Virtual reality in chemical and biochemical engineering education and training

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A B S T R A C T

With the advent of digitalization and industry 4.0, education in chemical and biochemical engineering has undergone significant revamping over the last two decades. However, undergraduate students sometimes do lack industrial exposure and are unable to visualise the complexity of actual process plants. Thereby, students might graduate without adequate professional hands-on experience. Similarly, in the process industry, operator training-simulators are widely used for the training of new and skilled operators. However, conventional training-simulators often fail to simulate reality and do not provide the user with the opportunity to experience unexpected and hazardous scenarios. In these regards, virtual reality appears to be a promising technology that can cater to the needs of both academia and industry. This paper discusses the opportunities and challenges for the incorporation of virtual reality into chemical and biochemical engineering education with an emphasis on the fundamental areas of technology, pedagogy and socio-economics. The paper emphasises the need for augmenting virtual reality interfaces with mathematical models to develop advanced immersive learning applications. Further, the paper stresses upon the need for novel educational impact assessment methodologies for the evaluation of virtual-reality-based learning. Finally, an ongoing case study application is presented to briefly discuss the social and economic implications, and to identify the bottlenecks involved in the adoption of virtual reality tools across chemical and biochemical engineering education.

1. Introduction

With rapid advances in technology, digital solutions are being widely embraced for teaching and for learning purposes (Quintero et al., 2019; Radianti et al., 2020). This includes the use of online learning platforms, interactive digital applications, and collaborative environments in education. Furthermore, the easy availability of portable digital devices including notebooks and smartphones fostered the digital embracement for education. Recently, immersive virtual environments are also being considered as a viable option for education and training owing to the availability, affordability, and rapid advancements in these technologies (Akkoyun, 2017; Jensen and Konradsen, 2018).

In academia, growing student numbers combined with the limited availability of physical resources is leading educational institutions to explore novel teaching alternatives that are, primarily, cost-effective in nature. Moreover, force-majeure situations such as the COVID-19 pandemic advocates for more educational robustness and distance learning options. Similarly, in industry, with increased automation and complexity of modern process plants, advanced training methods are becoming more desirable for the effective training of operators. In this regard, three-dimensional (3D) virtual reality environments, similar to those being used in the gaming and film industry, can be effectively utilised to generate learning environments (Schofield, 2012). Even though virtual reality is not a new technology, recent advancements have aroused increased interest among scholars (Akbulut et al., 2018). With the

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arrival of low-budget head-mounted displays (HMDs), immersive virtual environments are becoming more accessible for the purpose of education (Jensen and Konradsen, 2018).

Virtual reality (VR) can be defined as an interactive, three-dimensional (3D) computer simulation that seeks to immerse the user completely in an artificial environment (Bell and Fogler, 1996a; Pantelidis, 1997). In VR, a conscious effort is made to convince the user of being physically present in a virtual world (Bell and Fogler, 1997). Such perceptions are created with the help of advanced hardware components including HMDs and sensory devices (Bamodu and Ye, 2013). VR, and other mixed reality interfaces, provide an opportunity to deliver educational content that might not be easily possible when using traditional lecture-based education (Radianti et al., 2020). To date, VR technology has been widely deployed for developing visual training simulators for a wide range of industries, including virtual reality-based flight simulators, surgery-training simulators, and driving simulators (Schofield, 2012).

In the domain of chemical and biochemical engineering education, virtual laboratories are widely used for training of industrial chemists and undergraduate students in a safe and interactive environment (Shin et al., 2002; Villalba et al., 2008; Domingues et al., 2010). Such laboratories allow users to design and to perform virtual experiments effectively at a laboratory scale (Potkonjak et al., 2016). Virtual experiments usually require less time to setup and thus, allow users to conduct several experiments in a short period of time (Jong et al., 2013). For instance, Ramirez and co-workers (Ramírez et al., 2020) developed a virtual laboratory consisting of six experiments for an undergraduate course on chemical reaction engineering at the National University of Columbia. Similarly, Seifan and co-workers (Seifan et al., 2020) developed a virtual bioprocess engineering laboratory for the undergraduate chemical engineering students at the University of Waikato. Their virtual laboratory was developed as an open-source software and was designed to provide a basic understanding of fermentation technology. The authors reported that more than 90 % of the students found the fermentation laboratory effective for performing hands-on experiments virtually. de las Heras and co-workers (2021) evaluated the learning perception of undergraduate chemical and biochemical engineering students after replacing a physical fermentation laboratory with a commercial virtual laboratory. The study was performed at the University of Auckland in collaboration with the Technical University of Denmark. In their study a commercially available fermentation virtual laboratory provided by Labster, a web-based virtual laboratory, was used (LABSTER website, 2021).

