student perspectives and acceptance levels. To gain in-depth insights into specific technical and pedagogical needs, we conducted qualitative interviews with five Master's students in November 2025. The triangulation of the obtained results enables a robust validation of the identified requirements. Our findings indicate that students prioritize safety simulations (freedom to fail), real-time feedback, and industry-relevant content for virtual laboratories. Students also highlighted the value of an Artificial Intelligence (AI)-driven tutor to support experiment implementation. We identified high hardware costs and limited institutional integration of XR as key challenges. To ensure that our results can also be used for further research projects, we present actionable design requirements for a virtual battery laboratory and provide a comprehensive roadmap for future virtual laboratories regarding engineering education.**

Keywords—**virtual laboratories, engineering education, student-centered learning, extended reality, batteries**

I. Introduction

The digitization of various tasks has been evident for years, both in industrial environments and in the private sector. In addition to smart home applications, Artificial Intelligence (AI) and Extended Reality (XR) now play a central role. They help resolve everyday challenges and enable entirely new applications [1]. XR serves as an umbrella term for these immersive technologies (see Fig. 1), which will be presented in more detail below. For the clarification of the technical terms used in this paper, we refer to the definition according to the Reality-Virtuality Continuum by Milgram and Kishino [2]. Following this definition, Virtual Reality (VR) provides a fully synthetic environment, whereas Augmented Reality (AR) overlays digital information onto the physical world. Mixed Reality (MR) can be defined as the space between VR and AR, where physical and digital elements interact in real time. Examples range from visiting virtual museums using VR [3], playing video games via a VR headset [4], or improving healthcare through AI and wearables [5].

The education sector is also undergoing a significant digital transformation (Fig. 1). The use of digital technologies at universities introduces both advantages and challenges, such as VR-induced motion sickness [6, 7], which are further examined and discussed in Chapter II. To achieve climate protection objectives and to navigate future challenges, the increased use of digital tools to train sufficient numbers of qualified engineers is a welcome development.

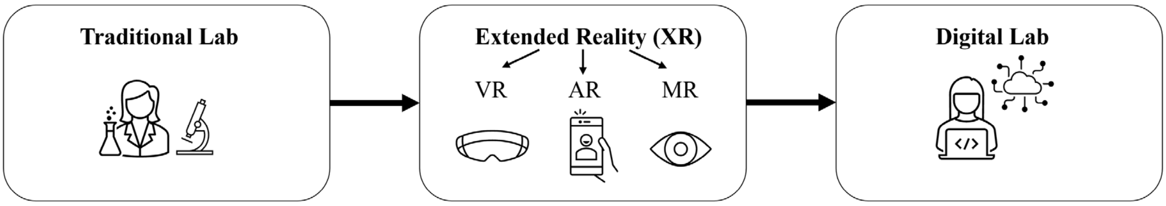

Fig. 1. The transformation path to the virtual lab.

According to the International Energy Agency (IEA) World Energy Employment Report 2025 [8], the energy sector is growing at twice the rate of the overall economy. By the end of 2024, 76 million people were employed in the global energy sector—an increase of 5.4 million compared to 2019 [8]. In Europe, for instance, approximately 1.8 million people worked in the renewable energy sector in 2024 [9]. The electricity sector has emerged as the largest employer in the energy industry, surpassing the fossil fuel sector for the first time. Since 2019, 75% of all new energy jobs have been concentrated in the electricity sector—spanning generation, grids, and storage [8]. Solar energy is the primary driver in this segment. In addition, approximately 800,000 new jobs were added in the electric vehicle and battery sector in 2024 alone [8]. In the United States, around 78,000 workers were employed in battery storage technologies in 2024 [9]. Based on a survey of over 700 companies, the IEA notes that the number of vocational graduates worldwide must increase by 40% to close the skills gap in these sectors by 2030 [8]. These figures highlight the urgent need for scalable training solutions, such as virtual laboratories, to prepare the next generation of qualified engineers. Furthermore, the development of scalable virtual laboratories aligns with the goals of Education for Sustainable Development (ESD) and

doi: 10.18178/ijiet.2026.16.9.2691

Sustainable Development Goal 4.7 (SDG 4.7), both of which call for ensuring that all learners acquire the knowledge and skills needed to promote sustainable development.

VR technology, for example, is used to qualify technicians and engineers for solar energy systems design and operation [10]. In a further publication [11], the results of a comparison between traditional teaching and teaching with VR technology are presented and discussed. The most important finding from this paper is that the students who applied VR achieved better learning outcomes than the control group. However, Arif *et al*. [12] identify that the pedagogical depth and systematic integration into teaching are currently missing. Additionally, Cortes *et al*. [13] demonstrate through their approach that student participation in VR development increases their learning motivation. We utilize these findings by identifying student needs, which serve as the primary source for defining the requirements of virtual laboratories.

To date, the literature on XR in engineering education remains largely generic, lacking domain-specific design guidelines for high-risk laboratory environments. While general requirements for virtual laboratories have been studied, no prior work has systematically derived student-centered requirements for a high-risk domain such as battery engineering, where safety constraints, including thermal runaway and high-voltage exposure, impose unique design demands. We address this gap by first identifying universal student requirements for virtual laboratories through a mixed-methods study. We then translate these findings into actionable design requirements for a virtual battery laboratory within the DiBaLa project [14] (introduced in Section III).

Therefore, this study applies a comprehensive mixed-methods approach and utilizes data triangulation to synthesize student desires with technological viability. Based on the results, we establish key requirements. In Section IV, actionable recommendations for future virtual laboratory implementation are shown to motivate further researchers and lecturers to develop digital laboratories for engineering education or other disciplines.

II. Literature Review

This chapter outlines the results of our literature review, focusing on the application of digital laboratories in academic teaching. Additionally, we provide an overview of the latest hardware and software for XR applications, and present examples of digital twins in the context of this paper.

