Proceedings of the Estonian Academy of Sciences,
2024, **73**, 2, 142–149
https://doi.org/10.3176/proc.2024.2.07
Available online at www.eap.ee/proceedings

MANUFACTURING ENGINEERING

Virtual labs for higher education in industrial engineering

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Received 9 October 2023, accepted 17 January 2024, available online 12 April 2024

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Abstract. The current digital transformation in manufacturing has a strong impact on the competencies needed by manufacturing companies. This leads to evolving requirements for digital training in industrial engineering courses. The concept of virtual labs in academic environments can be instrumental in teaching new digital skills through practical experience. This paper aims to examine the requirements and essential factors involved in designing virtual labs, proposing a framework to meet the requirements of virtual lab activities, integrating didactic and research purposes while examining the requirements and essential factors involved in designing virtual labs digital twin as an enabling technology. The framework is the result of the analysis of the technical aspects related to immersive technologies, such as extended reality, together with insights gathered from interviews and pilot testing conducted in workshops involving students, teachers, and lab managers from three institutions implementing virtual labs. The outcomes of this study include the digital model of four manufacturing labs as virtual labs that are openly available for academic purposes. This showcases a commitment towards offering quality and inclusive engineering education through cutting-edge virtual technologies.

Keywords: virtual lab, digital factory, digital twin, higher education.

1. INTRODUCTION

Manufacturing engineering is significantly impacted by the ongoing digital transformation, also impacting academic education to properly train the next generation of industrial engineers. This requirement is exemplified by the Digital Europe Programme[1] that highlights the pivotal role of higher education institutions in modernizing education, particularly across multidisciplinary courses and training programs focused on cutting-edge digital technologies and digital skills. Regrettably, university programs often lag behind in updates, struggling to keep pace with the rapid evolution of digital technology [1,2]. Consequently, there exists a deficiency in well-structured training programs to equip engineers for these changes [3].

From the educational standpoint, teaching practical topics related to smart manufacturing can greatly benefit from access to a laboratory environment that provides valuable opportunities to acquire knowledge concerning both hardware and software resources, their use, and the testing of their application in real-world scenarios, including the implementation of systems, products, and processes in hands-on experiments [4]. Digital twin (DT) [5] is a fundamental enabling technology for smart manufacturing that can enhance a lab by providing a virtual representation of the manufacturing processes and systems, while supporting the execution of simulation and optimization tools. These virtual environments can synchronize with their real-world counterparts and function as gamified training configurations, especially valuable in university engineering education. This approach allows students to engage in remote activities, incorporating virtual elements that interact with the real/physical elements present in diverse lab

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[1] https://digital-strategy.ec.europa.eu/en/activities/digital-programme

environments [6]. Recent projects (e.g., [7,8]) have undertaken the development of digital toolkits designed for the definition, performance evaluation, and visualization of production systems and processes in a digital learning environment. While considerable progress has been made in advancing methods and tools for e-learning platforms and interactive content, particularly in the context of distance engineering education [4], these e-learning tools often lack the necessary features to deliver a comprehensive learning experience when it comes to practical activities involving real laboratory equipment [9]. Extended reality (XR) technologies potentially enhance online distance and blended learning experiences, specifically by granting access to the DT of physical engineering teaching laboratories, thus increasing the number of students that can have direct experiences. The virtual lab concept provides a cost-efficient and flexible means of organizing lab activities, allowing for multi-access and a learning-by-mistakes approach within a safe environment [10]. In addition, the use of XR beyond 3D models of laboratory equipment further extends the capacities of both physical and virtual labs by creating scenarios where the real and virtual worlds can interact and synchronize in real time [11].

Despite the increasing importance of virtual labs and immersive learning concepts, their adoption in engineering and smart manufacturing education is still limited, with several challenges hindering the integration of virtual labs in virtual worlds [10]. Even though XR has potential benefits in cognitive and skill-based learning outcomes, there are currently limitations related to evaluation metrics and the level of realism of environments to properly support teaching activities and assessments [12]. There is a debate in the literature about the role of virtual labs in effectively balancing hands-on activities, particularly in engineering and smart manufacturing education. This debate extends to considerations of how teachers and laboratory staff should approach the incorporation of virtual labs into their educational practices [13].

