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ORIGINAL ARTICLE

A framework for virtual learning in industrial engineering education: development of a reconfigurable virtual learning factory application

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Abstract
Advances in digital factory technologies are offering great potential to innovate higher education, by enabling innovative learning approaches based on virtual laboratories that increase the involvement of students while delivering realistic experiences. This article introduces a framework for the development of virtual learning applications by addressing multidisciplinary requirements. The implementation of the framework can be eased by the use of the proposed virtual learning factory application (VLFA), an open-source solution that takes advantage of virtual reality to support innovative higher-education learning activities in industrial engineering. A complete design and development workflow is described, starting from the identification of the requirements, to the design of software modules and underlying technologies, up to the final implementation. The framework and the VLFA have been tested to implement a serious game related to the design and analysis of manufacturing systems, also collecting the feedback of students and teachers.

Keywords Digital factory · Virtual reality · Higher-education · Virtual laboratory

1 Introduction

The education of industrial engineers encompasses a wide range of disciplines, methodologies, skills and application scenarios. Engineers are expected to address complex problems, select appropriate tools and approaches, master them thoroughly and professionally, be able to draw valid conclusions and make informed decisions based on the obtained results (Abele et al. 2017).

To address this wide range of educational objectives, higher-education institutions have been incorporating an emphasis on developing both hard and soft skills in addition to traditional learning practices (Vogler et al. 2018). These skills include problem-solving strategies, teamwork and communication abilities. Pursuing hands-on experiential learning paradigms to go beyond traditional learning approaches is often the best strategy for higher education in engineering (Kolb and Kolb 2012; Hunter and Sparnon 2020). The passive role in the learning process can result in reduced student engagement, potentially leading to a superficial understanding of disciplinary knowledge (Guo et al. 2020).

The relevance of hands-on experiences is even more important in the education of industrial engineers, particularly because they are requested to deal with complex manufacturing processes and factory environments. Indeed, implementing this learning paradigm can pose specific challenges due to limitations in accessing industrial equipment, the cost and logistics involved in physical laboratory activities, or the impracticality of working with full-scale factories and associated engineering problems. Virtual laboratories based on virtual reality and other digital technologies offer a valuable means of immersing students in realistic engineering scenarios (Terkaj et al. 2024b), such as manufacturing

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systems (Terkaj et al. 2024a), providing them with opportunities to learn and practice (Reeves and Crippen 2021) in a safe, convenient, and fully controlled environment (Abulrub et al. 2011).

Furthermore, virtual environments facilitate the contextualization of various types of engineering challenges that otherwise could not be proposed to students due to cost, safety, or health considerations (Abulrub et al. 2011; Potkonjak et al. 2016). For example, students can explore a dangerous area or handle materials that typically require a high level of expertise. In addition, students can evaluate several solutions to the same problem, break down complex problems into sub-problems, and gain a deeper understanding of inherently complex real-life events (Abulrub et al. 2011).

Moreover, the incorporation of gamification elements in educational contexts can increase the attractiveness of learning activities (Fredricks 2014; Bower et al. 2017). In this perspective, gamification and serious games have been used to increase the involvement of students (Khalil et al. 2017), improve the attitude towards a lecture, or make a learning activity more enjoyable (Hew et al. 2016).

Additionally, as is typical in most engineering disciplines, the education of industrial engineers must keep up with the rapid advancements in technology. Regarding industry and the education of industrial engineers, the advancement of digital tools and technologies stands out as a highly impactful phenomenon (Abele et al. 2017). A report published by the European Commission states the significance and urgency of adopting digital technologies in education (Bourgeois et al. 2019), recognizing the key role played by schools in preparing young people for a technology-driven world. This report highlights two different but complementary needs: the need to develop useful digital skills in both students and teachers and the need to use new technologies to support, improve and transform learning and teaching. Numerous case studies report the effectiveness of these technologies in enhancing student performance and engagement (Radianti et al. 2020; Lo and Hew 2019; Yu and Xu 2022).

Despite these potential benefits offered by these educational technologies, their adoption remains limited (Xing and Marwala 2017; Li and Wong 2019) because of several obstacles standing between teachers and technological practices (Ertmer et al. 2006), e.g., external factors such as time constraints or lack of technical skills, as well as internal factors such as pedagogical preconceptions, values, and attitudes towards ICT (Kim et al. 2013; Mama and Hennessy 2013). The proliferation of complex digital tools presents a challenge for professors and students to become proficient in every available tool. This leads to the risk of making an a priori selection of digital tools that hinders the mission of higher education since digital competencies should not be constrained by a specific application or technology lock-in, limiting the possibility of migrating to alternative tools/technologies due to technical or economic barriers (Alshwaier et al. 2012).

This work contributes to the aforementioned field by presenting a prototype virtual factory application that supports teaching/learning activities in engineering higher education. The application is specifically designed to be freely downloaded and used, removing the need for educational institutions to invest additional funds. This approach enhances the accessibility and affordability of the application. The article is structured as follows: Sect. 2 presents the related works in the literature; Sect. 3 introduces the proposed framework for the development of Virtual Learning application in industrial engineering. Thus, an example of a reconfigurable Virtual Learning Factory Application (VLFA) is described in Sect. 4 while its testing and validation is reported in Sect. 5. Finally, conclusions are drawn and future development sketched in Sect. 6.

2 Related works

Virtual and augmented reality (VR/AR) have emerged as significant technology trends in higher education (Radianti et al. 2020), with the potential to enhance teaching, learning, and research experiences in various disciplines (Hořejší et al. 2019; Radianti et al. 2020) in both higher education (Kerga et al. 2014; Pourabdollahian et al. 2012; Srinivasa et al. 2021; Mahmood et al. 2021a, c), and vocational education and training (Spanellis et al. 2020).

Many universities and colleges have recognized the potential of VR/AR and have started exploring their applications. They have invested in creating VR/AR labs, developing immersive content, and incorporating these technologies into their curricula. The global market for virtual reality in the education market grew from \$8.67 billion in 2022 to \$11.95 billion in 2023, representing a compound annual growth rate (CAGR) of 37.9% (Research and Markets 2023).

Due to the promising growth of this sector, major companies such as Google, Microsoft, Facebook (through Oculus), and HTC have been actively promoting VR/AR technologies for educational purposes. They have developed and offered VR/AR platforms, tools, and applications that are specifically designed for educational institutions.

Nevertheless, the widespread adoption and implementation of AR/VR in higher education may still be in the early stages and can vary across institutions (Crumpton and Harden 1997; Kirkwood and Price 2014; Calvet et al. 2019). There are various reasons for this, as there are several significant challenges involved:

- Consistent investment in hardware, software, and infrastructure is required, such as high-quality headsets, computing devices, and network capabilities (Korkut and Surer 2023; Radianti et al. 2020).
- Accessibility concerns (cost, availability, and physical disabilities) for students need to be addressed(Wong et al. 2023; Radianti et al. 2020).
- Faculty members need to acquire the necessary skills and knowledge to integrate VR/AR into learning activities, including learning the tools, techniques, and pedagogical approaches involved (Wong et al. 2023; Jin et al. 2022).
- The customization of a virtual environment (VE) scene can require significant effort. The importance of a reconfigurable VE was addressed in early works based on OpenGL library, using an XML data interface first (Viganò et al. 2011), and an OWL ontology data repository later (Terkaj and Viganò 2017).
- Developing high-quality VR/AR content that aligns with specific educational objectives can be time-consuming and resource-intensive (Urgo et al. 2022; Jin et al. 2022).
- Lack of standardized platforms and compatibility across devices (Korkut and Surer 2023).
- The need for pedagogical redesign and alignment with learning outcomes (Wong et al. 2023).

A push towards the use of AR/VR came from the Covid-19 pandemic as a possible way to enable and enhance distance learning (Willcott 2021; Gasmi and Benlamri 2022). In line with this trend, VR technologies can be used to implement virtual laboratories (Reeves and Crippen 2021), where a virtual reality environment replicates a real laboratory setting. This approach has been successfully applied in fluid mechanics to demonstrate the usefulness of virtual tours to give pre-lab instructions and let the students get acquainted with a VR simulated pump (Zhao et al. 2019). The experiences carried out reported positive feedback from students who considered virtual tours highly informative and the VR equipment intuitive and useful for gaining practical experience before working in a real laboratory. Kapilan et al. (2021) described a training program for faculty members, organized remotely during the COVID-19 pandemic, addressing the use of virtual laboratories in different mechanical engineering areas. The training led to the implementation of a wide range of virtual laboratory activities, allowing the students to complete their classes and overcome the impossibility of accessing laboratories.

VR technologies have proven to be valuable in supporting self-learning approaches as well. Vergara et al. (2014) developed an interactive virtual platform (IVP) to enhance self-learning thanks to a virtual materials laboratory featuring an interactive compression test machine. The utility of virtual and augmented reality (VR/AR) technologies has also been investigated for the production of materials, seeking to increase academic performance, engagement, attitudes and self-efficacy of students towards the subjects. In a study by Srinivasa et al. (2021), the authors developed a software prototype that enabled the combination of modular virtual objects (VOs) to create virtual scenes without the need for programming skills.