A. State of the Art of Virtual Laboratories

This paper concentrates on the application of virtual laboratories, particularly those utilizing XR, see Table 1. All analyzed scientific publications (e.g., [7, 15–23]) were published in 2025. This approach ensures that we are able to incorporate the most recent advancements regarding XR relating to engineering education in our future research and development endeavors.

Table 1. Overview of selected papers

Source	Publisher	Year	Paper type	Venue	Domain	VR	AR	MR	Key findings
[7]	IEEE Xplore	2025	Review	Journal	Engineering	Yes	Yes	Yes	Review (11 reviews, 6530 studies): VR is popular & motivating, but lacks clear definitions & long-term evidence
[18]	IEEE Xplore	2025	Review	Journal	Education	Yes	Yes	Yes	Review (27 studies): Metaverse (VR/AR/MR) enhances pedagogy but faces privacy, access, & content challenges.
[19]	MDPI	2025	Review	Journal	Engineering	Yes	No	No	Review (342 studies): VR is effective for skills, engagement & cost-reduction in engineering education
[23]	IEEE Xplore	2025	Review	Journal	Engineering	Yes	Yes	Yes	Review (75 studies): VR boosts engagement, but lacks robust evidence & causes motion sickness.
[15]	MDPI	2025	Experiment	Journal	Engineering / architecture	Yes	Yes	No	Study: VR/AR is intuitive, easy to learn, and improves motivation, engagement, & academic performance
[16]	MDPI	2025	Review	Journal	Applied science	Yes	Yes	Yes	Review (56 studies): VR dominates higher education, AR in K-12. All XR boosts motivation/knowledge
[20]	MDPI	2025	Experiment	Journal	Engineering	Yes	No	No	Study: Multi-user VR with a real-time Digital Twin improves understanding, safety, and collaboration
[22]	MDPI	2025	Review	Journal	Engineering	Yes	Yes	Yes	Review (31 studies): Immersive tools boost engagement, but face challenges with cost & motion sickness
[17]	MDPI	2025	Review	Journal	Engineering	Yes	Yes	Yes	Review (235 studies): AR improves performance, motivation, creativity, engagement, & satisfaction
[21]	Frontiers	2025	Experiment	Journal	Engineering	Yes	No	No	Survey: “Student 5.0” approach using Digital Twins (non-immersive) resulted in high satisfaction and skill development

Varjosalo *et al*. [7] analyze up to 6530 studies from 2023–2024 and summarize that the number of papers in the context of VR applications for academic teaching have doubled since 2000. This finding underlines the topic’s relevance to engineering education. Moreover, the research findings repeatedly demonstrate that VR/AR tools represent effective, scalable, and cost-reducing solutions compared to a physical laboratory. These technologies lead to higher learning outcomes, greater knowledge retention, improved learning efficiency, and increased student engagement.

An additional relevant study [15] from 2024 investigated a non-immersive VR learning environment. The study found that the VR group achieved learning outcomes that were 29.2% higher and demonstrated better knowledge retention than those who received traditional instruction. A 2022 review article in mathematics education [24] examined the use of VR and AR technologies. It emphasizes the ongoing discrepancy between pedagogical requirements and technological implementation. The authors propose the concept of an education architect to bridge this gap, aligning didactic needs with XR development. Nevertheless, some of the review papers also identify challenges, including the cost of purchasing immersive tools [22] and the occurrence of motion sickness [22, 23].

B. Hard- and Software for XR Applications

Numerous hardware and software solutions can transform traditional on-site laboratories into digital environments. On the hardware side, VR headsets enable full immersion in a virtual environment, while MR headsets additionally incorporate cameras and thus integrate digital elements into the physical environment in real time. Current models within the XR landscape include the Meta Quest 3, Apple Vision Pro, Pico Ultra 4, and Magic Leap 2 [25–28].

The Meta Quest 3 is a standalone headset that uses dual RGB cameras and pancake lenses to provide high-fidelity passthrough. Powered by the Qualcomm Snapdragon XR2 Gen 2 processor, it enables the seamless integration of virtual objects into the physical environment. Hybrid sensors for computer vision are capable of recognizing hand gestures and providing intuitive interaction in addition to the use of traditional controllers [25]. Operating on Horizon OS, it received a Public Test Channel update in January 2026 with new functions, allowing physical surfaces to be transformed into virtual keyboards. This leads to easier interaction and a stronger convergence of the digital and physical worlds [29]. The Apple Vision Pro is also an MR headset and, in contrast to the Quest 3, additionally features eye tracking. As a result, no additional controllers are required, and interaction is enabled through eye and hand movements [26]. The Pico Ultra 4 stands out in comparison by offering 12 GB instead of 8 GB RAM, which is particularly advantageous for PC-VR streaming applications [27]. By contrast, the Magic Leap 2 places less emphasis on gaming and is designed for industrial applications, such as personnel training or remote maintenance. Therefore, it focuses on a lightweight design and is optimized for AR use [28].

In addition to hardware, there are specialized platforms such as Unity and Unreal Engine 5 that are dedicated to the development of digital XR content [30, 31]. Unity is known for its broad compatibility with different VR headset providers and its large developer ecosystem. Beyond game development, Unity can also be used for research, education, and industrial applications. The scripting logic is based on C#, and the platform provides an asset store offering prefabricated models, scripts, and interaction components [30]. Compared to Unity, Unreal Engine 5 focuses on high-end visualization with photorealistic rendering and physics-based simulations. The engine uses C++ as well as an additional visual scripting option via Blueprints, thereby meeting the high requirements for realistic simulations [31]. Furthermore, platforms such as LuminousXR enable the creation of interactive scenarios without programming experience through no-code solutions [32]. These software platforms enable the creation of digital shadows and digital twins through realistic 3D models and the integration of real-time data.