This paper aims to identify the requirements and leading aspects to be included in a framework for designing and using virtual labs in engineering and smart manufacturing education (Section 2), leveraging DT and XR technologies (Section 3). Virtual lab cases (Section 4) will provide a playground complementary to the existing learning methods, delivering quality and inclusive engineering education (Section 5) through state-of-the-art digital technologies. Finally, the conclusions (Section 6) summarize common patterns and challenges.

2. A FRAMEWORK FOR VIRTUAL LABS

The proposed framework for virtual labs aims at supporting teachers and institutions in the creation of virtual laboratories tailored for engineering and smart manufacturing education. Specifically, this concept of virtual labs is geared towards bachelor and master programs in industrial engineering, innovation, and business, specifically courses on smart manufacturing, product design, system design, or system control. The objective is to provide a set of requirements and guidelines working as a scaffolding for the implementation of different digital and interactive tools within the existing curricula, and assist the adaptation of teaching methodologies to align with the virtual lab concept. The framework and the specified tools under consideration are designed to be flexible and responsive to specific use cases. The requirements and leading aspects are based on the study of the scientific literature and the analysis of existing laboratories [13] as well as the teaching activities in three European institutions, i.e., University of Southern Denmark (SDU), Tallinn University of Technology (TalTech), and CNR-STIIMA. The tools have been tested and assessed during dedicated workshop activities, and could be included in the design of a new dedicated course for industrial engineering and innovation curricula (see Section 5). Figure 1 shows the main components involved in the framework and their dependencies to be considered along an iterative design process. The design of a virtual lab should balance the objectives of user interactions and the intended learning outcomes with the available resources [14]. The leading aspects that emerged from the analysis include the stakeholders, the different uses of the real and virtual labs, and their technological components.

The first design consideration entails the identification of stakeholders, which comprise a diverse group of contributors such as students, tutors, teachers, lab managers, researchers, and technicians. It is fundamental to ensure the alignment between users and activities occurring within the lab, regardless of the specific technologies involved. This alignment should be an integral component of a natural process of inclusion and utilization, where each stakeholder assumes a leadership role in specific aspects of equipment management or educational activities.

Secondly, the analysis of stakeholders should be connected with a clear understanding of the purpose and context of the activities incorporating the virtual lab concept [14]. Our collected data show that the exploitation of laboratory equipment focuses on research, carried out by doctoral or post-doctoral students, as well as training, bachelor and master courses, and thesis development. The interaction between stakeholders and the specific activities should lead to a clear definition of intended learning outcomes (ILOs) [15] and, consequently, the formulation of relevant usage scenarios.

Finally, the engagement of stakeholders and the formulation of educational activities and methodologies embracing the virtual lab concept are greatly influenced by the technical infrastructure of the laboratories, encom-