Moving beyond small-scale virtual laboratories, there are a handful of studies involving industrial-scale plants for education in literature (Rahim et al., 2012; Schofield, 2012; Ouyang et al., 2018; Pirola et al., 2020). Even though there has been significant developments in the education sector, the undergraduate chemical engineering students are mostly unable to visualise the scale and complexity of actual process plants (Norton et al., 2008). Due to logistic constraints and associated financial expenses, it becomes difficult to conduct plant tours and industrial field trips for students on a regular basis. Moreover, students are not allowed to operate process equipment in a real plant. Therefore, undergraduate chemical engineering students often do not get the necessary exposure and the opportunity to apply process theory to real-world problems. Similarly, in the process industry, operator training simulators (OTS) are necessary for the training of skilled operators. However, the conventional training simulators fail to capture the realism and do not give operators the actual experience of various unexpected and hazardous scenarios (Manca et al., 2016; Fracaro et al., 2021).

VR seems to be a potential technology for chemical engineering education that can cater to the parallel needs of both university and industry. VR can be used to develop industrial-scale virtual practice platforms that would aid in improving the overall understanding of process plants (Ouyang et al., 2018). In addition, VR can be used to replicate potential scenarios including start-up, emergency shut down, unsafe and hazardous scenarios, which can be visualised and replayed multiple times in safe, guided, and cost-effective environments (Richmond, 2016; Gani et al., 2020).

Even though VR technology has been utilised for education over the past decade, a comprehensive review on its application for chemical engineering education does not exist in the literature. In the case of academia, Bell and Fogler (Bell and Fogler, 1996a) discussed the status and research prospects for virtual reality in chemical engineering education. This is the only literature overview that has been carried out in this domain to date. In the case of process industry, Patle and co-workers (Patle et al., 2019) extensively reviewed the contributions of VR for OTS from the year 2000 to mid-2017. However, the authors did not discuss the wider technological/ pedagogical challenges and overlooked the various mathematical models that may be present behind VR-based systems.

In this paper, a review is carried out on using VR for chemical engineering education, with a focus on applications in academia and in process industry. The paper will discuss the opportunities and challenges in the utilisation of VR for education with an emphasis on the key areas of technology, pedagogy and socio-economics. The paper will review the existing practices of educational impact evaluation for virtual reality in the chemical engineering industry. Further, it will discuss the wider pedagogical implications and the prospects for educational research in this domain. It is to be noted that the review will be applied to virtual-reality-based case studies, and not virtual laboratories, in light of the overall motivation of this work.

In terms of the structure of this paper, Section 2 reviews the literature, which includes a review on virtual reality for chemical engineering academia and for process industry training. Thereafter, Section 3 discusses technological opportunities, Section 4 discusses wider pedagogical implications, whilst, Section 5 addresses social and economic implications, for VR in education and training respectively. Finally, Section 6 presents the conclusions and the directions for future research.

2. State of the art

In this section, an exhaustive literature search is done to review the previous work and to identify research prospects for chemical engineering education and training. Google scholar and Scopus database were employed with the keywords "virtual reality", "immersive environment", and "head-mounted display" to analyse the current state of the art studies reported in the literature. In addition, the keywords "chemical engineering", "process systems engineering" and "unit operations" were used to screen the studies specific to the chemical engineering domain. Original research articles were reviewed without any particular emphasis placed on the publication timeline.

2.1. Virtual reality for chemical engineering in academia

Various studies can be found in the literature that have made efforts to bring real process plants to the university setting with the help of virtual reality technology. Some of these studies are reviewed in the forthcoming text.