To the best of our knowledge, no prior scientific paper has systematically addressed the development of a virtual battery laboratory for academic teaching. Our study directly addresses this gap within the DiBaLa research project.

C. Application of Digital Twins

Fig. 1 illustrates the development path from a traditional on-site laboratory to a virtual laboratory. The left side depicts the traditional setting, where students must be physically present to conduct experiments. In this scenario, laboratory equipment must be operated on-site, requiring students to complete both safety training and a technical introduction to the experimental setup. In the intermediate step, VR, AR, and MR technologies are integrated, allowing 3D models to be operated instead of real devices. The final step is a virtual laboratory that is fully digital and can be used independently of time and location.

Researchers and developers can convert original CAD data into 3D models to reconstruct laboratory equipment [33]. Digital twins in particular contribute to the digitalization of laboratory environments and to students' learning success by bringing a faithful representation of real devices into a virtual environment [34, 35]. Using the example of a battery laboratory, safety training can be conducted in advance through an immersive 360° walkthrough combined with AR elements. Students can operate cell testers in a virtual, safe environment and be supported by interactive step-by-step guidance. Furthermore, battery measurement data, such as voltage curves, currents, or temperature profiles, can be visualized directly as MR overlays, allowing relationships to be intuitively understood. Thus, digital twins and virtual laboratory environments enable location- and time-independent, safe operation while promoting deeper understanding through the seamless integration of theory and practice [30].

III. Methodology

A four-phase mixed-methods design is the core of our applied methodology (Fig. 2). In the first phase, we conducted a systematic search across scientific databases (e.g., IEEE Xplore, MDPI, Scopus) to identify relevant studies with regard to virtual laboratories, including VR, AR, and MR in engineering education (see Chapter II). To consider the most recent technological advancements and current research trends, the review focuses on papers published in 2025. This selection includes both comprehensive review papers, which provide an overview of the state-of-the-art and past research results, and primary studies on XR experiments with students. These experimental papers were analyzed to evaluate their immersive capabilities (Table 1). The design of the data triangulation framework, which is implemented in the subsequent phases, is based on this foundational analysis.

Within our research project DiBaLa [14], which focuses on the development of a virtual battery laboratory, an online survey containing 14 questions was developed based on the Phase 1 findings. The aim was to identify students' requirements and expectations for virtual laboratories in academic teaching (see Phase 2 in Fig. 2). In Phase 3, five qualitative student interviews were conducted to triangulate the quantitative results. This phase intentionally included Master's students to serve as an 'expert-check', leveraging their advanced academic experience to validate and refine the requirements identified by the entry-level students in Phase 2. We structured the interviews into five thematic sections, concluding with a question on the most critical factors for virtual lab development. Finally, the results of the first three phases were synthesized in Phase 4 to provide actionable recommendations for future virtual laboratories (e.g., virtual battery labs), as illustrated in Fig. 2.

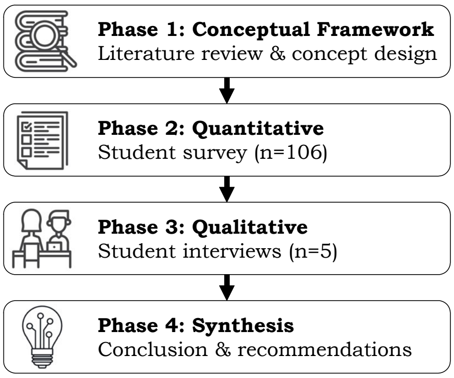

Fig. 2. The four-phase mixed-methods research design.

IV. Results and Discussion

As already described in the methodology chapter, our mixed-methods approach consists of a total of four phases, see Fig. 2. In one of these phases (Phase 2), a quantitative study was conducted using a student survey in October 2025. To obtain more detailed information from the students and to better understand the reasons behind certain answers in a personal conversation, we conducted interviews with five students in November 2025 in Phase 3. The results of both the quantitative and qualitative studies, which we conducted at the University of Wuppertal (Germany), are presented below and synthesized to formulate comprehensive recommendations for future virtual laboratories.

A. Survey Design and Results

The survey consists of a total of five subject areas. The first part of the survey deals with demographic data and information about the degree program and the number of semesters. The second part serves to determine previous experience with virtual laboratories. As developers of a virtual battery laboratory, it is important to determine student wishes and expectations. We have created the third topic area of the survey for this purpose. The fourth topic area deals explicitly with experience with XR. Finally, the survey concluded with an open-ended question allowing participants to provide unrestricted qualitative feedback.

The 14 survey questions were developed by operationalizing the core dimensions identified in the literature review (Section II). Specifically, we translated findings on technological acceptance, the demand for real-time feedback, and the pedagogical necessity of safety in high-risk engineering education into targeted Likert-scale items and open-ended questions. For example, to assess general attitudes towards digitalization, students were asked: 'To what extent do you consider the implementation of digital tools in university education to be useful?' (rated from 1 = not at all useful to 5 = very useful). Furthermore, to identify concrete functional requirements, the question 'Which specific contents or experiments should be integrated into the digital laboratory?' was included. This process allowed for a direct mapping of student-identified needs against the state-of-the-art features found in Phase 1.

A total of 106 engineering students from the University of Wuppertal participated in the survey. The sample population consisted primarily of Bachelor's students (91.51%), with Master's students making up the remaining 8.49%. Most participants (81.13%) were male and between 18 and 20 years old (60.38%). As the surveys were conducted within a large foundational course (Fundamentals of Electrical Engineering), it is evident that 73.58% of the participants were in their first semester at the time of the survey.