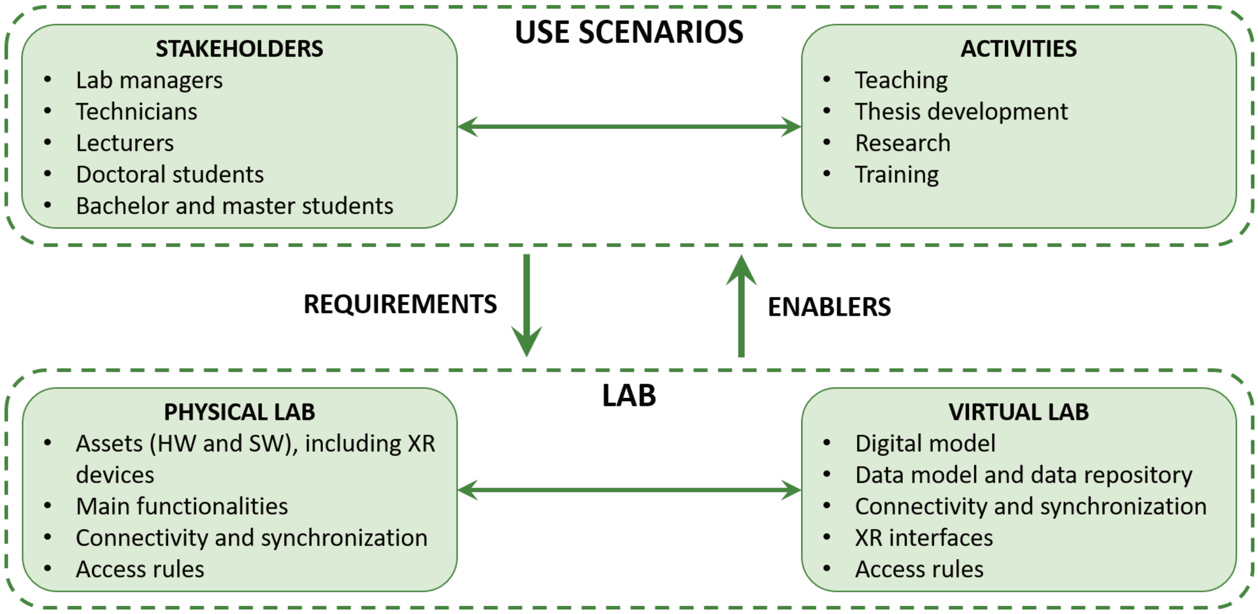

Fig. 1. Leading elements for the design and use of virtual labs with DTs and XR technologies in engineering education.

passing both the physical and virtual components. The physical lab consists of assets, both hardware and software, which work as facilitators and in some cases as constraints in configuring virtual labs. Consequently, the third leading aspect of technical specifications identified in this study extends the design criteria of the selection of appropriate technology and level of realism proposed by Stahre et al. [14].

DT is possibly the most important among the enabling technologies for virtual labs. The commonly accepted definition of DT, initiated in [16] and further specified in [17], comprises a real-world scenario (e.g., a physical lab with assets and agents), a digital counterpart of the same scenario, and a two-way connection between them, which is supported by robust communication infrastructure and extensive deployment of sensors and actuators. The real and digital counterparts are possibly synchronized in real time, updating their states once changes happen in the system. This process requires extensive data collection and analysis, which are already leveraged in optimization, decision-making, and forecasting methodologies.

Drawing from the available use cases, the DT concept can be selectively leveraged by including only certain components, depending on the implementation or technological level. We acknowledge scenarios where the DT loop is not closed or where only a subset of assets is fully digitalized. Nevertheless, the connectivity infrastructure constitutes a fundamental technology in the framework as it supports both DT functionalities and the possibility of publishing and accessing resources (e.g., through open online repositories), providing easy tool integration into new systems and laboratory use cases. XR technologies serve as major, but not essential, drivers for enhancing accessibility and interaction within the virtual lab environment and course curricula. The access to powerful computers able to run virtual interactive scenarios and the availability of specific headsets and controllers support advanced interaction techniques, sense of presence, and immersiveness, thus improving the user experience quality in the use of the proposed tools.

3. DEVELOPMENT OF VIRTUAL LABS

The digital representation of the virtual lab relies on comprehensive data that must be collected, elaborated, and formalized in terms of assets, i.e., basic components that constitute the laboratory, including physical objects (e.g., machine tools, parts, conveyors, buffers) as well as processes and plans. However, it must be noted that the virtual lab is not necessarily a complete digital twin of the physical lab. Indeed, real assets may be neglected and virtual assets may be added if needed to support the activities. Herein, the proposed modeling of virtual labs adopts an ontology-based approach for the development of DTs in manufacturing [18] since a common data model for the representation of lab assets enables interoperability and fosters reuse of the results.