A popular trend in the adoption of VR in education revolves around serious games or gamification, i.e., the exploitation of a game paradigm to implement learning activities. Many contributions in the literature refer to the benefits of gamification techniques in increasing competitiveness and attention while developing cross skills such as collaboration and creativity (Caponetto et al. 2014; Villalustre Martinez and del Moral Perez 2015; Dicheva et al. 2015). Furthermore, serious games in education have also been acknowledged for potential impact on the sense of achievement, engagement, and motivation of the students (Manzano-León et al. 2021), although these results have not always been confirmed (Mekler et al. 2017). Within this area, some contributions leveraging on VR (immersive, non-immersive and semi-immersive) and gamification techniques to support learning in the field of manufacturing engineering have been considered.

Hořejší et al. (2019) proposed a serious game named *Workshop* for production engineering, addressing the production of parts in a manufacturing workshop. The aim is to teach students from different backgrounds technical skills related to machining manufacturing processes. The game is structured in terms of a virtual reality environment of a mechanical workshop, where the users can select a machine tool (lathe, drilling machine, milling machine) to operate the machining of a part, according to a given process plan and related parameters. To enhance the realism of the setting, production orders are provided through a production plan, while blueprints and process tags for parts are also available. The focus is on the manufacturing process, and support to the users is provided in terms of spoken comments played during the interaction with specific objects (e.g., a machine tool or a part). During the execution of a manufacturing process, the animation is run to show what is happening and, upon completion, the user is informed with audio and textual feedback about the successful outcome of the operations. The gameplay experience is organized in a set of steps with increasing difficulty to be accomplished. Muller et al. (2017) presented a similar application as a virtual workshop for the training of mechanical engineering students. The virtual reality environment is used to let the student experience operating a CNC machine and check the results of the execution of machining processes. The application takes advantage of a head-mounted display (HMD) and relative controllers.

Lee et al. (2002) proposed a virtual training workshop for remote training activities in the field of manufacturing.

The environment provides a virtual ultra-precision machine for turning and a virtual inspection machine for surface metrology, presenting a user interface that closely mimics the real one. The training addresses a single-use case related to the machining and measuring of a spherical mould.

A learning experience focused on human-robot collaboration in a manufacturing environment has been addressed by the *Beware of the robot* application (Matsas et al. 2012). The setup grounds on HMD for both video and audio interactions, a Microsoft Kinect™ sensor to monitor the movements of the user together with traditional interaction devices (mouse and keyboard). The experience was organized in terms of a set of tasks to be accomplished according to a use case shared with the participants, thus, without a predefined set of levels.

Buń et al. (2019) exploited virtual reality to teach lean manufacturing approaches and methodologies while addressing the assembling of a product. A virtual training application was developed to enable students to learn an assembly procedure while interacting with the product in the virtual environment. An unrealistic use case related to the assembling of Lego bricks is adopted to obtain a final part. The effectiveness of the virtual training is assessed in an additional class experience by comparing the performance of students who did not carry out the virtual training, showing a significant benefit.

Ye et al. (2018) presented a VR-based serious game for higher education, consisting of a virtual laboratory for realistic and immersive experiments in control engineering. The authors exploit a web-based architecture taking advantage of a javascript 3D environment running in a web browser, with a server providing multiple experiments/levels and supported by simulation models to implement the realistic behaviour of virtual objects.

In addition, the intersection of video games and learning approaches led to the development of frameworks supporting the design of serious games. The Mechanics, Dynamics, and Aesthetics (MDA) framework (Hunicke et al. 2004) considers three fundamental design components, i.e., actions, processes, and data that are available in the game (*mechanics*), run-time behaviour and dynamics of actions (*dynamics*), and the desirable emotional responses of the player (*aesthetics*). Focusing on serious games for learning, Winn (2009) highlighted the need to extend the MDA framework to consider the contributions of designers and players to building the gaming experience. To this aim, the Design, Play and Experience (DPE) framework was proposed (Winn 2009), consisting of four main layers (Learning, Storytelling, Gameplay, User Experience) that are instantiated for each of the three main components, namely design, play and experience. In addition, DPE points out the relevant role of the adopted technology in making a serious game effective.

More recently, Urgo et al. (2022) specialized the DPE framework for designing learning applications in the field of industrial engineering (DPE-IE) within higher education, providing an implementation and demonstration example of the configuration and analysis of a manufacturing system. This framework has been taken as a reference to structure and summarise the characteristics and functionalities of the described VR-based learning applications for industrial engineering (Table 1). This summary underlines the focus of virtual reality on learning practical concepts through the application of conceptual and theoretical knowledge, mainly in realistic situations. Although the described examples are focused on a specific class of users, VR-based learning applications are suitable for activities ranging from the bachelor's degree to the continuous training of experienced engineers. The benefits of using virtual reality are maximised in its exploitation to mimic real environments. Thus, realistic use cases are a fundamental factor. Most of the available tools and approaches have been demonstrated with a single user, probably due to the increased complexity of implementing a multi-player environment. Nevertheless, this feature is strongly requested to support teamwork in higher education. Finally, the exploitation of advanced interaction technologies (e.g., HMD) should be further addressed since their maturity has significantly improved in the last years, paving the way to their effective and successful use in learning activities.

3 A framework for the development of virtual learning applications in industrial engineering

The literature analysis underscores significant challenges in making VR-based usable and effective to support educational activities in industrial engineering in the form of lessons, exercises, demonstrations of industrial cases and virtual labs. In response, we propose a framework for the development of Virtual Learning applications that foster the use of VR in higher education by reducing development time and assisting educators lacking strong expertise in VR and software development.

At the core of the framework (Fig. 1) lies the digital model of the Virtual Environment (*VE Digital Model*) that helps decouple the generation of the case-based contents from the development and configuration of technology-intensive tools. The objective of the framework is to enable teachers and supervisors to focus on generating learning contents that instantiate the VE digital model, while software experts develop digital tools and data interfaces. Figure 1 depicts the data flows and the components of the framework, some of which are derived from the layers of the DPE-IE design framework (Urgo et al. 2022):

Table 1 Summary of VR-based learning applications in industrial engineering education

		Learning applications					
		Workshop (Hořejší et al. 2019)	Beware of the robot (Matsas et al. 2012)	Virtual training workshop (Lee et al. 2002)	Lean manufacturing workshop (Buń et al. 2019)	Mechanical engineering virtual workshop (Muller et al. 2017)	VR NCSLab (Ye et al. 2018)
Learning	Skills to acquire	Practical	Practical	Practical	Practical	Practical	Practical
	Assessment	n/a	QNTQUAL	QNT	QNT	QNT	QNT
	End users	B.S. M.S.	B.S. M.S. VET	M.S.	B.S. M.S.	B.S.	B.S.
Storytelling	Use case	Realistic	Realistic	Realistic	Unrealistic	Realistic	Realistic
Gameplay	Levels	Yes	No	No	No	No	Yes
	Progression	Automatic	Automatic	n/a	Automatic	Automatic	Automatic
	Players	Single	Single	Single	Single	Single	Single
User Experience	Interface and interactivity	VE-interact. textual acoustic	VE-interact. avatar acoustic	VE-interact. textual	VE-interact. textual	VE-interact. textual	VE-interact. textual graphical
Technology	Interaction hardware	KVM	HMD	KVM	HMD	HMD	HMD

QNT, quantitative; QUAL, qualitative; B.S., students from Bachelor of Science courses; M.S., students from Master of Science courses; VET, vocational education and training; VE-interact., interaction with the virtual environment through interfaces, controllers, etc.; KVM, keyboard, video and mouse; HMD, head-mounted display

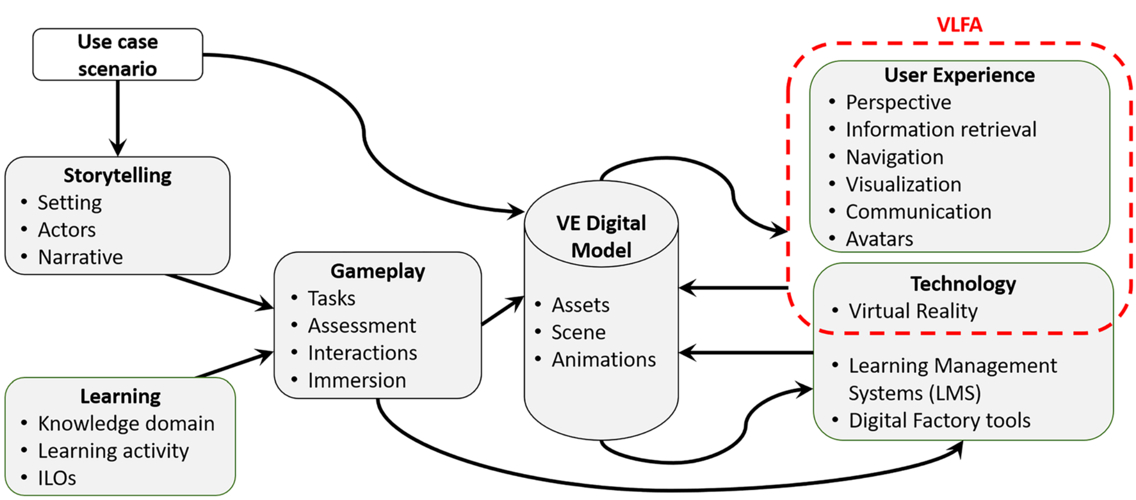


Fig. 1 Framework for the development of virtual learning applications in industrial engineering

- *Learning* The definition of the content and pedagogy of learning activities in industrial engineering.
- *Storytelling* The definition of the stage and story used to convey content that is relevant for the learning goals.
- *Gameplay* The definition of what users will be able to do in the virtual environment and what will be they asked to do.
- *User Experience* The design of interfaces defining what the user can see and hear.
- *Technology* Specification of the technologies used to implement the Virtual Environment, including the reconfigurable Virtual Learning application and related digital tools.