Notably, 94% of students had already worked in a physical laboratory and many of them expressed a particular enjoyment of applying theoretical knowledge in practice. In contrast, only two of the 106 students surveyed have had the opportunity to gain experience in a digital laboratory. In addition, only 4.72% of the interviewees have used XR in a university course in the past. However, 87.74% of the students surveyed already have experience with XR (VR: 68.87%, AR: 18.87%) outside of universities or schools. Students have mainly gained these experiences by playing video games (60.38%) and visiting exhibitions (e.g., museums).

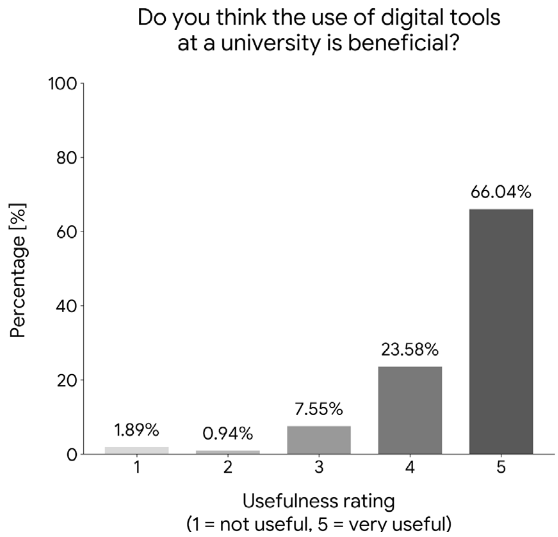

Fig. 3. Distribution of student ratings regarding the utility of digital tools in university teaching ($N = 106$).

For the development of our digital battery laboratory, it is important to determine how students perceive the utility of XR technology in academic teaching. Our survey results show that the acceptance of digital learning tools is overwhelmingly high, with nearly 90% of respondents considering the use of XR technology at universities to be useful or very useful (Fig. 3). Another question concerns the benefits that students expect to gain from the use of digital laboratories, as shown in Fig. 4. While our literature analysis shows that digital tools generally increase motivation (e.g., [15–17]), our quantitative data suggests a distinct departure from this trend, as only 50% of participants reported motivation as an expected benefit. The majority of students (75.47%) identified safety as the top priority when working with digital laboratories (Fig. 4). They define safety as the essential freedom to fail without risking personal harm or damaging expensive equipment. This result warrants further investigation in the first test phase of our digital battery laboratory. Furthermore, a comparison with previously published papers in the context of learning from errors (e.g., [36]) is necessary to get a better understanding of this topic.

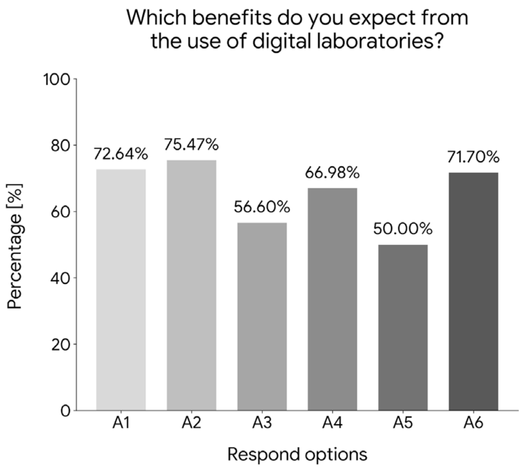

Fig. 4. Student expectations: Mapping the perceived educational and operational benefits of digital laboratories (N = 106). A1: higher flexibility, A2: safety (learning from mistakes), A3: adaption to individual learning pace, A4: improved learning outcome, A5: increased motivation, A6: better understanding of theoretical content.

Another finding of the question shown in Fig. 4 is that students see higher flexibility (72.64%) and the development of a better understanding of the theoretical content they have learned (71.70%) as advantages of digital laboratories. The results from [20] support students' assessment, as they have concluded that digital laboratories can help build a better understanding.

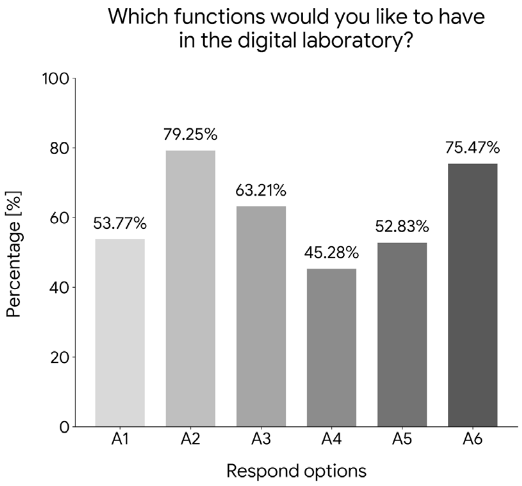

Fig. 5. Student survey results showing the percentage of agreement for various desired functions in a digital laboratory (N = 106). A1: measurement data export, A2: real-time simulation, A3: feedback on learning progress, A4: communications with other students, A5: communications with lecturer, A6: unlimited repeatability.

A further question that is presented in detail in this paper concerns the features and content that the virtual battery lab should possess (Fig. 5). Approximately 80% of the students answered that they would like to have real-time simulations. Another significant feature is that students can repeat the experiments in the virtual environment without restriction (75.47%). The third most common student wish, with 63.21% of the vote, is for feedback on their learning progress.

Another focus of our survey is to find out what content a digital laboratory should offer for academic teaching. The majority (83.96%) of survey participants stated the importance of content relevant to their future professional context (Fig. 6). Other content that students consider important for digital laboratories includes instructional videos (58.49%), safety training for physical laboratory experiments (56.60%), and guidance on using measuring instruments (56.60%), see Fig. 6.