The virtual reality (VR) visualization of the virtual lab is important for realizing its full potential. Although

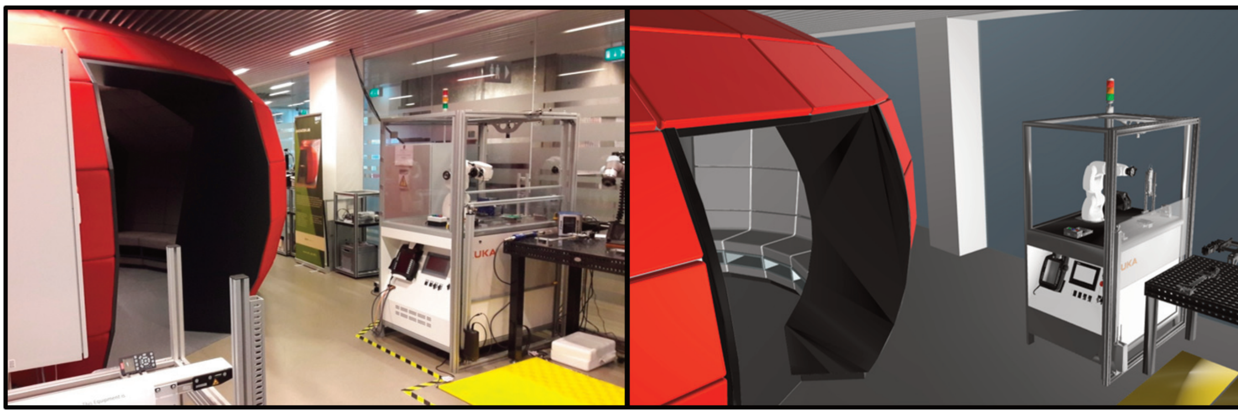

Fig. 2. Smart Factory lab: real vs. VR environment.[4]

numerous state-of-the-art VR tools exist, many of them come with licensing restrictions or accessibility limitations. The web application VEB.js[2] has been chosen to display the VR scene of the labs, allowing remote access. VEB.js is an open reconfigurable model-driven virtual environment application based on Babylon.js, supporting the loading of a 3D scene by either setting URL parameters or importing JSON files. VEB.js works on any operating system and browser that supports WebGL.

4. USE CASES

This section presents four lab use cases with different levels of virtual lab development. Each lab is described in terms of main assets, technologies, purpose, stakeholders, and intended uses. The virtual labs are freely available for academic purposes, thus providing open resources for the educational and research communities. (More details about the use cases can be found on the online VirLaDEE book).[3]

4.1. Smart Factory lab

The Smart Factory lab (Fig. 2) supports research and teaching in Technology Entrepreneurship and Innovation at the SDU by enabling the physical implementation of simulations and DT. The main stakeholders are the lab manager, researchers, and students in the study program of Bachelor of Science in Engineering, Innovation & Business. The activities in the lab include building production systems as part of the course in production technologies as well as research in matrix-structured manufacturing systems [19].

The physical lab and the equipment are divided into three areas: 1) a student area, consisting of four conveyor belts; 2) a research area, consisting of one active area with a matrix-structured manufacturing work cell (composed of a work cell, a universal robot, a welding table, etc.) and two smaller workbenches with tools for light assembly work; and 3) a red igloo area designated for meetings and presentations.

4.2. IVAR lab

The IVAR (Industrial Virtual and Augmented Reality) lab (Fig. 3) at TalTech is aimed at developing applications for industrial use cases through XR technologies. The applications are developed to support teaching, training, and specialized industrial solutions in R&D project partnerships with external stakeholders [20]. The laboratory supports user-centered application development and interface testing by means of quality of experience (QoE), together with the implementation of XR exergame aimed at clinical tests and rehabilitation. The lab belongs to a complex ecosystem of industrial and university training services and educational activities as it is part of the Flexible Manufacturing and Robotic Centre of the SmartIC Estonian Research Infrastructure Roadmap initiative.