Within the described framework, a key requirement for digital tools, including visualization ones, is to be reconfigurable and model-driven, to facilitate domain-specific content customization. Considering the focus on the industrial domain, the key element of the framework is represented by a reconfigurable Virtual Learning Factory Application (VLFA) that implements the User Experience component, a relevant part of the Technology components, and partially the Gameplay one.

The following subsections will delve into the main details of the framework, eliciting the requirements for developing the VLFA. The Learning (Sect. 3.1), Storytelling (Sect. 3.2), and Gameplay (Sect. 3.3) components are mainly related to the design of the learning content, hence the requirements will be general in the form of enablers. Conversely, the requirements stemming from the User Experience (Sect. 3.4), Technology (Sect. 3.5), and VE Digital Model (Sect. 3.6) will be detailed more specifically.

3.1 Learning

The learning component serves as the foundational element that enables effective and engaging learning experiences in an educational context. It involves defining the kwowledge domain, the learning activity and explicitly list the Intended Learning Outcomes (ILOs) (Biggs and Tang 2011) that the students will acquire using the application. The ILOs can be grouped according to different classes of knowledge, as defined by (Anderson et al. 2001), i.e. Factual knowledge, Conceptual knowledge, Procedural knowledge, and Metacognitive knowledge. The resulting general requirements for the VLFA are:

R.1 The virtual environment and the interactions must be able to adapt to the specific ILOs.

R.2 Two types of users can participate in the VE, i.e., student (trainee) and teacher (supervisor). The student is the target of the intended learning outcomes, while the teacher facilitates the knowledge acquisition. This can help combine autonomous learning of the student with teacher guidance (Jiang et al. 2018).

More details and guidelines for the generation of learning contents can be found in Urgo et al. (2022), referring to applications in industrial engineering.

3.2 Storytelling

The storytelling component encompasses the actors, setting, and narrative that is experienced in the virtual environment (VE). This component must be customized for the selected use case scenario, therefore the general requirements for VLFA can be defined as follows:

R.3 The VE must give access to a realistic representation of the industrial context, implementing visualization experiences that also represent the dynamics of the system (Chandra Sekaran et al. 2021). This will help the student play the role of an engineer.

R.4 The VE must provide relevant details such as products, processes, machines, failures, monitoring, etc. (Alpala et al. 2022). This will enable a narrative revolving around the need to analyze, design, install, manage, or maintain industrial products, processes, systems, or facilities.

3.3 Gameplay

The gameplay component defines the mechanics and dynamics of the virtual environment that are designed taking into consideration affective goals such as immersion, intellectual problem-solving, competition, creation, discovery, advancement and completion, application of abilities, and learning (Urgo et al. 2022). The following general requirements for VLFA can be specified:

R.5 The VE must be able to support the execution of tasks with different complexity based on the ILOs (Udeozor et al. 2023). In addition, the VE must enable the direct learning assessment or be integrated with a learning assessment tool.

R.6 Multiple players can participate in the VE to stimulate collaboration and team working skills and interactions among students (Cooney and Darcy 2020).

R.7 Immersion in the VE must be provided to let the user have a close-to-reality experience, including the simulation/animation of elements involved in industrial processes (Chandra Sekaran et al. 2021; Alpala et al. 2022). For instance, a part is loaded on an assembly station; a workpiece is machined on a lathe; a pallet is moved along a conveyor.

3.4 User experience

The user experience plays a critical role in delivering an industry-related experience and aiding in the attainment and evaluation of the intended learning outcomes. To ensure the effectiveness of the virtual environment, it is essential that the level of detail (LoD) of the virtual environment is comparable with the real industrial facility in terms of both quality and dimensions (Urgo et al. 2022). Relevant requirements are listed below:

Table 2 User experience requirements for different types of users and play modes

Requirements	Single-player	Multiplayer	
		Student	Teacher
R.8 Perspective			X
R.9 Information retrieval	X		X
R.10 Navigation	X	X	X
R.11 Animation interaction	X		X
R.12 Trajectory visualization	X		X
R.13 Live communication		X	X
R.14 Avatar		X	X

R.8 Users can take a third-person perspective in the VE to improve awareness and perception (Gorisse et al. 2017). In particular, students can be forced to take the same perspective of the teacher, while teachers can take the perspective of a student to assess what the student is doing.

R.9 Users can retrieve information related to assets in the VE (e.g., ID, description, position, slides, data sheets, 3D files, failure logs of a workstation) through specialized interfaces (Schleußinger 2021), such as panels that become visible upon selecting a specific asset.

R.10 Navigation techniques and metaphors must enable the user to freely discover the (industrial) environment (Montano Murillo et al. 2017; Nilsson et al. 2018).

R.11 The user can interact with the simulations/animations in the VE (Chandra Sekaran et al. 2021), e.g. start and pause animations.

R.12 The user can visualize the 3D trajectory of assets that are moving in the VE (Buschmann et al. 2014) (e.g., path visualization with red lines). This enables a better understanding of the system dynamics.

R.13 Users can communicate via voice or text chat to enhance collaboration (Wen and Gheisari 2020).

R.14 The multiplayer mode must be enhanced by avatars (Freeman et al. 2020; Dewez et al. 2021) that show the position and point of view of each user.

Table 2 maps a subset of requirements that are affected by the type of user (student/teacher) and play mode (single-player/multiplayer). The users are able to access different functionalities, i.e., a limited set is available to students and a complete one to teachers.

3.5 Technology

The technology component defines how the application must be developed, implemented and integrated with data sources to enable the other layers to work correctly. Herein, the following technical requirements apply:

R.15 Virtual Reality must be used to enhance the realism of the experience with reference to industrial scenarios (Chandra Sekaran et al. 2021).

R.16 The application must be developed as an open (Blayone et al. 2017) and multi-platform (Sibbaluca et al. 2020) tool to support the democratization of the Virtual Learning application in higher education.

R.17 The VE app must be reconfigurable to enable the representation of multiple industrial engineering cases (Galambos et al. 2015).

R.18 The VE must have data interfaces that enable its model-driven reconfiguration (Berardinucci et al. 2022).

In addition to VR, other digital tools may be employed and integrated for learning assessment (e.g. Learning Management Systems Kraleva et al. (2019)) and to generate data consumed by the VE (e.g. simulation of industrial processes).

3.6 VE digital model

As anticipated, the digital model of the VE plays a central role in the framework because it integrates data from heterogeneous sources organized in a ready-to-use way for the VFLA, leading to the following requirements:

R.19 An effective VE digital model must be based on a data model (Berardinucci et al. 2022) that facilitates the generation of new instances.

R.20 The VE must be stored and shared in format that is easily accessible by VLFA and other digital tools to enhance interoperability (Havard et al. 2019).

R.21 A standard format for 3D models must be used (Chandra Sekaran et al. 2021).

The model-driven reconfiguration of the VE is supported by the data model, and the storage of the VE digital model, thus providing the capability of easily delivering meaningful contents for different industrial engineering applications(cf. R.18).

4 A reconfigurable virtual learning factory application

The proposed reconfigurable Virtual Learning Factory Application (VLFA) has been designed and implemented taking into account the requirements defined in the previous section to provide teachers with the required functionalities while focusing on learning objectives. The VLFA is primarily tailored for industrial engineering education, but it can also be applied to other domains.

Several alternative frameworks exist to support the development of software applications based on virtual reality (R.15), and most of them are aimed at the development of video games (e.g., Unity,[1] Unreal Engine[2]). The VLFA is based on the open-source ApertusVR library[3] (Paniti et al. 2020, 2021) supporting the development of VR-based applications that are integrated into a distributed architecture to enable the interaction between human users and software agents. ApertusVR meets the open and non-commercial requirement (R.16) so that the VLFA can be available to higher-education institutions without the need to acquire expensive licenses and hardware. The VLFA can be downloaded and is freely available for non-commercial uses.[4]

The following subsections will present the general architecture of ApertusVR (Sect. 4.1) and the specific architecture of the VLFA (Sect. 4.2).

4.1 Architecture of ApertusVR

ApertusVR is structured as a distributed eXtended Reality (XR) engine orchestrating different software modules that interact on a local or global network, thus enabling multiple users from different geographical locations to collaborate in an XR environment.

