Journal of Infrastructure, Policy and Development 2025, 9(1), 9054.
https://doi.org/10.24294/jipd9054

Article

Virtual laboratories for engineering and science education in open and distance learning

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CITATION

Ukhurebor KE, Egenti G, Uduehi I, et al. (2025). Virtual laboratories for engineering and science education in open and distance learning. Journal of Infrastructure, Policy and Development. 9(1): 9054. https://doi.org/10.24294/jipd9054

ARTICLE INFO

Received: 10 September 2024
Accepted: 9 October 2024
Available online: 13 January 2025

Abstract: Higher education (HE) consists of both conventional and non-conventional methods of learning. Open and Distance Learning (ODL) is a non-conventional system where teachers (often referred to as facilitators) are physically not present. The conduct of practical in engineering and science education using ODL remains a challenge due to inadequate technology and the dispersion of the students, which results in a graduate skills gap in ODL programs. There is a possibility of using a cloud computing set-up, as well as platforms for the creation of simulated virtual practical settings (virtual laboratories-VLs), which could be accessible by ODL engineering and science and education-based students notwithstanding their locations. This paper adds to existing knowledge on VLs and discusses these inadequacies in engineering and science education with emphasis on the enhancement of online and collaborative learning, as well as the possible laboratory (lab) requirements. In addition, the paper highlights contemporary trends and some issues in VLs and remote labs.

Keywords: engineering education; higher education; open and distance learning; virtual laboratories; pedagogy

1. Introduction

All higher education (HE) systems consist of both conventional and non-conventional methods of learnings (Ukhurebor et al., 2024a). Open and Distance Learning (ODL) institutions practice non-conventional modes of learning or what is often referred to as remote learning. Remote learning refers to any learning procedure in which the facilitator and the learners are separated geographically (Torres and Cruz, 2022). Also, it offers distance education to students who do not attend on-campus classes. Laboratory (lab) practice is the prerequisite for the graduation of science and technology learners. In most developing nations, the challenges in engineering and science education are associated with inadequate resources for implementing advanced blended learning systems. According to the United Nations Report (2022), the challenges include the insufficiency of institutional infrastructure, inadequate modern labs, inaccessibility to good quality internet services, and unstable electricity.

The dispersed nature of ODL students and the expensive cost of l labs equipment have made it a challenge to replicate labs in their several study centres. Nevertheless, effective means of carrying out practical courses is extremely essential in engineering and science education-based programs (Umennem and Hlalele, 2020).

According to Umennem and Hlalele (2020), it is challenging for ODL-based HE system to practice hands-on (face-to-face) practical classes owing to the discrete nature of the learners, and this has significantly contributed to a high proportion of attrition (the number of individuals who leave a program of study before it has finished), particularly among engineering and science education-based programs. Nevertheless, some studies have revealed that the utmost challenge of ODL-based HE system is the high proportion of attrition of learners, and it remains a main concern for several HE systems (Ndunagu et al., 2022; Utami et al., 2022; Yılmaz and Karataş, 2022).

Contextually, engineering and science education is crucial for creatively emerging solutions and developmental innovations the HE desires for sustainable advancement and development. However, developing remote/virtual/ labs (VLs), an online lab resource, that uses feedback for the improvement and development of critical thinking skills is not common. A VL is a medium of learning that stimulates and integrates practical exercises and activities just like real or normal experiments (Nurdini et al., 2020). VL has revolutionised s engineering and science programs in HE, and there is a rising request for VL-based education to substitute or complement remote, practicable, and reasonable hands-on (face-to-face) practical learning. This will enable a ubiquitous educational system in a flexible setting, from any location at any time. A VL provides learners with the infrastructure needed to complete lab tasks without having to physically visit the lab facilities from any place and at any time (Obada et al., 2023). The educational component of engineering and science courses, which includes technology, is widely acknowledged as an essential part of the learning process. These experiences and understandings are conveyed through various forms, including lab classes, sessions, exercises, and project designs. Engineering and science education-based courses are generally technologically driven in advanced countries, and the number of science and technology graduates continues to grow in these developed countries as opposed to developing countries (Abiodun et al., 2024; Nnadozie et al., 2023; Ukhurebor et al., 2024a,b). The inadequate science and technology skill output affects science, technology, and innovations, and there is an inequitable implementation of science and technology education in developing countries with the dispersed nature of the learners in ODL.