Several bachelor and master students access the laboratory to develop systems and solutions for both thesis work and course-related project work. Doctoral students employ the equipment for industrial process optimization, production monitoring, machine integration, and development of XR applications in different fields. The specific course curricula involving the laboratory include Production Digitalization, Digital Manufacturing, Microcontrollers and Practical Robotics, Machine Automation, Internet of Things for Industry.

[2] https://virtualfactory.gitbook.io/vlft/tools/vebjs

[3] https://virladee.github.io/book/docs/UseCases.html

[4] https://virladee.github.io/repo/scenes/IVAR/IVAR.html

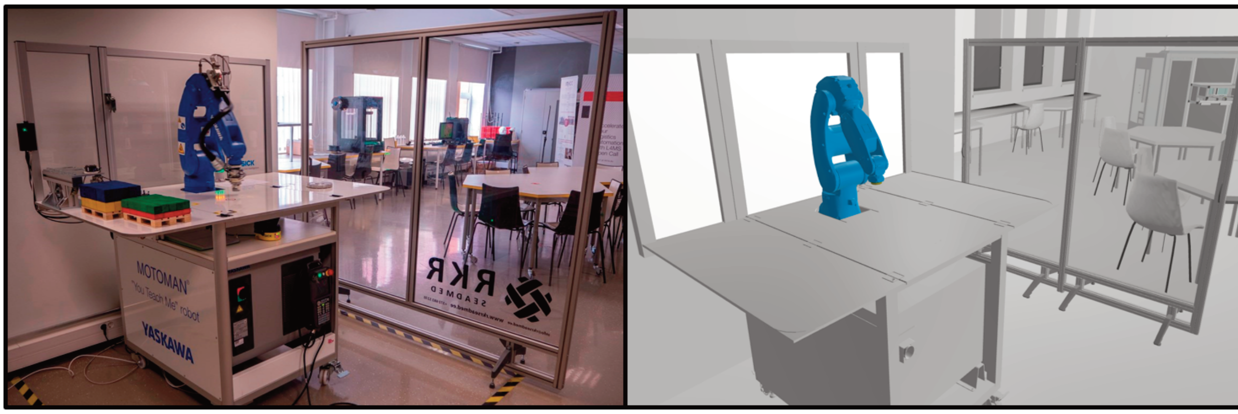

Fig. 3. IVAR lab: real vs. VR environment.[5]

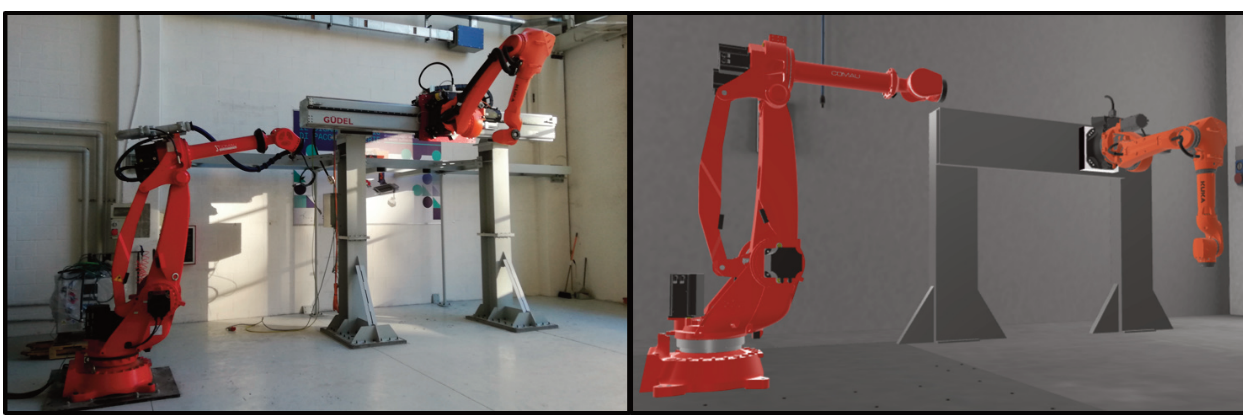

Fig. 4. DARB lab: real vs. VR environment.[6]

The lab includes industrial equipment (two industrial robots, a collaborative robot, a CNC machine, a mobile robot platform, an IoT real-time monitoring system, a 3D scanner, a custom-made industrial conveyor belt), XR equipment (different headsets, visors, trackers, motion controllers), and workstations.