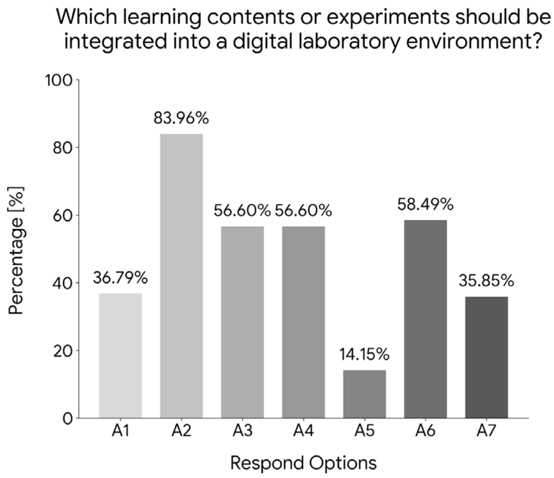

Fig. 6. Student preferences regarding the integration of specific learning contents within a digital laboratory environment (N = 106). A1: Lecture-relevant content, A2: Practical relevance in a professional context, A3: Safety training for on-site laboratory experiments, A4: Instruction for the use of measuring instruments, A5: Podcasts, A6: Educational videos, A7: Educational games

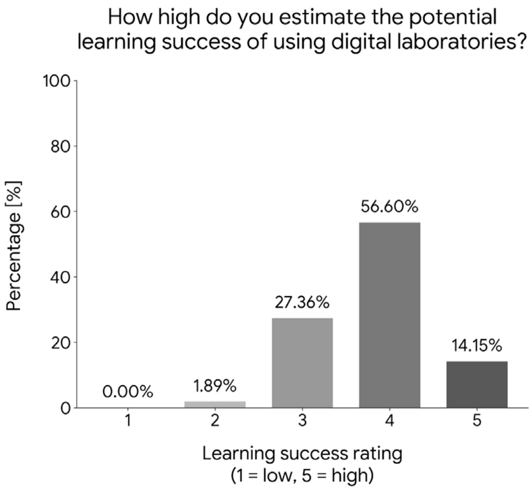

Fig. 7. Distribution of student ratings regarding the learning success by using digital laboratories (N = 106).

The final question of the survey, analyzed in detail in this paper, evaluates whether students believe digital laboratories enhance learning success. As shown in Fig. 7, approximately 70% of the respondents rated the potential learning success as either high (4) or very high (5). This result further illustrates that students strongly favor the integration of digital laboratories and perceive them as highly beneficial.

The results of the quantitative analysis (student survey), presented in this chapter, provide an initial overview. In order to gain deeper insights into the wishes and expectations of the students, as well as the significance of these results, we carried out an inferential statistical analysis and a qualitative analysis in the form of student interviews, which are presented in the following chapters.

B. Inferential Statistical Analysis

We conducted our inferential statistical analyses in Visual Studio Code using Python (version 3.13.12), the SciPy library (version 1.17.1), and the pandas library (version 3.0.1). We applied Welch's two-sample t-tests for questions with continuous, Likert-scaled variables, as this variant does not assume equal variances [37] and is therefore robust to substantially unequal group sizes present in this study [38]. We used Fisher's exact test for questions with binary categorical variables (yes/no responses), given the small subgroup sizes. The sample consisted of 106 students, of whom 97 were enrolled in a Bachelor's program and 9 in a Master's program. Regarding gender distribution, 86 participants identified as male, 16 as female, and 4 as non-binary. Due to the insufficient group size (n = 4), we excluded the non-binary participants from the gender-based inferential tests.

To assess whether demographic characteristics influenced the students' requirements and attitudes towards the virtual battery laboratory, a series of inferential statistical tests was conducted. Comparing Bachelor's and Master's students on the perceived meaningfulness of digital tools (five-point Likert scale: 1 = not meaningful at all, 5 = very meaningful) yielded no statistically significant difference ($|t|$ = 0.69, p = 0.508). Similarly, no significant difference was found for the expected learning success ($|t|$ = 1.45, p = 0.178). The same pattern was observed when comparing male and female participants on perceived meaningfulness ($|t|$ = 0.36, p = 0.720). For the categorical items concerning desired laboratory features, including real-time simulation and immediate learning feedback, Fisher's exact tests revealed no statistically significant gender differences (all $p > 0.05$).

These results suggest that the demand for a virtual laboratory is consistent across the sample, regardless of academic level or gender. The low standard deviation for expected learning success (SD = 0.68) further supports this interpretation, indicating that students share a uniform and clearly defined set of requirements for the virtual laboratory. This demographic consistency strengthens the generalizability of the identified requirements within the studied population and supports their applicability as a foundation for the design of the virtual battery laboratory.

C. Interview Design and Results

We structured the interviews around five key thematic areas derived from the preliminary quantitative survey: adoption gap between the desire for virtual laboratories and current learning methods, exercises that are practically relevant, freedom to fail, simulation fidelity, and advantages of a digital battery laboratory. Table 2 lists the categories and key findings. Finally, the students were asked what they thought was the most important advice for developers of a virtual laboratory.

Table 2. Key results of students' interviews. S: Student, M: Master

ID	Level	Adoption Gap	Practical Relevance	Freedom to Fail	Simulation Fidelity	Application: Battery Laboratory	Key Recommendation
S1	M	Effort, cost, hardware barriers	Practical circuit basics	Fear of public failure	Realistic components & graphic, learn by failing	Simulating hazards & aging	Test with diverse users (level/discipline)
S2	M	New field, pandemic as trigger	Hands-on device familiarity	Safety from shock/damage	Favors gamification, immediate feedback	Good for long-term experiments	Realistic process, anonymous AI support
S3	M	Lack of offering, hardware barriers	Virtual tours, device explanations	No fear of damage	Realistic, immediate feedback, clear goals	Compresses time, teaches basics	Intuitive design, relatable visualization
S4	M	Analog labs can't keep up	Simulate real industry projects	Enabling safe failure	Correct data, immersion via VR/AR	Safe, individual learning	Develop with user/industry feedback.
S5	M	Mismatched education goals	Realistic simulations, projects	No fear enhances learning	Realistic action, logical feedback	Deeper insight via simulation	Student-focused, safe, intuitive design

As illustrated in Table 2, five students were interviewed who are currently enrolled in a Master's program. We selected this group to obtain feedback from experienced students, in addition to the quantitative survey, in which nearly 92% of the participants were Bachelor's students. Due to the previous experience of the Master's students, we classify this qualitative survey as an expert check, leveraging their advanced academic experience to validate and refine the requirements identified by the entry-level students. Hence, the inclusion of both Bachelor's and Master's levels ensures a holistic perspective, capturing requirements from both entry-level students and advanced learners to address the needs across different stages of academic education.