ApertusVR is based on a *no vendor lock-in* approach for virtual and augmented reality on different operating systems and through virtual and augmented reality hardware (R.16), sharing the same virtual reality scene simultaneously.

The foundation of the ApertusVR architecture is ApertusCore, a C++11 programming library that is modular, embeddable, platform-independent, and easily configurable, thus fulfilling modern software requirements. ApertusCore provides basic software interfaces and modules for logging, handling events, loading plugins and configurations, and synchronizing distributed data among the participants of a virtual reality scene over the internet/intranet. The main feature of ApertusCore is the so-called *Distributed Plugin Mechanism* that enables the involvement of humans in a multi-user virtual reality scene and the integration of Internet of Things (IoT) elements like hardware, software, robot, or any kind of smart device.

ApertusVR extends the functionalities of ApertusCore through additional plugins supporting XR (i.e., AR, VR, and MR) capabilities, and their seamless integration into new or existing software projects. These plugins are based on a high-level abstraction layer over the hardware vendors to enable different display and control devices in any product or service (Fig. 2).

4.2 Architecture of the VLFA

The VLFA has been developed to fulfil the requirements described in Sect. 3 while taking advantage of the ApertusVR libraries (Sect. 4.1). The VLFA architecture (Fig. 3) has been designed according to the typical scheme used for multiplayer games (R.6). Thus, users act together in a *virtual room* while sharing the same virtual environment and associated events. Each room is managed by a room host (Sect. 4.2.2). The access to the rooms is managed by the lobby server (Sect. 4.2.1) while a client application (Sect. 4.2.3) provides the users with the capability to access the virtual environment and interact with it and the other users. Customized behaviours and functionalities are then enabled according to the type of user (e.g., teacher, student) (R.2). The client application and the room host have been developed thanks to the distributed functionalities provided by ApertusVR, as well as its capability to support the parallel running of different software modules. The lobby server provides other functionalities, such as the search and creation of a room.

In single-player mode, the client application is responsible for satisfying the requirements which are related to visualization and interaction.

In multiplayer mode, the client application is only responsible for the visualization, while the room host handles the interactions. The lobby server manages the setup of the room host, therefore the client application displays only the results given by the room host.

4.2.1 Lobby server

Multiplayer games are typically developed using a lobby server, i.e., an application whose primary purpose is to

[1] https://unity.com/.

[2] https://www.unrealengine.com.

[3] https://apertus.gitbook.io/vr/.

[4] https://apertus.gitbook.io/vr/vlft_application.

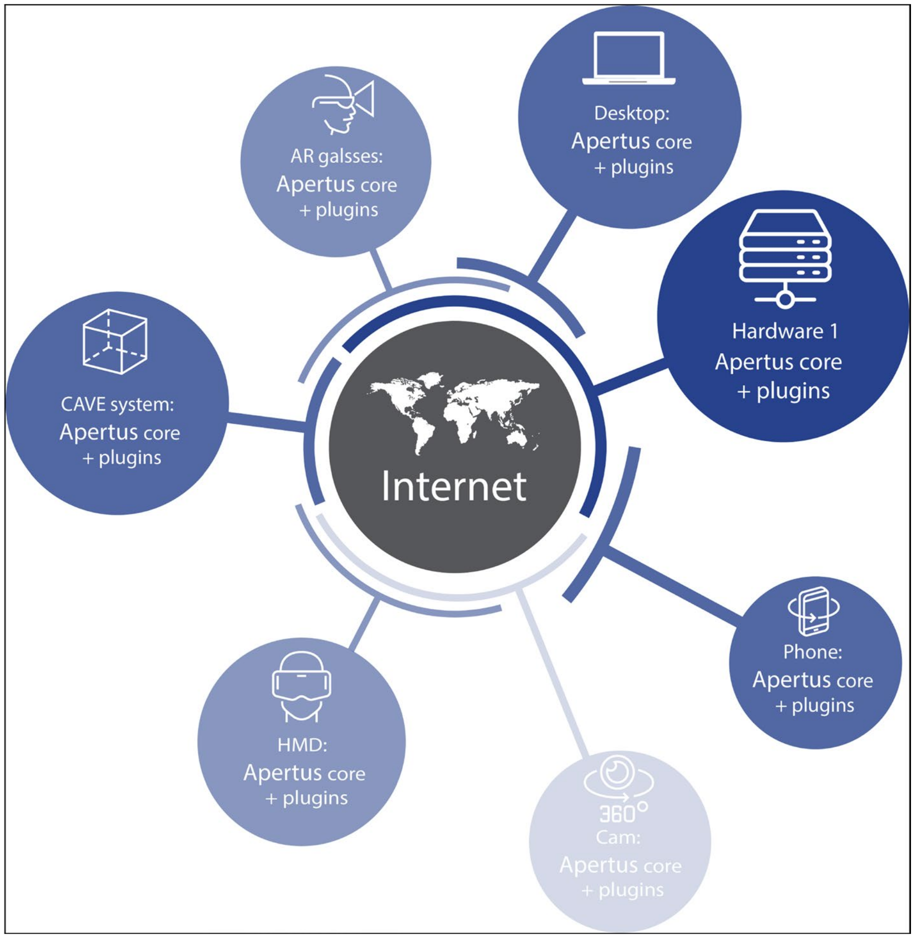


Fig. 2 Architecture of the ApertusVR libraries (http://apertusvr.org/)

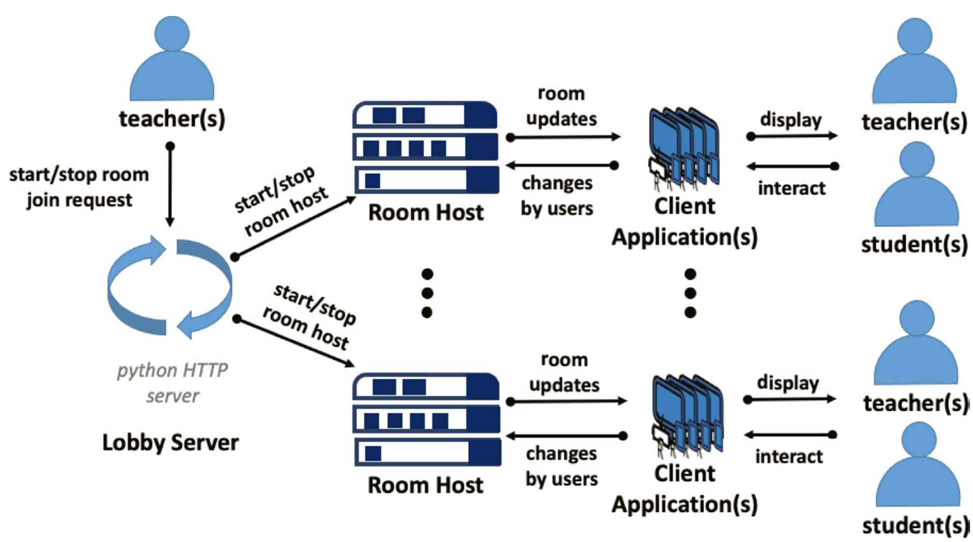


Fig. 3 Architecture of the VLFA

enable players to meet and arrange games. Thus, a lobby server application is included in the VLFA to provide the capability to run and access rooms representing different industrial cases or versions. The lobby server (Fig. 3 on the left) provides the following functionalities:

- Start and shut down online rooms.
- Search for online rooms.
- Join online rooms.

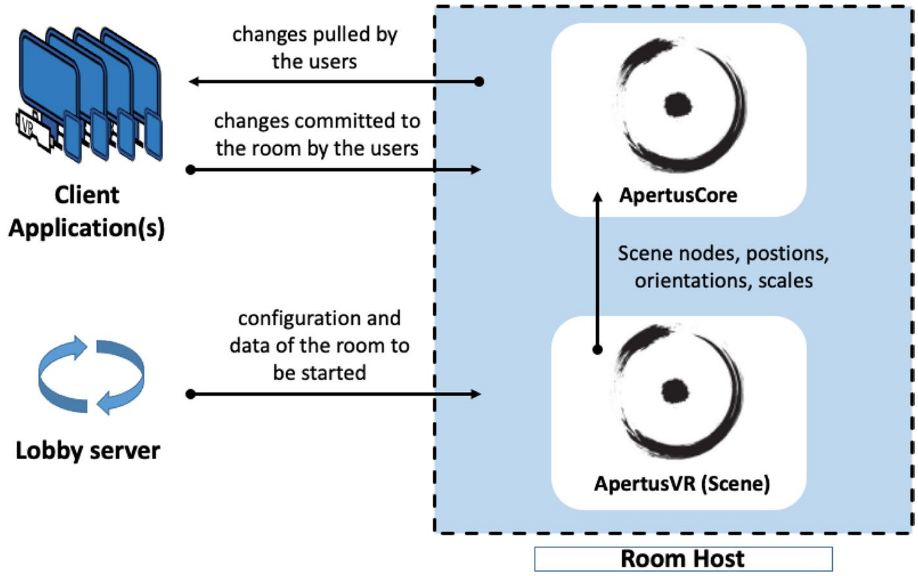


Fig. 4 Architecture of the VLFA room host

The lobby server itself is an HTTP server developed in Python language and interacts with the client application through simple HTTP requests.