The first known application of virtual reality for chemical engineering education was that developed by Bell and Fogler (Bell and Fogler, 1996b) in the department of chemical engineering at the University of Michigan in Ann Arbor. They developed a vir-

tual reality application, Vicher (Virtual Chemical Reaction Module), for chemical reaction kinetics and reactor design education at the undergraduate level. The module consisted of a welcome centre, two reactor rooms, and two microscopic exploration areas. The microscopic areas allowed the student users to observe the catalytic reaction mechanisms at a molecular scale.

Norton and co-workers (Norton et al., 2008) developed a virtual immersive environment to cater to the educational needs of both industry and university. They developed an interface based on spherical imagery of a real operating plant that was integrated with interactive learning activities. The interface was based on a Crude Distillation Unit (CDU) of BP's Bulwer Island Refinery in Brisbane, Australia. The immersive platform was developed by using high resolution industrial photography.

Herritsch (2011) developed a desktop-based virtual reality interface in the department of chemical and process engineering at the University of Canterbury, New Zealand. The interface was based on the skim milk powder processing facility of the Fonterra Co-operative Group, New Zealand. The application integrated and presented a browser-based 360-degree panoramic view, process flow diagram, and a 3D map of the milk powder plant. The VR interface was developed in Adobe Flash Builder, which can be easily used by the student users. Further, Rahim and co-workers (Rahim et al., 2012) assessed the usability of the same desktop-based interface by recruiting eight undergraduate students for a study. The authors report that the student users were satisfied with the virtual reality application since most of them found it really easy to learn and navigate. It is worth mentioning that during the recent times, low-budget VR headsets for mobile phones, such as Google cardboard, enables several users to experience similar browser-based virtual environments at the same time (Radianti et al., 2020).

Schofield (Schofield, 2012) developed a software, ViRILE (Virtual Reality Interactive Learning Environment), for undergraduate chemical engineering education. The software simulated the operation of a polymerisation plant that consisted of a reactor section and three distillation columns. The interface was developed based on process plant simulation data that was generated using steady state flow sheeting software (i.e. a commercial process simulator) and C++ programming. However, in this study, the authors do not discuss the educational impact of the proposed software on the student community.

Ouyang and co-workers (Ouyang et al., 2018) developed a virtual practice platform that included virtual section scenes of a chemical plant. The user has options to move around the plant, and to understand the structure and operation of various process equipment and pipelines. Further, they also evaluated the performance of the virtual platform by gathering feedback from the student users in the form of a questionnaire.

Pirola and co-workers (Pirola et al., 2020) developed a virtual immersive crude distillation unit (CDU) for undergraduate classroom education. The immersive platform allows the students to take a virtual tour of the plant and to get involved in time-bound interactive virtual exercises. Further, they also evaluated the educational impact of the project by conducting a test involving 22 questions on the theory of the CDU. The participants included 34 Bachelor degree students from the discipline of Industrial Chemistry at the University of Milan, Italy. The test was conducted both before and after performing the virtual exercises by the users. The authors report that the overall score obtained by the students doubled in the latter case followed by a strong positive feedback about the virtual learning platform.

The above studies show that virtual reality can be used to develop immersive learning environments for chemical engineering education. However, most of the studies do not discuss the educational impact of virtual reality on the undergraduate student community. The existing case studies only discuss the short-term benefits and ignore the wider implications. Therefore, novel methodologies are necessary for educational impact evaluation.

The software technologies that were employed for interface development in the listed case studies are summarised in Table 1.

2.2. Virtual reality for operator training in chemical industries

The role played by operators in chemical industries is becoming increasing challenging due to increased automation in modern plants (Patle et al., 2019). In this regard, OTS are widely used for training new operators and for refreshing the skills of existing operators (Manca et al., 2012a,b). Such training systems aid in enhancing the knowledge and the experience of industrial operators. However, the traditional two-dimensional OTS fail to provide a sense of realism to their users.

The virtual reality-based OTS supports the effective training of operators in a safe and supervised environment. Such systems can simulate demanding operating conditions, thereby training the operators to perform the corresponding operations at the plant. This includes exposure to noise disturbances, improper lighting conditions, and risky situations without jeopardising the plant operators (Manca et al., 2016). Moreover, such training simulators can be used to replicate various rarely-occurring scenarios including start-ups, shutdowns, and accidents (Manca et al., 2012a,b; Fracaro et al., 2021). In addition, virtual reality gives an opportunity to experiment coordination and communication that might involve a team of operators for task accomplishment (Nazir et al., 2012). Such training interfaces can also be developed to be multilingual, and can be utilised to train process operators in their preferred language (Patle et al., 2019).