The results from Phase 3 indicate that financial constraints are the primary obstacle hindering the adoption of XR-based virtual laboratories by universities. All interviewees confirmed the necessity of integrating practical, career-relevant examples into the laboratory. This qualitative finding reinforced the primary quantitative result from Phase 2 that students require the essential freedom to fail, removing the major obstacle of risking costly damage and personal harm in physical laboratories. Regarding safety, one student stated: 'The freedom to make mistakes without worrying about the cost of damaged hardware is a great advantage of using VR.' One further interviewee explained that the fear of social exposure in traditional laboratories is a significant barrier: 'It is a matter of ego; there is this fear of being exposed in front of everyone, similar to being called on in a lecture where people might notice that you lack the basics.' By providing a private, virtual space, virtual laboratories allow students to overcome these social anxieties. It is also of significance to the student that the primary value of the virtual environment is the ability to 'truly learn through mistakes' without the pressure of peer judgment or the risk of damaging expensive equipment (e.g., battery module tester). These results suggest that XR laboratories serve as "risk-free" environments that are essential for a deeper understanding of fundamental technical principles and also prepare students for their future careers in industry or research.

To achieve the necessary practical relevance and functional realism, the students also emphasized that it is essential for the virtual laboratory to look realistic and contain all necessary components of a physical laboratory. A key recommendation is that people from different disciplines and levels of education participate in the test phase of the developed virtual laboratory in order to obtain comprehensive feedback. Further recommendations are: integration of AI support, realistic processes, and simulating errors and demonstrating their consequences in the real world.

D. Recommendations

In the fourth phase, the synthesis phase, of our applied methodology, the most important results are highlighted in order to make actionable recommendations (Table 3). The key findings prioritize safety ('freedom to fail') and realistic simulations to bridge the theory-to-practice gap. To fully leverage the 'freedom to fail', simulations should include high-risk scenarios such as a thermal runaway of a high-voltage battery, which would be too hazardous to replicate in a physical laboratory setting.

Table 3. Student-centric design requirements

Category / Topic	Requirement / Finding	Actionable Implementation (Battery Laboratory)
Content relevance	Integrate essential industry tasks	Implement industry-standard battery testing procedures, such as Constant Current Constant Voltage (CCCV) charging profiles, using real-world cell and driving data.
Safety & learning	Prioritize safe failure modules (freedom to fail)	Develop a thermal runaway simulation where students can trigger short circuits without risk, visualizing chemical reactions that are invisible in reality.
Design fidelity	Ensure functional realism (parameters and data)	Ensure that virtual multimeters and Battery Management System (BMS) interfaces display real-time synchronous data (voltage, state of charge, temperature).
Didactic support	Integrate anonymous AI support	Integrate an AI-driven tutor that provides context-sensitive hints if a student connects battery modules with incorrect polarity.
User involvement	Involve students throughout the entire process	Collaborative User Experience (UX) workshops with students from different engineering branches to identify discipline-specific mental models and adjust the interface for diverse prior knowledge.
Validation	Validate with diverse external users and disciplines	Cross-curricula pilot testing to evaluate if the learning modules (e.g., safety protocols, electrochemical analysis) align with the specific educational objectives of various engineering disciplines.

The study further recommends integrating anonymous AI-driven support to provide instant feedback and assistance for users who hesitate to ask real tutors. In addition, validating the prototype of the virtual laboratory through testing across diverse disciplines and people with different levels of education ensures broad accessibility. Furthermore, to enhance functional fidelity and align the digital experience with industry standards, the laboratory must incorporate realistic testing protocols. Integrating standard procedures like CCCV profiles ensures that students practice the exact diagnostic and operational tasks required in professional battery testing. Additionally, it is important to involve students in the entire process of developing a virtual battery laboratory.