4.3. DARB lab

The DARB (Disassembly using Autonomous Robot for Batteries) lab (Fig. 4) of CNR-STIIMA has the mission of studying innovative solutions to control the tasks performed by robots by merging the perceptual and automation aspects, thus boosting what robots can do autonomously in a smart manufacturing context [21]. The main stakeholders include the lab manager and the research group in robotics. In addition, master and doctoral students are typically involved in activities at similar robotic labs.

The lab is currently under development. The equipment currently comprises a disassembly cell with a robot and rotary-tilting table, a cell composed of two robots and an AGV, a mobile industrial manipulator, two PC stations with soft PLCs, force measurement systems and various sensors. The robots are equipped with quick coupling systems to use multiple tools.

4.4. PERFORM lab

The PERFORM (Personal Robotics for Manufacturing) lab (Fig. 5) of CNR-STIIMA aims at developing and validating robotic technologies that help people improve their productivity and quality of work in the manufacturing industry. Specifically, the research activities are focused on human–robot collaboration, task and motion planning, and the physical interaction between man and robot. The

[5] https://virladee.github.io/repo/scenes/IVAR/IVAR.html

[6] https://virladee.github.io/repo/scenes/DARB/DARB.html

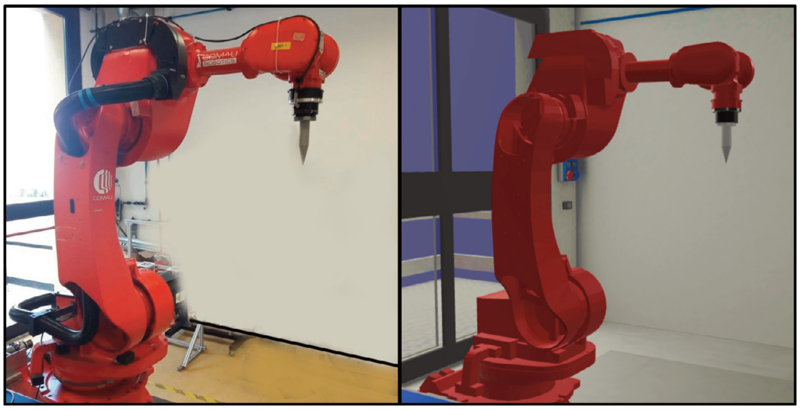

Fig. 5. PERFORM lab: real vs. VR environment.[7]

main stakeholders are the same as those of the DARB lab.

The lab has an advanced state of development as it benefits from the results and resources of past and ongoing research projects. The equipment consists of two COMAU NS16 robots, a robot controller, a conveyor, and several sensors and tools.

5. CURRICULA

The virtual lab concept has been tested during three five-day workshops organized in 2022–2023 (May 2022 in Tallinn, November/December 2022 in Sønderborg, May 2023 in Tallinn). Each workshop was attended by mixed groups of participants, including ten university students (both bachelor and master level), lab managers, teachers, and experts. The workshops were aimed at:

- establishing and improving the virtual lab concept for teaching;
- testing and verifying the prototype virtual labs;
- collecting feedback from students before and after the workshop via a questionnaire and interviews.

The workshops included lectures, advanced tutorials about digital tools (e.g., VR, discrete event simulation), exercises with virtual labs, and visits to physical labs. The experience of the students was assessed through two questionnaires (administered before and after the experience), focusing on the perceived competencies and role of virtual labs in engineering education: background knowledge, hard skills (e.g., simulation, XR technology), soft skills (e.g., communication, teamwork), engagement in lab activities, virtual lab concept. In general, the participants perceived an improvement in their technical skills and appreciated the virtual lab approach, recognizing that some course assignments can be performed without accessing the physical lab. However, they continued to place value on real labs and hands-on interaction with physical devices. More importantly, they saw opportunities to virtualize part of the current teaching activities.