The “connectivism learning theory” which host most of the studies of VL, examines and evaluates VL in comparison to “physical labs”. Engineering and science education also aims to encourage the development of ground-breaking technologies and present the possibilities of global competitiveness with the general HE system (Obada et al., 2023). Through the use of a variety of techniques, contemporary industrial engineering and science education and training have enhanced educational outcomes and made higher-quality education more accessible to trainees and students. Using computers and other modern technology in the classroom is essential, and teachers need to be receptive to novel ideas in order to avoid using antiquated instruments to teach students about contemporary issues (Sinan et al., 2024a,b). E-learning has received a lot of attention lately, (Mai-inji et al., 2024), and the idea of remote web-based labs and VLs based on software simulation has been crucial in helping to overcome challenges and advance remote distance learning (DL). A shortage of labs and practical work in an online learning environment is one of the limitations that VLs assist to solve. But as time has gone on, the nature of labs has evolved as well, with novel technologies being used in labs and shifts in the purpose of labs work. While the idea of DL labs, or e-learning, is important for training and education, there are still a number of unresolved issues (Stefanovic, 2013). VL and other synthetic learning environments like the simulation labs are being employed more and more in professional and non-professional courses of study throughout HE institutions as pedagogical practices (Chowdhury et al., 2019; Elme et al., 2022; Sellberg et al., 2024). VLs and simulation labs are not quite the same. VLs offer a combination of hands-on experience and simulations. They are educational resources where the user and the instruments are physically separated. What connects both labs is the internet where the user interacts with the lab through a computer or smartphone interface for tasks such as configuring, controlling, and monitoring results. Students can study scientific principles and concepts in a virtual setting by participating in simulations of experiments or other hands-on undertakings (Sellberg et al., 2024). These simulations offer students a flexible and accessible approach to studying and interacting with the labs as a setting for work, and they can be utilised in addition to, or instead of traditional labs experiences on campus. These simulations' theoretical and conceptual underpinnings, however, are still largely strange to most institutions in developing nations (Chowdhury et al., 2019; Elme et al., 2022; Sellberg et al., 2024). This article aims to contribute to the existing knowledge on VLs in engineering and science education. It highlights the objectives for setting up instructional labs, as well as the complementary impact of simulation and VLs.

The fundamental objectives of labs

The objectives of engineering and science labs for instruction have never been broadly ascribed, and several educators have never expressed them clearly. There are two issues that can arise from these inconsistencies: First of all, creating a lab experience without well-defined objectives for learning is akin to creating a product without well-defined requirements, which could result in ineffectiveness and inadequate results. Second, innovation becomes difficult due to the absence of targets to inspire change and standards for evaluating changes (Feisel and Rosa, 2005). The increase of DL programs that use the Internet or other technologies to deliver undergraduate engineering and scientific degrees with labs has made the issues increasingly apparent. Therefore, it is crucial to establish clear objectives and standards for achieving these objectives in engineering and science instructional labs. The "Accreditation Board for Engineering and Technology, Inc (ABET)" faced a challenge in defining the objectives of instructional labs when distance education programs began requesting accreditation. Despite well-understood criteria for assessing the cognitive factors of engineering and science education, there was no clear understanding of labs. This constraint hindered institutions from determining if their curricular objectives for a degree were being fully met. To address this issue, ABET approached the “Sloan Foundation”, a charitable foundation that supports DL systems, to fund a colloquy to gather expert/experienced engineering educators for the determination of the objectives for the assessment of effectiveness of distance-delivered engineering lab programs. The steering committee concluded that the question was not “what are the objectives of distance-delivered labs?” but “what are the fundamental objectives of engineering instructional labs?” independent of the technique of delivery. The colloquy in San Diego, California, involving fifty engineering educators from various institutions and disciplines, resulted in the creation of thirteen objectives. Each objective had a title and a brief explanation and was written using a verb to specify the action students should perform as a result of their lab experience (Feisel and Rosa, 2005; Peterson and Feisel, 2002). The objectives were aimed at improving students’ lab skills.