Various studies can be found in the literature that have examined the role of immersive virtual reality systems for operator training. Some of these studies are reviewed in the forthcoming text.

Chen and Zhou (Chen and Zhou, 2012) developed a virtual reality-based pipeline simulation system for chemical process training. They proposed a data-driven simulation framework for the pipeline system. In addition, they also discussed the process path calculation method for a set of pipelines involved in the transportation of fluids. This system enables the process operators to visualise the process path update in a real-time virtual environment and enhances the training experience by allowing the operators to visualise the effects of fluid flow in addition to the 3D virtual view of the pipeline system.

Manca and co-workers (Manca et al., 2013) proposed the integration of a dynamic process simulator and a dynamic accident simulator within an immersive virtual environment for operator training. The authors applied the proposed framework to a case study involving the process of hydrodealkylation of toluene to benzene. They simulated an accident caused by a hole in the pipe that connected the toluene storage tank to the reaction section. The study demonstrated the effectiveness of the dynamic interface for hazard identification, education and training of industrial operators.

Manca and co-workers (Manca et al., 2014) proposed an automated assessment procedure for industrial operator training in a 3D virtual environment. It involves an automated computer algorithm which saves every result from a performance assessment module that dynamically tracks the operator. The authors also illustrated the approach with the help of a case study of a real polymerisation plant. The automated procedure can be used as a feedback mechanism to track the progress during operator training.

Luo and co-workers (Luo et al., 2015) proposed an integrated simulation framework based on virtual reality and dynamic process modelling. They developed a 3D model of an existing ethylene plant that could interact with the dynamic model and the asso-

Table 1
Overview of existing case studies for chemical engineering academia.

Process/ plant considered	Title of article	Software technology	Year	Reference
–	Vicher: A virtual reality based educational module for chemical reaction engineering	World ToolKit (WTK)	1996	(Bell and Fogler, 1996b)
Crude distillation plant	Development and deployment of an immersive learning environment for enhancing process systems engineering concepts	LiveStage Pro software	2008	(Norton et al., 2008)
Milk powder processing plant	A desktop virtual reality application for chemical and process engineering education	Adobe Flash Builder 4.0	2012	(Herritsch, 2011) (Rahim et al., 2012)
Polymerisation process plant	Mass effect: A chemical engineering education application of virtual reality simulator technology	C++ programming	2012	(Schofield, 2012)
Chemical process plant	A Unity 3D-based interactive three-dimensional virtual practice platform for chemical engineering	Unity 3D software	2018	(Ouyang et al., 2018; Unity Technologies, 2020)
Crude distillation plant	Immersive virtual crude distillation unit learning experience: The EYE4EDU project	Eyesim software	2020	(Pirola et al., 2020)

ciated control system. The interface allows the operators to walk through the virtual plant and to monitor the working of the units. Moreover, it facilitates operator training on alarms, controls and graphics that are similar to the actual chemical process plant.

These studies highlight that immersive virtual reality environments allow process operators to experience the actual feel of the plant conditions. Thus, the operators gain the necessary training to prevent accidents and to handle emergency situations in an effective manner. However, similar to the case of virtual reality in academia, the existing case studies do not propose a training assessment methodology to evaluate the operators. A standardised framework is necessary to evaluate the level of learning acquired by the operators. An overview of the existing case studies for operator training in chemical industries is presented in Table 2.

Following the literature review, opportunities and shortcomings have been identified in three fundamental areas for chemical engineering education. This includes the spheres of technology, education and socio-economics as depicted in Fig. 1.

In the technology sphere, virtual reality is primarily used in chemical engineering education as a visualisation tool for viewing 3D models of process plants. However, it can be augmented with a set of comprehensive mathematical models for advanced applications in an immersive environment. At the same time, the technological readiness of undergraduate students to embrace virtual reality tools for education is an important factor (Ismail and Hashim, 2020).