V. Conclusion

The aim of this paper is to identify students' needs and wishes for a virtual laboratory in the context of engineering education. Relevant papers from the fields of engineering and educational sciences were analyzed, and the literature review informed a student survey conducted in October 2025 at the University of Wuppertal with predominantly Bachelor's students. The results showed that students value the ability to make mistakes in the virtual laboratory ('freedom to fail'), which could involve safety risks or damage in physical laboratories. Another important feature is real-time simulation. This indicates that students should be involved in the development process to ensure that such features can be implemented effectively. In summary, the core student-centric requirements identified are safety simulations (freedom to fail), real-time feedback, AI-driven tutoring support, and industry-relevant content. Inferential statistical analysis revealed no significant differences between Bachelor's and Master's students or between male and female participants across key variables (all $p > 0.05$), indicating that these requirements are broadly applicable as a foundation for the virtual laboratory design. However, the generalizability of these findings should be interpreted in light of the limitations outlined below, particularly the single-institution sample and the uneven subgroup sizes. We also used the survey results to develop a questionnaire for qualitative interviews. The experts were five Master's students from the University of Wuppertal with more laboratory experience than the Bachelor's students in the quantitative survey. The Master's students supported many of the results of the quantitative survey and added that an AI-driven tutor would help students implement experiments in the virtual laboratory. Industry-related examples would also help prepare students for their future careers. To transfer the results of the mixed-method approach to the development of a virtual battery laboratory, we presented concrete application examples. For the students' desire for 'freedom to fail', a thermal runaway and its effects on a battery system could be integrated into the VR laboratory. The paper also offers recommendations for virtual laboratories in other disciplines to encourage lecturers and researchers worldwide to develop XR-based laboratories. This study contributes on two levels: at a general level, we provide an empirically validated framework of student-centered requirements for virtual laboratories in engineering education. At a domain-specific level, we demonstrate how this framework can be translated into concrete design requirements for a high-risk laboratory environment. The virtual battery laboratory serves as the primary application case, given its unique safety constraints, such as thermal runaway scenarios and high-voltage systems. These contributions bridge the gap between generic XR research in education and the design challenges of hazardous engineering environments. Certain limitations in our study design must be acknowledged, especially the sample size and uneven subgroup distribution, which limit our statistical power to detect subtle differences. In addition, all our data comes from a single German university, and the quantitative sample consists predominantly of Bachelor's students in electrical engineering, which limits generalizability to other countries and institutional contexts. Future research needs to test these user requirements on a much larger, multi-institutional scale across various engineering disciplines and examine whether they change over time. Once the virtual battery laboratory has been developed and deployed, future validation studies could use frameworks like the Technology Acceptance Model (TAM) to assess students' behavioral intention and include a control group of students using traditional laboratory settings to isolate the pedagogical benefits of the XR-based approach. Within our DiBaLa project, the findings are currently being translated into practice through digital twins of battery testing equipment and temperature cycling chambers. Additionally, a student workshop is planned to test the prototype and gather feedback. Further results will be presented in upcoming papers to provide a deeper insight.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Heiko Fechtner: conceptualization, methodology, writing, general literature research, survey design, interview design, conducting survey and interviews, analysis of the empirical study, recommendations, inferential statistical analysis; Nicole Klewicz: writing, survey design, interview design, conducting interviews, analysis of the empirical study, literature research regarding software, hardware, and digital twins. Josephine Martini: writing, survey design, interview design, conducting interviews, creation of graphics, literature research regarding current state of the art, inferential statistical analysis; Benedikt Schmuelling: conceptualization, writing, supervision. All authors had approved the final version.

Funding

This research was funded by the Foundation for Innovation in Higher Education (Stiftung Innovation in der Hochschullehre) under project code 3003-1293 (DiBaLa) as part of the "Freiraum 2025" funding program.

Acknowledgment

The authors would like to express their gratitude to the Foundation for Innovation in Higher Education (Stiftung Innovation in der Hochschullehre) for its support. Furthermore, the authors thank all students who participated in the survey for their valuable contributions to this research.

References

[1] A. Hamad and B. Jia, "How virtual reality technology has changed our lives: An overview of the current and potential applications and limitations," *International Journal of Environmental Research and Public Health*, vol. 19, no. 18, 11278, 2022. doi: 10.3390/ijerph191811278

[2] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," *IEICE Transactions on Information and Systems*, 1994.

[3] X. Wang, Y. Li, B. Ling, H.-M. Chen, and H.-N. Liang, "ResponsiveView: Enhancing 3D artifact viewing experience in VR museums," *IEEE Transactions on Visualization and Computer Graphics*, vol. 31, no. 5, pp. 2870–2879, 2025. doi: 10.1109/TVCG.2025.3549872

[4] D. Hirobe *et al.*, "User-centric locomotion techniques for virtual reality games: A survey of user needs and issues," *IEEE Trans. Games*, vol. 17, no. 2, pp. 460–473, 2025. doi: 10.1109/TG.2024.3498325

[5] P. A. LaBoone and O. Marques, "Overview of the future impact of wearables and artificial intelligence in healthcare workflows and technology," *International Journal of Information Management Data Insights*, vol. 4, no. 2, 100294, 2024. doi: 10.1016/j.jjimei.2024.100294

[6] U. A. Chattha, U. I. Janjua, F. Anwar, T. M. Madni, M. F. Cheema, and S. I. Janjua, "Motion sickness in virtual reality: An empirical evaluation," *IEEE Access*, vol. 8, pp. 130486–130499, 2020. doi: 10.1109/ACCESS.2020.3007076

[7] J. Varjosalo, P. Räty, V. Heilala, R. Hämäläinen, and T. Kärkkäinen, "The role of VR in education: A two-phase review of umbrella reviews and recent primary studies," *IEEE Access*, vol. 13, pp. 145938–145952, 2025. doi: 10.1109/ACCESS.2025.3598952

[8] International Energy Agency, "World energy employment 2025," *IEA*, Paris, 2025.

[9] IRENA and ILO, "Renewable energy and jobs: Annual review 2025," International Renewable Energy Agency, Abu Dhabi; and International Labour Organization, Geneva, 2026.

[10] N. AlQallaf, A. AlQallaf, and R. Ghannam, "Solar energy systems design using immersive virtual reality: A multi-modal evaluation approach," *Solar*, vol. 4, no. 2, pp. 329–350, 2024. doi: 10.3390/solar4020015

[11] F. E. V. D. Anjos, A. D. O. Martins, G. S. Rodrigues, M. A. Sellitto, and D. O. Silva, "Boosting engineering education with virtual reality: An experiment to enhance student knowledge retention," *ASI*, vol. 7, no. 3, 50, 2024. doi: 10.3390/asi7030050

[12] Y. M. Arif, A. F. Karami, S. A. Rohma, and S. Criollo-C, "Advancing engineering education through serious games: A systematic literature review of technological innovation, challenges, and future directions," *IEEE Access*, vol. 14, pp. 35225–35242, 2026. doi: 10.1109/ACCESS.2026.3669416

[13] D. H. Cortes, A. Gregg, M. Lee, L. L. Pauley, and I. Osunbunmi, "WIP: By students, for students: Development of custom virtual reality applications for teaching and learning in engineering courses," in *Proc. 2024 IEEE Frontiers in Education Conference (FIE)*, Washington, DC, USA, 2024, pp. 1–4. doi: 10.1109/FIE61694.2024.10893592