The fundamental purposes of engineering and science instructional labs are to provide students with the skills to measure physical quantities, analyse models, experiment, analyze data, design, demonstrate creativity, and be competent for the selection, modification, and operation of engineering and science tools and resources. These objectives are based on the undergraduate curriculum and aim to furnish students and learners with the knowledge and expertise in solving and tacking real-world problems.

Objectives 1 and 2 involve the application of suitable sensors, instrumentation, and software devices to make measurements of physical quantities; Objectives 2 and 3 focus on identifying the fortes and limitations of theoretical models for the predictions of real-world activities; Objectives 3 and 4 involve the development of experimental approaches, equipment, and procedures, and the interpretation of ensuing data to characterize a technological or engineering material, constituent, or system; Objectives 5 and 6 involve learning from inadequacies and demonstrating independent thought, creativity, and competence in selecting, modifying, and operating appropriate engineering tools and resources; Objectives 9 and 10 focus on safety, communication, teamwork, ethics in the lab, and sensory awareness. By completing these objectives (1–13), students will be equipped to make sound engineering judgments and solve real-world problems.

2. VL in engineering and science education

Lab experiments are crucial for students to understand engineering and science subjects effectively, improving their working habits, problem-solving skills, and attitudes towards education. Conventional labs require students to conduct experiments according to the protocol, prepare reports, analyse data, and interpret results, which can hinder their observation capability and result analysis skills. To improve these skills, it is suggested to introduce a lab class in each course, with well-maintained experimental setups, experienced instructors, and qualified faculty members. However, students often face difficulties in understanding content and instructions due to poor facilities, distractions, and low critical thinking in experiments. The availability of the latest lab equipment can motivate students to engage in the learning process and integrate knowledge and learning processes. An innovative design-oriented labs can help overcome these problems by integrating knowledge and learning processes, increasing teamwork, and designing new experiments. A VL can help overcome these problems by providing a computer-assisted activity that allows students to conduct experiments in a real or VL environment using a suitable computer-based interface. VLs can be used as a supplement to conventional labs, enhancing students' knowledge and helping them become independent learners. They are also more economical compared to conventional labs due to the elimination of equipment, staff, maintenance, and operating costs associated with traditional labs (Kapilan et al., 2021). To put this into context from the Nigerian Standpoint, the Africa Centre of Excellence on New Pedagogies in Engineering Education (ACENPEE), Ahmadu Bello University, Zaria, Nigeria is organized to ensure that excellence in teaching and learning is at the forefront at the university. Based on this mandate, the project has provided a platform for promoting excellence, innovation, and collaboration in engineering education. The project has provided the space for the development of a set of tools for strategic decision-making to provide quality measures for the alignment of teaching and learning. One of the set of tools is the promotion of VLs to improve online and collaborative learning. Besides that, it improves the student's learning experiences.

One of the distinguishing elements of engineering education is the lab requirement, and ACENPEE and other institutions and instructors face the challenge of introducing real labs online. However, with the rapid development of communication technology, it has become simpler. New possibilities include simulation environments, automated data acquisition, and remote control of instruments. There are two approaches to conducting labs online: simulation and remote labs. Simulations are equivalent to physical labs but provide limited experimentation capabilities. Remote labs allow students to work on real equipment and instrumentation, but many do not provide a sense of real presence in the lab. Therefore, efforts should be made to ensure that the right resources are available to meet the peculiarities of the students and learners.