Starting and shutting down online rooms is only possible for users with teacher roles through an admin interface (Sect. 4.2.3) that will send an HTTP request containing the name of the online room to be activated or deactivated. This request is received by the lobby server, which will create a new process for the host of the specified room. The host loads the scene and sets up the room according to the specific settings and data (Sect. 4.3). Thus, the new online room is added to the list and made available for other clients to join. A stop request will be similarly received by the HTTP server causing it to kill the related process at the host, shutting down the selected room and removing it from the list of active online rooms.

Client applications connect to the lobby server to look for available online rooms. The visibility of the online rooms can be managed according to specific classes of users. Upon selecting the room to connect, the lobby server routes the connection of the client application to the specific room host (Sect. 4.2.2).

4.2.2 Room host

The VLFA room host (Fig. 4) is responsible for setting up and managing an online room as well as synchronizing the scene between multiple clients. Different hosts are instantiated for each room (R.17), consisting of two main modules: ApertusCore and ApertusVR.

The ApertusVR module creates the scene grounding on data related to the VE Digital Model (Sect. 4.3). This process exploits the functionalities provided by the *nlohmann/json* library,[5] supporting the automatic creation of C++ classes starting from the nodes in a JSON file.

The ApertusCore module is responsible for managing the room and handling communication with the client applications. When a user joins an online room, a connection is established between the ApertusCore module of the client application and the room host. This connection and synchronization process is facilitated through *RakNet*,[6] a C++ class library developed with a focus on online gaming to support networking and related services. This connection enables the data synchronization between the ApertusCore modules of the room host and the connected clients, with the aim of providing them with a continuously updated scene. Specifically, the following types of data are synchronized:

- Position and orientation of the assets in the scene.
- Position of the other users (i.e. position and orientation of their point of view)
- Dynamic events in the scene, e.g., animations.
- Messages among users.

4.2.3 Client application

The VLFA client application (Fig. 5) is the main software module that enables users (both students and teachers) to access the virtual environment. As for the room host, also the client application is composed of two main modules: ApertusCore and ApertusVR.

The ApertusCore module in the client application is responsible for communicating with the ApertusCore

[5] https://github.com/nlohmann/json.

[6] https://github.com/facebookarchive/RakNet.

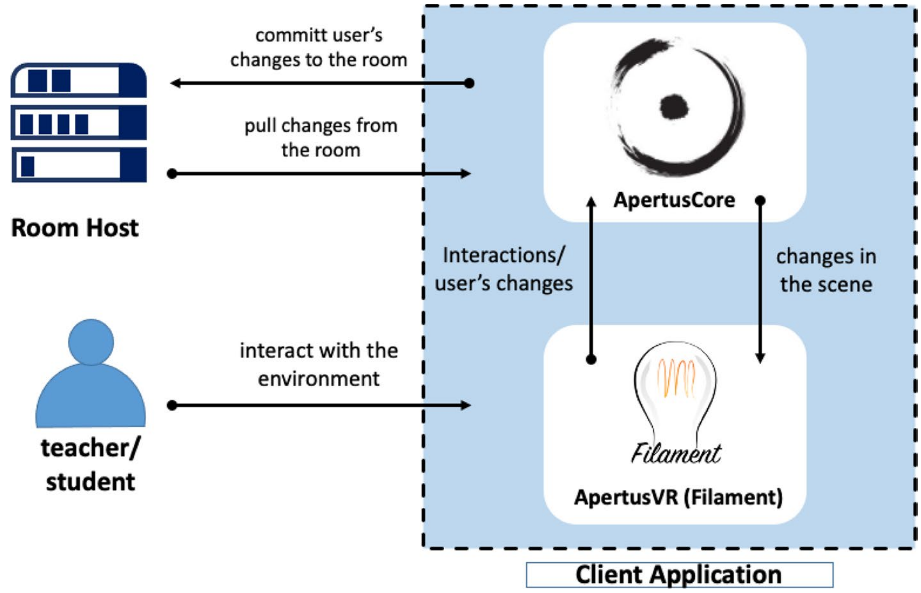


Fig. 5 Architecture of the VLFA client application

module in the room host (Sect. 4.2.2) to guarantee their synchronization. The two ApertusCore modules are very similar, though with the essential difference that the one in the client application only communicates with the host, while the latter communicates with all the client applications connected to the room itself. Upon joining an online room through the lobby server (Sect. 4.2.1), a direct connection is established between the client application and the host process of the room. Through this connection, all the nodes, assets, and events in the scene are synchronized. The ApertusCore module operates through HTTP communications based on the curl library.[7]

The ApertusVR module is responsible for rendering the scene in the client application as well as providing proper interaction functionalities to the users. The ApertusVR module can be further broken down into two layers: the *virtual reality* and *user interface*.

The *virtual reality layer* is responsible for rendering the VR scene and handling animations and movements of objects (R.3, R.4), including the avatar of users in multiplayer mode (R.14). The main window of the client application is used to show the environment in real time. Within the rendered scene, common functionalities for a virtual reality environment are provided to the users, i.e., the navigation within the environment (R.10), the selection of objects and the ability to highlight the associated 3D model. Photo-realistic rendering is implemented to create a faithful representation of the environment (R.7). The rendering process is based on Filament,[8] a real-time physically based rendering engine able to perform efficiently on mobile platforms. Filament is open source and available for Android, iOS, Linux, macOS, Windows, and WebGL, thus addressing the requirement R.16.

The *user interface layer* is a UI overlay rendered on top of the virtual reality layer and is based on *Dear ImGui*,[9] a free graphical user interface library for C++ (R.16). The interface layer provides the users with various functionalities, including:

- *Login* The login menu starts the connection for an identified user, thus providing specific functions or penalizations (e.g., access to specific online rooms).
- *Single-player* This menu enables the use of the application in single-player mode. The user is provided with a list of available rooms that can be joined. The user will experience the full set of functionalities of the rooms, but no other users will be able to join.
- *Multiplayer* In multiplayer mode, the user is provided with a list of available online rooms by the lobby server (Sect. 4.2.1). Upon joining a room, a connection with the room host is initiated (Sect. 4.2.2), thus the user will be able to enter the room and interact with other users (R.6).
- *Admin* The admin menu provides the teacher with specific functionalities, namely the possibility to start and shut down online rooms (Sect. 4.2.1).
- *Settings* Through this menu, the user can customize keyboard commands to move and interact with the scene, as well as enable advanced rendering options (e.g., light settings).

7 https://github.com/curl/curl.

8 https://github.com/google/filament.

9 https://github.com/ocornut/imgui.

- *Interaction with the scene*. UI modules enable the user to interact with the environment. By clicking on an asset in the scene, the UI provides specific information, e.g., its description or available attachments like data files, pictures, etc (R.9). Buttons in the UI are also available to start, stop, pause and rewind the animation of the scene (R.11). A specific button of the UI activates the tracking of the movements of the objects in the VE, by rendering their paths as coloured lines (R.12). The possibility of modifying the scene (e.g., moving the assets) is available in single-player or admin mode. Further functionalities are provided to the teacher in the admin mode (R.2), specifically the capability to force the point of view of all users in the scene to be the same as the teacher, and vice-versa, i.e., forcing the point of view of the teacher to match the one of a user (R.8).
- *Messages* The client application manages messages to the other users in the same virtual room, enabling the possibility to interact within the same environment (R.13).

4.3 Data interfaces

According to the reference framework (Sect. 3), the VLFA can easily manage various industrial cases by customizing the room configuration (R.17), thus enabling the change of ILOs (R.1) and tasks (R.5).

Instead of embedding models, information and data in the application, the contents to be rendered in the VLFA are dynamically loaded from the VE Digital Model (R.18), which contains data about the scene, animation events, and 3D models.

The *scene* is defined by a digital model serialized as JSON file (R.18, R.20) according to a predefined schema[10] (R.19) that contains:

- The list of assets to be rendered in the scene.
- Asset definition, e.g., ID, type, description, etc.
- Position, orientation, and scale of the assets.
- Reference to 3D representation files.
- Relations between assets (e.g., decomposition, connection, assignment)

Animation events define the dynamic evolution of the scene and are serialized as a JSON file (R.20) according to a predefined schema[11] (R.19) supporting the following classes of events:

- *Animation*, a sequence of rototranslations defining the updated absolute position and orientation of an asset.
- *Animation additive*, a sequence of rototranslations, defining the updated position and orientation of an asset with respect to the current ones.
- *Show*, triggering the asset to be visible in the scene.
- *Hide*, triggering the asset to be not visible in the scene.
- *Attach*, attaching the placement of an asset to another asset in the scene.
- *State*, triggering a change in the state of an asset. States can be used to change the 3D representation and/or properties of the asset.
- *Link*, link to a file with information about the asset.
- *Trail*, enable/disable the persistent path visualization of the asset.