[14] H. Fechtner, A. Popp, U. Spaeth, and B. Schmuelling, "Concept of a digital battery laboratory for academic training of future battery experts," in *Proc. 2025 IEEE Frontiers in Education Conference (FIE)*, Nashville, TN, USA, 2025, pp. 1–5. doi: 10.1109/FIE63693.2025.11328185

[15] E. M. D. González, R. Belaroussi, O. Soto-Martín, M. Acosta, and J. Martín-Gutierrez, "Effect of interactive virtual reality on the teaching of conceptual design in engineering and architecture fields," *Applied Sciences*, vol. 15, no. 8, 4205, 2025. doi: 10.3390/app15084205

[16] T.-C. Huang and H.-P. Tseng, "Extended reality in applied sciences education: A systematic review," *Applied Sciences*, vol. 15, no. 7, 4038, 2025. doi: 10.3390/app15074038

[17] G. Lampropoulos, A. Del Bosque, P. Fernández-Arias, and D. Vergara, "Augmented reality in engineering education: A bibliometric review," *Information*, vol. 16, no. 10, 859, 2025. doi: 10.3390/info16100859

[18] M. M. Uddin *et al*., "Metaverse on education: reviewing opportunities and challenges," *IEEE Open Journal on Immersive Displays*, 2025. doi: 10.1109/OJID.2025.3592612

[19] G. Lampropoulos, P. Fernández-Arias, A. Bosque, and D. Vergara, "Virtual reality in engineering education: A scoping review," *Education Sciences*, vol. 15, no. 8, 1027, 2025. doi: 10.3390/educsci15081027

[20] N. Norambuena *et al*., "Integrating digital twins of engineering labs into multi-user virtual reality environments," *Applied Sciences*, vol. 15, no. 7, 3819, 2025. doi: 10.3390/app15073819

[21] E. Ramírez-Cedillo, M. Armendáriz-Rodríguez, J. García-Ávila, D. Quintero-Sánchez, A. A. Ortiz-Espinoza, and A. Vargas-Martínez,

"Student 5.0: Immersive learning in next-gen automation of manufacturing systems courses for the Industry 5.0 era," *Front. Educ*., vol. 10, 2025. doi: 10.3389/feduc.2025.1416761
[22] V. Reis, J. Santos Baptista, and J. Duarte, "Immersive tools in engineering education—A systematic review," *Applied Sciences*, vol. 15, no. 11, 6339, 2025. doi: 10.3390/app15116339
[23] Sunardi, Meyliana, S. W. H. L. Hendric, and Y. Rosmansyah, "Exploring immersive virtual reality in higher education: Research gap and future direction—A scoping review," *IEEE Access*, vol. 13, pp. 76308–76321, 2025. doi: 10.1109/ACCESS.2025.3565385
[24] J. W. Lai and K. H. Cheong, "Adoption of virtual and augmented reality for mathematics education: A scoping review," *IEEE Access*, vol. 10, pp. 13693–13703, 2022. doi: 10.1109/ACCESS.2022.3145991
[25] Meta. (Feb. 5, 2026). Meta quest 3: Next-gen virtual reality headset. [Online]. Available: https://www.meta.com/quest/quest-3/
[26] Apple. (Feb. 5, 2026). *Apple Vision Pro*. [Online]. Available: https://www.apple.com/apple-vision-pro/
[27] PICO4 Ultra-VR-MR-headset | PICO Germany. (Feb. 5, 2026). [Online]. Available: https://www.picoxr.com/de/products/pico4-ultra
[28] Magic Leap 2 | Augmented Reality | Optics Technology. (Feb. 5, 2026). [Online]. Available: https://www.magicleap.com/magic-leap-2
[29] A. Williams, "Meta quest 3 gets a futuristic new feature," *Forbes*, Feb. 2, 2026.
[30] Unity. (Feb. 5, 2026). Unity Engine: 2D- und 3D-Entwicklungsplattform | Unity. [Online]. Available: https://unity.com/de/products/unity-engine
[31] Unreal Engine 5. (Feb. 5, 2026). [Online]. Available: https://www.unrealengine.com/en-US/unreal-engine-5
[32] Luminous XR, Immersive VR Training for Enterprises | Transform Learning—Luminous XR. (Feb. 5, 2026). [Online]. Available: https://www.luminousxr.com/immersive-training/
[33] C. Zhang, R. Pinquié, A. Polette, G. Carasi, H. de Charnace, and J.-P. Pernot, "Automatic 3D CAD models reconstruction from 2D orthographic drawings," *Computers & Graphics*, vol. 114, pp. 179–189, 2023. doi: 10.1016/j.cag.2023.05.021
[34] Z. H. Khan, S. Mekid and S. Mitchell, "Designing remote labs in outcome based education using digital twin and metaverse," *IEEE Teaching Excellence Hub*, 2024.
[35] N. Suhail, Z. Bahroun, and V. Ahmed, "Augmented reality in engineering education: enhancing learning and application," *Front. Virtual Real.*, vol. 5, 2024. doi: 10.3389/frvir.2024.1461145
[36] M. Goppold, M. Frenz, and V. Nitsch, "User feedback of apprentices on an augmented reality system for learning from errors in TVET," *Trends in Vocational Education and Training Research*, 2022.
[37] B. L. Welch, "The generalisation of student's problem when several different population variances are involved," *Biometrika*, vol. 34, no. 1–2, pp. 28–35, 1947.
[38] G. D. Ruxton, "The unequal variance t-test is an underused alternative to student's t-test and the Mann–Whitney U test," *Behavioral Ecology*, vol. 17, no. 4, pp. 688–690, 2006. doi: 10.1093/beheco/ark016