Engineering instructional labs serve three main purposes: answering specific questions, determining design performance, adding to the body of knowledge, and providing practical experience. The ABET engineering criteria require all programs to demonstrate graduates' ability to design, conduct experiments, analyse and interpret data, design systems, components, or processes, use necessary techniques and tools, provide adequate classrooms and labs, and include college-level mathematics and basic science. The ABET Report 1999 emphasizes the importance of consistency between traditional and DL programs, ensuring graduates can demonstrate the same capabilities (Feisel et al., 2005). Therefore, online/distance learning institutions must provide the same learning environment as traditional learning processes. However, problems arise when there is no clear statement of lab objectives. This can lead to inefficiency and difficulty in innovation, as there are no targets to inspire change and no standards for judging changes. This issue has become more apparent with the advent of programs offering undergraduate engineering degrees using the Internet or other distance learning technologies. Therefore, online/DL institutions must provide the same learning environment as traditional learning processes. Therefore, creating simulation and remote labs requires some level of expertise to enhance experiential learning. In what follows, simulation and remote labs are highlighted.

2.1. Simulation labs

Simulations are crucial in engineering and science education, particularly in lab exercises. Edwin Link developed the Flight Simulator in 1928, which was used to train thousands of military pilots before and during WWI. Simulations are used in various industries such as aviation, chemical, petroleum, nuclear, and other engineering and science applications. Finite Element (FEM) structural analysis tools and SPICE, a circuit design and analysis software, have revolutionized simulation software development for engineering and science processes (Baher, 1999). Online engineering and science education presents a challenge for educators to convert real to VLs, and simulation software has become a vital tool in substituting physical labs. Simulation environments can train and expose students to practical knowledge, such as Virtual Experimentation (Hodge et al., 2001). Simulations are widely used on campus and for online/DL. Engineering and science educators find simulation attractive due to portability, ease of use, and cost-effectiveness. However, the practical knowledge and experience gained by the student depends on the authenticity, constraints, and capabilities of the software. Simulation criteria include modularity, multi-platform portability, compatibility with existing code, compatibility with hardware, extendable libraries, advanced repair features, executables, add-on packages, performance, an intuitive GUI, and multimedia capabilities. Simulation labs are primarily used for pre-lab experience, substituting for physical lab exercises, and substituting when the system studied is expensive, or large and not practical for a typical educational lab. Students can access the software via Web Browser or install it on their PC (Balamuralithara and Woods, 2009).

2.2. Remote labs

Distance education is increasingly being used in HE institutions worldwide, particularly in engineering and science education, where practical exercises are crucial for developing theoretical knowledge in real-world problems. Simulation-based labs cannot provide a “feel” for real things, as students need to use real devices and execute commands on real tools. To provide meaningful and relevant practical experiences while being online, a computer-based system is needed. This system would interface students with the physical world through a web browser, allowing them to send commands that can be pre-processed on their side. The experiment would then be executed in a real lab on real equipment, with the results displayed on the student’s side. Remote labs, initially used for control and robotic labs, have become more common in other engineering and science fields (Steinemann et al., 2002). These labs utilize the LabView web server developed by National Instruments, allowing students to access lab tools from a distance. The application areas of remote labs include shared remote labs, localized remote labs, distant remote labs, and technical review labs. Shared remote labs allow students to share expensive equipment, localized labs allow for experimentation at any time, distant labs are useful for distance learners, and technical review labs are useful for professionals testing specific systems or equipment from their desks. To build a complete web-based remote lab, components include client stations, a personal computer with internet access, and an intermediate system/network connecting the client’s station and remote lab server. The Remote Lab

Server is a server that grants access to the experimentation units, which are a set of equipment and devices used for conducting experiments, and the Instrumentation Unit is a set of instruments used for real-time measurement (Balamuralithara and Woods, 2009).