Finally, the gLTF[12] format has been adopted for the representation of *3D models*. It is an open and royalty-free interchange format for virtual reality applications, enabling efficient transmission and loading of virtual reality scenes and models by game engines and applications (R.16, R.21). The glTF format supports highly detailed representations of geometries, materials, and shaders thanks to the implementation of the physically based rendering (PBR) pipeline (R.7).

5 Testing and validation

This section presents the testing and validation of the proposed framework (Sect. 3). The attention is focused on demonstrating the capabilities of the reconfigurable VLFA (Sect. 4) in meeting the specified requirements, but, for the sake of completeness, all the components of the framework are addressed to demonstrate how it facilitates the development of complete applications tailored to specific learning objectives. Specifically, the framework was employed to model the industrial case of a manufacturing assembly line (Sect. 5.1), enabling learning activities related to the design and analysis of manufacturing systems (Sect. 5.2). The VE Digital Model was instantiated accordingly (Sect. 5.3) to feed the digital tools, in particular the VLFA (Sect. 5.4).

In addition to technical assessments, feedback from key stakeholders constitutes an integral part of the validation process (Sect. 5.5). This feedback was solicited from both educators, who leverage the framework to design and implement learning activities, and students, who interacted with the specific virtual learning environment facilitated by VLFA.

[10] https://virtualfactory.gitbook.io/vlft/kb/instantiation/assets/json.

[11] https://virtualfactory.gitbook.io/vlft/kb/instantiation/animations.

[12] https://github.com/KhronosGroup/glTF.

5.1 Use case and storytelling

The use case scenario involves a factory producing damped cabinet hinges on an assembly line (Berardinucci et al. 2022). This assembly line is organized in a flow shop architecture and composed of 19 workstations and 4 buffers. The initial 3 workstations are placed around a rotating table, whereas the remaining 16 workstations are placed along the main conveyor that transports pallets with the work-in-progress hinge.

In this context, the storytelling involves two actors: junior engineers and a senior supervisor. Junior engineers will analyze the real manufacturing system in terms of the types of parts processed, production volume requirements, system characteristics, and potential constraints like floor space availability. This setting offers a tangible understanding of their role in solving real-world manufacturing issues, directly applying previously acquired knowledge. The senior supervisor will guide junior engineers through the manufacturing system while addressing the challenges related to the learning objectives.

Ensuring compelling storytelling and a high-quality representation of the use case is crucial for users to feel fully engaged in interacting with the simulated system (R.3, R.4).

5.2 Learning objectives and gameplay

The learning activities have been designed within the scope of a serious game, as presented by Urgo et al. (2022). The types of knowledge (Anderson et al. 2001) pertinent to the domain of manufacturing system design and analysis can be classified as follows:

Factual knowledge	Pertains to comprehending the precise characteristics and functionalities of production equipment.
Conceptual knowledge	Involves understanding the role of production resources (e.g., machine tools, transporters, buffers) within a specific system configuration.
Procedural knowledge	Entails the application of methodologies, techniques, and tools for analyzing the performance of the manufacturing system.

For each type of knowledge, it is possible to define specific Intended Learning Outcomes (ILOs), as detailed by Urgo et al. (2022). For instance, for the application to industrial engineering under consideration, *Conceptual knowledge* is associated with the following ILOs (R.1):

- Classify the pieces of equipment.
- Identify the flow of parts within the manufacturing cells in the virtual environment.
- Identify the type of manufacturing system architecture.

The development of the gameplay component considers storytelling and learning objectives as input. In particular, the gameplay is structured into three levels, each associated with specific types of knowledge:

What is a factory made of?	Players are introduced to the factory environment, familiarizing themselves with components and terminology (*Factual knowledge*). No animation is required at this level.
How does a factory work?	This level aims at imparting knowledge about products and processes (*Conceptual knowledge*). The manufacturing system must be animated for players to observe part routing and manufacturing processes.
Performance of a factory.	Players identify scenarios or verify hypotheses, selecting appropriate modelling approaches (*Procedural Knowledge*). Quantitative estimation of performance indicators is involved, with animation and supplementary data supporting the analysis.

Each level comprises tasks (R.5) with associated challenges and questions, as detailed by Urgo et al. (2022), with answers forming the assessment basis.

During gameplay, students assume the role of junior engineers, while teachers play the role of senior supervisors (R.2), all interacting (R.6) within the same dynamic environment (R.7).

5.3 Instantiation of the VE digital model

The detailed digital model of the assembly line was originally instantiated according to an ontology data model (Urgo and Terkaj 2020) (R.19) that allows characterizing each

Fig. 6 Room selection

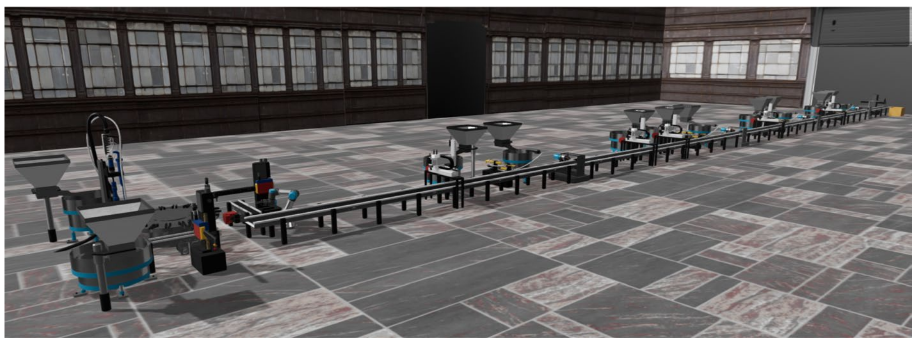


Fig. 7 Assembly line in the virtual environment

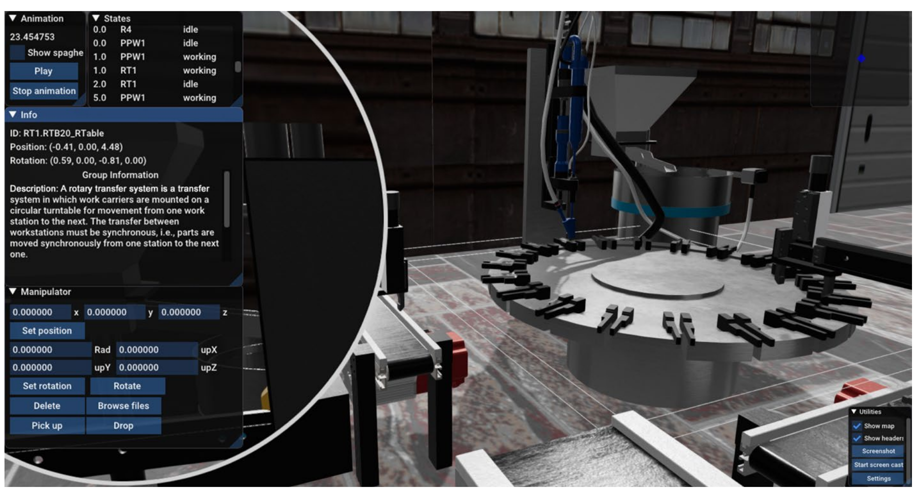


Fig. 8 Details of the rotating table in the assembly line

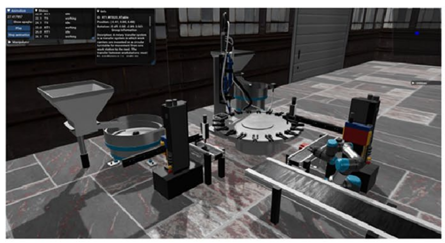
asset in terms of properties (e.g., placement, capacity, 3D representation) and relations (e.g., connections, assignments) (R.4). The ontology model can be exported to a set of JSON files (R.20) that can be used to generate the reconfigurable scene and the animations in VLFA (R.17, R.18), as described in Sect. 4.3. All ontology and JSON files are available online[13] (R.16).

The 3D representation of physical assets (e.g., products and workstations) was originally developed in a B-REP-based CAD environment and then exported to glTF format (R.21) while creating a hierarchical structure that extends

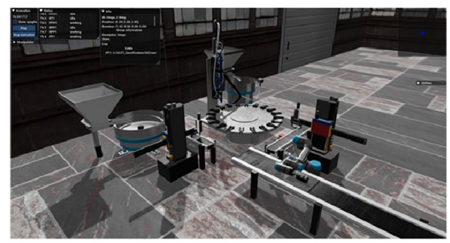
[13] https://virtualfactory.gitbook.io/vlft/use-cases/assembly-line.