Grounding on the experience from existing courses and the virtual lab workshops, a pilot master-level course, named VirLaDee Digitalization, has been designed to take advantage of virtual labs while clearly defining the ILOs. Upon successful completion of the course, students are expected to know the concepts of Industry 4.0, be able to design and create digital and simulation environments of production systems, integrate VR solutions, be able to select key performance indicators (KPI) for production systems, be able to use and integrate machine vision tools in practice, and choose a right tool for AI implementation. The course curriculum is organized into lectures, classwork, and group-based activities.[8]

6. CONCLUSIONS

The proposed framework for the design and use of virtual labs in industrial engineering education can support lab activities while teaching practical topics for smart manufacturing. The framework acknowledges both the educational and technological perspectives in virtual labs by including use scenarios, key stakeholders, and technical specifications. The framework is coupled with best practices deriving from four cases of virtual labs with different enabling technologies, stakeholders, and educational backgrounds.

The experience coming from the organization of three virtual lab workshops with students led to the elaboration

[7] https://virladee.github.io/repo/scenes/PERFORM/PERFORM.html

[8] https://virladee.github.io/book/docs/Curricula.html

of lessons learned. It is important to provide the users with complete guidelines, use case descriptions, and specific foreseen activities. The adoption of technologies, such as DT and XR, requires a balance between performance and ease of use, especially in smaller institutions [22]. System connectivity, synchronization performance, data handling, and access to repositories are also essential requirements to be addressed and solved centrally by the institutions promoting virtual labs.

These challenges could be tackled with multi-level strategies that take into account different skills, expertise, and effective applications. Possible collaborative extended projects could be considered for synchronizing physical labs and the respective DT functionalities for lab environments located in different institutions. Moreover, an accurate analysis of the added value of the virtual lab concept by institutions delivering engineering courses should guide its planning and design from the beginning. This analysis paves the way for the development of the DT with the three leading elements of the framework (stakeholders, activities, and specifications of the lab) for a continuous evolution of the physical and virtual environments.

ACKNOWLEDGMENTS

This work was co-funded by the European Union's Erasmus+ Programme, project No. 2020-1-DK01-KA226-HE-094270. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

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Virtuaalsed laborid kõrghariduses tööstustehnoloogia valdkonna õpetamiseks

Walter Terkaj, Kari Kleine ja Vladimir Kuts

Praegune digitaalne transformatsioon tootmisvaldkonnas mõjutab tugevalt tootmisettevõtetele vajalike oskuste loetelu. See toob kaasa uued nõuded tööstusinseneri kursuste e-õppe koolitusele. Virtuaalsete laborite kontseptsioon akadeemilises keskkonnas võib olla tööriistaks uute digioskuste omandamisel praktilise kogemuse kaudu. Artikli eesmärk on uurida virtuaalse labori kavandamisega seotud nõudeid ja olulisi tegureid ning pakkuda välja raamistik, mis vastaks labori tegevuse nõuetele, integreerides didaktilisi ja uurimiseesmärke ning kasutades digitaalsete kaksikute tehnoloogiaid.

Loodud raamistik on virtuaal- ja liitreaalsuse tehnoloogiate tehniliste aspektide anaüüsi tulemus, mis koosneb intervjuudest ja piloottestidest, mis viidi läbi töötubades, kus osalesid üliõpilased, õpetajad ja laborijuhid kolmest virtuaallaborit rakendavast teadus- ja õppeasutusest. Uuringu tulemused hõlmavad nelja tootmislabori digitaalse kaksiku mudelit virtuaalsete laboritena, mis on akadeemilistel eesmärkidel avalikult kasutatavad. See näitab pühendumust pakkuda tipptasemel virtuaaltehnoloogiate abil kvaliteetset ja kaasavat inseneriharidust.