2.3. Selection of the online labs

The choice of online lab depends on the educational goal of the experiment. Computer, software, and electronics engineering experiments are more likely to be conducted through simulation, while power, civil, and control engineering experiments are suitable for remote labs. Institutions like ACENPEE should focus on key points before selecting the appropriate online lab. The pedagogical needs of the experiment should be identified to avoid oversimplification and to ensure students are exposed to real data, interaction with real equipment, and calibration. Remote labs are preferred if the experiment requires students to gain theoretical knowledge and conceptual understanding. Economical and resources factors should also be considered when choosing between remote and simulation labs. Space, financial support, and sufficient technical assistance are critical for establishing simulation labs. The price of simulation software, license period, and expertise availability are also important factors. Participants should be identified, especially for distance education institutes (Steinemann and Braunn 2002; Chen et al., 1999.)

There are typically two types of students who can use these labs (novices and mature students): novices who need to build practical skills, remote labs are preferable for these categories of students. Simulation environments with good pedagogical features can re-ignite learning curiosity in mature students, who may lack learning capabilities due to years of experience. Well-designed software provides effective explanations of theoretical concepts.

As these VL platforms suggest the potential growth of open-access online learning in engineering education, ACENPEE reviews periodically the possible attrition factors amongst its prospective students nationally in the event of robust implementation of the VLs. In what follows, an overview of the attrition in ODL is discussed.

3. Attrition in ODL

ODL-based educational system involves any formal or informal learning activity through the use of ICT to decrease distance, both physically and mentally, and this provides flexibility for both students and instructors in terms of place and time (Asanga et al., 2023; Hussaini et al., 2023; Nur Izzuddin Izham et al., 2022). Before the COVID-19 pandemic, ODL-based educational systems were hardly widely used in some nations (Abiodun et al., 2024; Engzell et al., 2021; Garg et al., 2020; Nneji et al., 2022). When the COVID-19 pandemic hit most nations in 2020, the governments of these nations issued several measures, including a movement control order; thus, some institutions were required to implement an ODL-based educational system as students are only allowed to study from home (Nneji et al., 2022; Papademetriou et al., 2022; Stanistreet et al., 2021). Lab practice is the pre-requisite for engineering and science (technology)-based learners' graduation (Ndunagu et al., 2023). In developing countries, the existing challenges to engineering and science (technology)-based education are linked to insufficiency of available resources for the development of the educational system (Amadasun et al., 2024; Hussaini et al., 2023; Mai-inji et al., 2024; Nneji et al., 2023; Nnadozie et al., 2023; Sinan, Nwoacha, et al., 2024; Sinan et al., 2024; Umennem and Hlalele, 2020). Nnadozie et al. (2023) and Uzoma (2018), as well as other studies, affirm that engineering and science (technology)-based education is critical for creatively developing solutions and innovations that HE needs for sustainable development.

Self-regulated learning has been recognised in several previous literature reviews as one of the key elements that may cause students to drop out (Nur Izzuddin Izham et al., 2022). The variables and difficulties that students encounter in ODL learning and delivery, considering the COVID-19 pandemic period, are nonetheless far less well understood (Kumar et al., 2021; Nneji et al., 2022; Nur Izzuddin Izham et al., 2022). Hence, there is a need to enhance steps towards a better understanding of the crucial elements influencing attrition in the ODL-based educational system in engineering and science education, particularly from the perspective of VL.