Fig. 9 Multiple users with avatar in the virtual environment

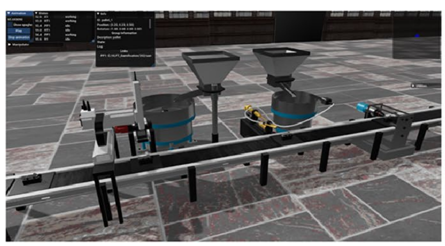
Fig. 10 Example of animation sequence in the assembly line



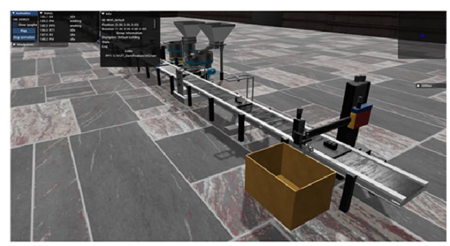
(a) Sequence step 1



(b) Sequence step 2



(c) Sequence step 3



(d) Sequence step 4

Table 3 Verification of the user experience requirements

Requirement	Verification of the requirement
R.8 Perspective	A user with teacher role can manage and track the perspective of students via the *Student control* panel (Fig. 9)
R.9 Information retrieval	An item can be selected to retrieve information about its properties and state. These are displayed in the *Info* and *States* panels, and can be edited in the *Manipulator* panel (Fig. 8)
R.10 Navigation	A virtual camera is associated with each user in the VE to enable free navigation with a personal point of view. Additional features can be enabled from the *Utilities* panel, e.g., map display, screenshot capture (Fig. 9)
R.11 Animation interaction	The animation is controlled by the *Animation* panel (Fig. 8)
R.12 Trajectory visualization	A trail display mode can be enabled to show and track with a red line, while the animation is being played, the trajectory of a selected item (Fig. 11)
R.13 Live communication	In multiplayer mode, users can communicate using the *Chat* panel (Fig. 9)
R.14 Avatar	In multiplayer mode, users are visualized as low-poly, human-shaped avatars (Fig. 9)

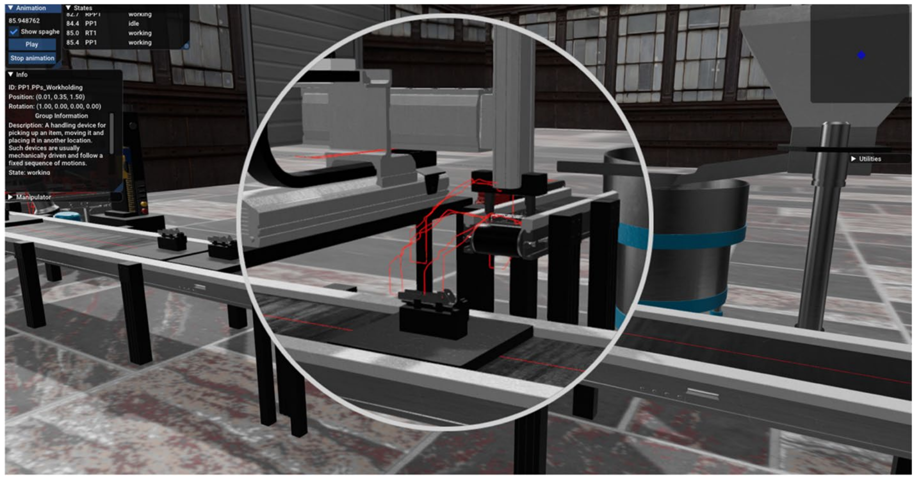


Fig. 11 Trail display

up to the level of detail that is needed for animations (R.7) and the reuse in modular assemblies. The 3D models have been further detailed with the addition of a material library consisting of PBR texture sets (including several types of maps like diffuse, roughness, normal, and displacement) that can be applied in a software tool that manages the import and export of glTF files (e.g., Blender[14]).

5.4 Technology and digital tools

The reconfigurable VLFA is the main technology that enables the implementation of the overall framework. As presented in Sect. 4, VLFA is an open (R.16) VR-based (R.15) reconfigurable (R.17) and model-driven (R.18) tool. Indeed, VLFA provides access to multiple rooms (Fig. 6), each instantiating the application with different settings, scenes and gameplay.

Based on the configuration presented in Sects. 5.1, 5.2, and 5.3, it is possible to visually demonstrate that the VLFA provides users with a realistic representation (R.3) of the assembly line (Fig. 7), including relevant details (R.4). For example, Fig. 8 shows a hinge component on a rotating table. Multiple users (R.6) can act and interact in the same virtual environment (Fig. 9), providing an immersive experience with the dynamic behaviour of the system (R.7) (Fig. 10). The remaining requirements to be assessed are those related to the user experience (Sect. 3.4). Table 3 reports the verification of these requirements.

Besides the VLFA, other digital tools have been used in the scope of the framework. The presentation of the game challenges and the derived assessment have been implemented taking advantage of digital forms to be filled (e.g., *Microsoft Forms*[15]) providing a wide range of functionalities for the definition of questions to be asked and the assessment of the replies. Different classes of questions have been used, e.g., numerical, multiple-choice, assigning labels in a picture, select the right words in a sentence. The JSON file of the VE have been automatically generated from an ontology-based formal model (Urgo and Terkaj 2020) by using *OntoGui*[16] (Terkaj 2017).

5.5 Feedback from users

The described framework (Sect. 3) has been leveraged for the development of a reconfigurable Virtual Learning Factory Application (Sect. 4), exploited in learning activities involving engineering students. This section presents an analysis of feedback collected from both the users of the VLFA application (i.e., engineering students) and the teachers who designed the learning activity and implemented it exploiting the reconfigurable VLFA. As per such, student feedback focuses solely on the VLFA, while teacher feedback also covers the framework.

5.5.1 Feedback from students

The serious game (Sect. 5.2) was tested by university students during the activities of the Erasmus+ Virtual Learning Factory Toolkit (VLFT) project (Mahmood et al. 2021b). Specifically, 16 university students attending Politecnico di Milano and TalTech University were grouped into four heterogeneous teams to carry out the serious game (Urgo et al. 2022) relying on VLFA (Sect. 5.4) and the presented industrial case (Sect. 5.1). After completing the tasks of the serious game, questionnaires were administered to evaluate various aspects related to the learning experience: perceived interest, perceived utility, and sense of presence and flow. These specific variables were chosen due to their known association with more effective learning outcomes (R.1). Additionally, participants were asked open-ended

[14] https://www.blender.org/.

[15] https://forms.office.com/.

[16] https://virtualfactory.gitbook.io/vlft/tools/ontogui.

questions to gather feedback on positive and negative aspects encountered during the experience. This feedback serves as valuable input for future developments and improvements in the application.

Interest is a driving force that fosters learning and plays a crucial role in academic achievement. It encompasses both a momentary psychological state of focused attention on a specific topic and a long-term predisposition towards that subject matter (Harackiewicz et al. 2016). Interest is closely related to intrinsic motivation and is often regarded as a measure of intrinsic motivation. Different theories explain intrinsic motivation and its functioning. While some experts argue that all behaviour is driven by external rewards (e.g., money, status, or food), other theories emphasize the importance of intrinsic motivation where the activity itself is the reward (Ryan and Deci 2020). In the context of this specific case, interest can be understood as the extent to which individuals perceive the activity of using the educational game to be personally enjoyable (Venkatesh et al. 2002). To evaluate the subjective experience of the participants while navigating in the virtual factory, some subscales of the Intrinsic Motivation Inventory (IMI) (Deci and Ryan 2004) have been adapted. In particular, the interest/enjoyment of the participants and the usefulness of the application have been evaluated. Both of the subscales consisted of seven statements, and the participant had to answer on a 5-point Likert scale the degree of agreement towards each statement.

Two other dimensions of the experience were assessed: the Sense of Presence, and the flow experienced. These two variables seem to be strictly connected to the motivation to perform a task (Lourenco et al. 2008; Özhan and Kocadere 2020). Witmer and Singer (1994) defined presence as the subjective experience of being in an environment other than the physical one in which one is actually located. To measure the sense of presence, three subscales of the ITC-SOPI questionnaire, namely spatial presence, realness, and involvement, were proposed by Lessiter et al. (2001). Flow, in the field of psychology, refers to a state of intense engagement, focus, and enjoyment in the activity at hand. Sometimes referred to as *in the zone*, flow states are known to enhance performance (Jackson et al. 2008). To assess the flow experienced, the Short Flow State Scale (Jackson et al. 2008), formed by 9 items, was used.

Furthermore, five open-ended questions were presented to the students:

- Which aspect of the serious game (both virtual environment and assigned tasks) did you find enjoyable or engaging?
- Were there any aspects you found boring or did not enjoy?
- Why do you think such an activity could be useful or not useful to an industrial engineering student?
- How could this virtual environment be more useful for a student?
- In your opinion, what aspects strictly related to the virtual environment (not to the task performed) - for example, graphics, sounds, colours, etc. - have diminished or increased the realism of the environment itself?

Participants reported moderate interest and high perceived usefulness with respect to the navigation experience in the environment, obtaining an average score of 3.77 ± 0.92 and 4.27 ± 0.68 on the relative scales. As regards the sense of presence, the ITC-SOPI scales obtained an average score of 3.16 ± 0.23 (*spatial presence*), 2.27 ± 0.65 (*involvement*), and 2.34 ± 0.82 (*realness*), while the flow was scored 3.77 ± 0.69. All scores are to be interpreted in a range from a minimum of 1 to a maximum of 5.