To identify the factors contributing to student attrition to the ODL-based educational system from the perspective of VLs, Nur Izzuddin Izham et al. (2022) carried out a systematic literature review relating to student attrition using the ODL-based educational system. Quantitatively, by identifying these factors, which include the technological factor (Al-Mawee et al., 2021; Martinez et al., 2020), financial factor (Abdullah, 2018; Tat et al., 2018; Zuhairi et al., 2019), environmental factor (Martinez et al., 2020; Saidi et al., 2021; Son et al., 2020), personal factor (Wu, 2020; Zuhairi et al., 2019; Tat et al., 2018), communication factor (Abdullah, 2018; Al-Mawee et al., 2021; Van Cappelle et al., 2021), emotional factor (Shabunina et al., 2021) and self-regulation factor (Van Cappelle et al., 2021; Shabunina et al., 2021; Son et al., 2020; Wu, 2020), a variety of recommendations were made which includes creating a conceptual framework to better mitigate student attrition. However, it is possible to develop a conceptual framework that will more effectively reduce student attrition by objectively recognising these aspects. Hence, Nur Izzuddin Izham et al. (2022) developed a new conceptual framework to show the consolidated factors that can lead to student attrition. The ability of students to control their study patterns is arguably the most crucial component of the ODL-based educational system. This is because some students need instruction from lecturers in person and are unable to learn alone. Regarding communication aspects, lecturers and instructors are particularly crucial in ensuring that material is shared both within and outside of class during the ODL-based educational system. This is because the ODL-based educational system makes it difficult for students to meet with lecturers and instructors in person after class if they have any further questions. Lastly, in environmental factors, both parties need to have an internet connection for the ODL-based educational system to function properly. Assessment processes such as test-taking, assignment submission, and learning might all be hampered by weak internet connection.

For the time being, the ODL-based educational system has come to stay (Nur Izzuddin Izham et al., 2022). Consequently, it is crucial to have learners ready for situations in the future where the ODL-based educational system will be the main study mode. To mitigate student attrition, enable lecturers (teachers) and instructors (facilitators) to teach effectively without the need for a physical classroom, and ensure that students (learners) obtain an education of the same calibre as they did in person, the area of online learning has to be investigated and broadened (Chowdhury et al., 2019; Elme et al., 2022; Sellberg et al., 2024). In engineering and science education, the routine teaching methods used in VLs are mainly closed off (Hsu et al., 2023; Sari et al., 2020). Hence, this article will contribute to paving ways to investigate and design a VL as a control mechanism for the management of attrition in science and technology disciplines in the ODL-based educational systems.

4. Conclusion and directions for future studies

Computer and communication technology have revolutionized engineering and science education, making online learning an accessible alternative to physical labs. Simulation labs offer flexibility, explanation of theoretical concepts, and repetition, but are often criticized for lacking real experiences. 3D implementation improves the simulation environment. Remote labs allow users to control and experiment on real equipment via the internet, offering a combination of real and simulation lab advantages. As the discussion of online labs grows, different viewpoints emerge, and the fundamental objectives as highlighted in this article can serve as a framework to enhance this discussion. ACENPEE is a key initiative within the ACE Impact Project, aiming to revolutionize engineering education in Africa through innovative teaching methods and cutting-edge pedagogies like the development of robust online labs to address the urgent need for updating engineering training in response to the rapidly changing technological landscape. This can be vital in determining how VLs can help in the management of attrition rates in engineering, disciplines in ODL institutions.

Author contributions: Conceptualization, KEU; methodology, KEU; software, KEU; validation, KEU; formal analysis, KEU; investigation, KEU; resources, KEU; data curation, KEU; writing—original draft preparation, KEU, GE, IU, IO, DA, AOA, DOO, KKA, BSE, AAT, GJ, JO, UCN and BME; writing—review and editing, KEU, GE, IU, IO, DA, AOA, KKA, BSE, AAT, GJ, JO, UCN and BME; supervision, KEU; project administration, KEU; funding acquisition, KEU, AOA, GJ, JO, UCN and BME. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors appreciate the authors whose articles were used for this study. Also, the authors are grateful to their respective institutions and appreciate the "Africa Centre of Excellence on Technology Enhanced Learning (ACETEL), National Open University of Nigeria, Abuja, Nigeria", for supporting this study.

Data availability statement: Completely, data produced or investigated during this work were involved in this submitted article.

Conflict of interest: The authors declare no conflict of interest.

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