These results can also be interpreted in light of the answers to the open-ended questions. Regarding the aspects that involved and interested the participants the most, two aspects were underlined: the possibility of freely exploring the environment ($N = 4$) (e.g., “I liked the possibility of approaching the machines with a very high level of detail in the VR environment”), and the animations ($N = 8$) (e.g., “The animation part is the most interesting part because you can see the dynamics of the factory”).

However, the students criticized some aspects always related to the animations ($N = 3$) (e.g., “I found the processes too repetitive, there was no cobot working with an operator or an AGV/Drone as a transfer system”). This could explain the questionnaire’s scores of realism and involvement.

The participants emphasized various aspects that they found useful in the application. The answers mainly concerned the importance of visual exploration ($N = 8$) (e.g., “in reality it is difficult to see and examine each machine with endless time available, while here we can”, “you can approach something both school and university can’t show you”) and on the practical side of the experience (e.g., “if we do not take some experience like this one, our studies are too theoretical”, “It’s a very important experience to get in touch with concrete things, difficult to see and to learn in the university otherwise”). In addition, two students highlighted that carrying out activities in such a context would be more engaging than frontal lessons and that it is easier to remember concepts when they are experienced in person.

Concerning the improvements to be made (i.e., the last two open-ended questions), the students highlighted the issue of realism ($N = 5$) and immersion, especially since they would prefer to use the scenario through immersive virtual reality. This feedback can explain the rather low score of sense of presence. Finally, $N = 2$ students highlighted that it would be important to add sound within the virtual environment as well.

5.5.2 Feedback from teachers

As mentioned in Sect. 5.5.1, the framework has been used to support a serious game approach for industrial engineering (Sect. 5.2) in the Erasmus+ Virtual Learning Factory Toolkit (VLFT) project (Mahmood et al. 2021b), involving eight professors and assistants from the universities involved. Furthermore, the VLFA has also been used in four courses at Politecnico di Milano, addressing tools and methodologies for the design and analysis of manufacturing systems, both at the undergraduate and graduate level, and one laboratory course. Additional feedback related to both the framework and the use of the reconfigurable VLFA has been collected from the teachers involved in these learning activities. The list below summarises feedback related to the effectiveness of the learning activities:

Positive feedback

- XR technologies enable the implementation of virtual laboratory activities for cases and topics that traditionally required visits to external locations (e.g., a factory). This is a key enabler for students to be challenged to higher-level engineering problems (e.g., identify the bottleneck of a real production line) that usually required a pre-processing of the problem by the teachers, inevitably structuring or simplifying the original challenge.
- The VE serves as a sandbox for students, offering them a safe space to freely experiment and apply try-and-fail approaches without risking their safety or the integrity of the objects being studied.
- The use of XR technologies, together with significant levels of detail and realism, undoubtedly captivates the interest of students. This attraction may stem from the hype surrounding these technologies in recent years, as well as the novelty they offer compared to traditional university courses.
- The proposed framework and application enable autonomous learning activities of the students also ready to be used remotely and/or asynchronously.
- Learning in a virtual environment stimulates students to independently seek information, thereby linking what they find to a specific need to understand or know something, which generally enhances the effectiveness of their learning experience.

Negative feedback

- While XR technologies initially spark excitement and engagement due to their novelty, this enthusiasm often wanes over time, reverting to conventional patterns of behaviour, characterised by fluctuating attention levels and capability to go beyond the surface level of knowledge.
- The distributed organization of information and knowledge within the virtual environment (e.g., associated with the different objects in the virtual factory) presents a challenge for students in identifying and acquiring all relevant information. As a result, students may lack certainty about the completeness of their knowledge acquisition, highlighting the importance of instructional design and guidance within virtual learning environments.

Additional feedback has been collected for the specific technical characteristics of the framework and the developed VLFA:

Positive feedback

- The reconfigurability and modularity of the VE and its associated functionalities are essential for practical implementation in university courses. This enables the possibility of continuously enriching and improving the learning activities, differentiating the use cases and related details over the semesters and years, and allowing the teachers to leverage the same use cases with different levels of difficulty or details for multiple courses.
- The capability to force the point of view of all users in the scene to be the same as the teacher is a fundamental functionality to give instructions or indications in the virtual environment, thus enabling the possibility of delivering short lectures or demonstrations, ensuring that all participants are focused on the same content.
- The possibility of forcing the point of view of the teacher to match the one of a user provides a tool to deliver dedicated support to specific students. Coupled with messaging functionalities, this feature facilitates effective remote assistance and support to individual students.
- The availability of animations, and also the highlighting of trajectories of moving parts, is a powerful tool to understand the dynamic behaviour of a complex system (e.g., a factory). This significantly enhances the ability to understand dynamic systems, addressing barriers that are often more pronounced when using traditional learning approaches.
- The proposed framework and the VLFA provide students with the flexibility to interact with it through diverse technologies such as desktop computers, head-mounted displays (HMD) and operating systems.

Negative feedback

- The effort needed to set up a high-quality case in the virtual environment remains significant, even though VLFA takes advantage of a model-driven generation that can reuse digital models. Existing catalogues of equipment and technology providers could support this phase.The significant investment required for developing virtual learning activities underscores the importance of integrating such activities into a comprehensive revision of engineering curricula. By incorporating virtual learning experiences into curricula, educational institutions can maximize the utility of these tools across various levels of education, from undergraduate to graduate programs.

The prevailing sentiment of the feedback from teachers is positive, agreeing that incorporating firsthand experiences, particularly in a virtual setting, alongside traditional theoretical lectures can enhance the overall effectiveness of learning experiences in engineering education. The structure of the framework consists of systematic steps that contribute to a perception among educators that the approach is robust and effective in fostering student understanding and skills development.

The use of VLFA does not compromise the essential presence of the professor, maintaining a crucial connection between the virtual learning environment and the guidance of the teacher. Furthermore, the capability to utilize the application in multiplayer mode is deemed a significant educational advantage. This feature would facilitate group discussions, collaborative or competitive task assignments, and a multifaceted learning experience that extends beyond direct engagement, encompassing the valuable observation of behaviours and approaches of their peers.

Overall, the integration of the framework appears to be a valuable enhancement to the educational landscape, providing a dynamic and immersive learning environment for students in engineering courses.

Finally, educators have underscored the imperative of enhancing interactive experiences within the virtual environment. This entails providing a broader range of activities that enable students to modify and interact with various objects present in virtual settings. The emphasis is not only on quantity but also on quality, ensuring that these activities contribute meaningfully to the overall learning experience. By offering a more extensive array of actions and modifications, students can feel engaged, leading to more immersive and effective learning outcomes. The creation of diverse scenarios that dynamically respond to the actions of students can significantly enhance the unpredictability and adaptability of the virtual learning environment.

6 Conclusions

This article has presented a framework for the development of Virtual Learning applications aimed at supporting teaching/learning activities in industrial engineering higher education thanks to the exploitation of a realistic virtual environment. The work has addressed the framework for these applications, the definition of the requirements, the description of the development in terms of functionalities of the reconfigurable Virtual Learning Factory App (VLFA) and a final demonstration of its use for the representation of a manufacturing environment. Specifically, digital models and virtual reality technologies enable students to deal with real-world industrial problems that are normally impossible to manage with traditional learning approaches and tools.

The VLFA supports the implementation of a virtual laboratory (Reeves and Crippen 2021), i.e., an emulated physical laboratory delivered through digital technologies, offering students the capability to freely and safely interact with the environment through specific devices (e.g., keyboard, handheld controllers, etc.). Similarly to physical laboratories, virtual laboratories also enable students to test the acquired knowledge in specifically designed scenarios and situations, fusing relevant knowledge with the capability to exploit it. In addition, virtual laboratories supported by the VLFA provides teachers with the capability to design a complete learning activity, including the assessment, and deliver it to the students for remote and asynchronous use.

A crucial direction for the future developments of the VLFA is the implementation of functionalities enabling students to modify the virtual environment and directly experience the impact of these actions on the behaviour and performance of the factory. The VLFA already enables change in the placement of assets. Still, it would be valuable to let students change the route of the parts and assignments of operations, remove and add assets, rearrange the layout, etc. These extensions would move the experience from a *confirmation* laboratory towards an *open inquiry* one (May 2020).

A second direction for improvement relies on exploiting technological advances in virtual reality. Thanks to the plugin-based structure of ApertusVR, it will be possible to use a head-mounted display (HMD) to increase the realism and immersion of the experience.

Furthermore, existing digital factory technologies and approaches (Manzini et al. 2018; Terkaj et al. 2019) will automate and facilitate the design and development of realistic and significant use cases offered through VLFA.

Finally, the VLFA will better support self-learning and assessment with novel functionalities, providing students with 1) targeted information and/or suggestions based on what is being done and 2) the automatic assessment of basic exercises and tasks in the virtual environment.

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Data availability The industrial case supporting this study is openly available in a GitHub repository (Terkaj and Urgo 2024) (https://github.com/difactory/repository). Another GitHub repository (https://github.com/MTASZTAKI/ApertusVR) hosts the described software application. The authors confirm that the data, tools, and documentation supporting the findings of this study are available within the article and through the links provided in the manuscript.

Declarations

Conflict of interest The authors declare no conflict of competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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