In the education sphere, the literature exposes two key issues. Firstly, it identifies the need to quantify the impact of virtual reality tools for chemical engineering education. Secondly, the literature draws attention to the purposeful application of virtual reality tools for specific groups of learners with different learning goals.

Finally, the limited number of examples from the literature suggests that there is a bottleneck in the adoption of virtual reality tools across chemical engineering education. The associated challenges are discussed under the wider social and economic implications.

This paper will address each of the above spheres in the sections that follow.

3. Technological opportunities and challenges

This section focusses on the technological opportunities and wider challenges involved in developing virtual reality tools for chemical engineering education. An overview of the generic virtual reality-based interface that can be developed and deployed

for chemical engineering education is shown in Fig. 2. Firstly, any computer-aided design (CAD) software is used to prepare three-dimensional models of different process equipment and operating environment. Further, commercial virtual reality software is used to create immersive three-dimensional virtual environments, for which the CAD model is given as an input. The virtually immersive experience can be enhanced with the help of accessories including virtual reality headsets and optical sensors. Further, the virtual reality interface can be augmented with mathematical models to develop interactive learning activities for the purpose of education as evident from Fig. 2.

3.1. Technological opportunities

As stated earlier, virtual reality is mainly used in chemical engineering education as a visualisation environment for viewing 3D models of process plants. Moving beyond visualisation, such tools can be augmented with mathematical models to enhance the immersive learning experience.

In the domain of chemical engineering education, specific applications of mathematical models include the virtual operation of dynamic process plants, the testing of hazardous scenarios, and, the simulation of potential explosions in a chemical reactor (Norton et al., 2008; Patle et al., 2019). In this regard, either first-principle models, data-driven models, or a set of hybrid models can be used to develop dynamic process simulations and interactive learning modules. An overview of the different modelling approaches and their key features for virtual reality-based systems is depicted in Fig. 3.

3.1.1. First-principle models

These models can be used to capture the real behaviour of process plants with the help of comprehensive thermodynamic property models and transport equations. Various studies have made use of first-principle models to enhance the educational capabilities of virtual reality-based systems in chemical engineering.

Schofield (Schofield, 2012) augmented a real-time mathematical model by using C++ programming to a virtual polymerisation plant. Further, an economics and costing model was integrated into the virtual reality-based system. Such simulated systems allow students to gain a better understanding and exposure to real processing plants.

Pirola and co-workers (Pirola et al., 2020) made use of the DYNSIM software by AVEVA to obtain the dynamic simulation of

Table 2
Overview of existing case studies for operator training in chemical industries.

Process/ plant considered	Title of article	Software technology	Year	Reference
Pipeline simulation system	Virtual reality-based chemical process simulation of pipeline system	Vega software	2012	(Chen and Zhou, 2012)
Hydrodealkylation of toluene to benzene	Bridging between virtual reality and accident simulation for training of process-industry operators	UNISIM	2013	(Manca et al., 2013)
Polymerisation plant	Procedure for automated assessment of industrial operators	–	2013	(Manca, Nazir and Colombo, et al., 2014)
Ethylene plant	Integrated simulation platform of chemical processes based on virtual reality and dynamic model	3D Max	2015	(Luo et al., 2015)
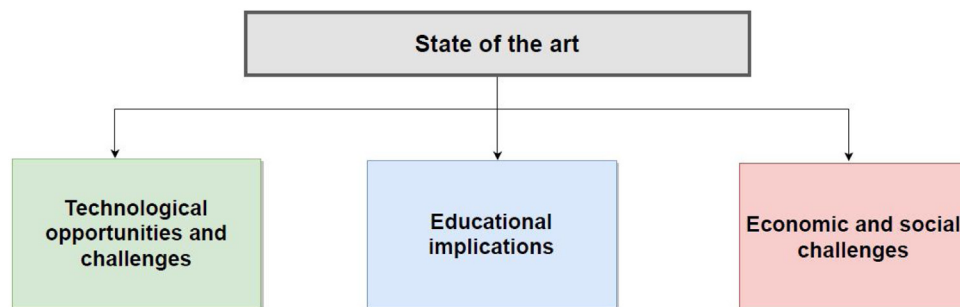
Fig. 1. Schematic diagram showing the identified spheres with research prospects for chemical engineering education.
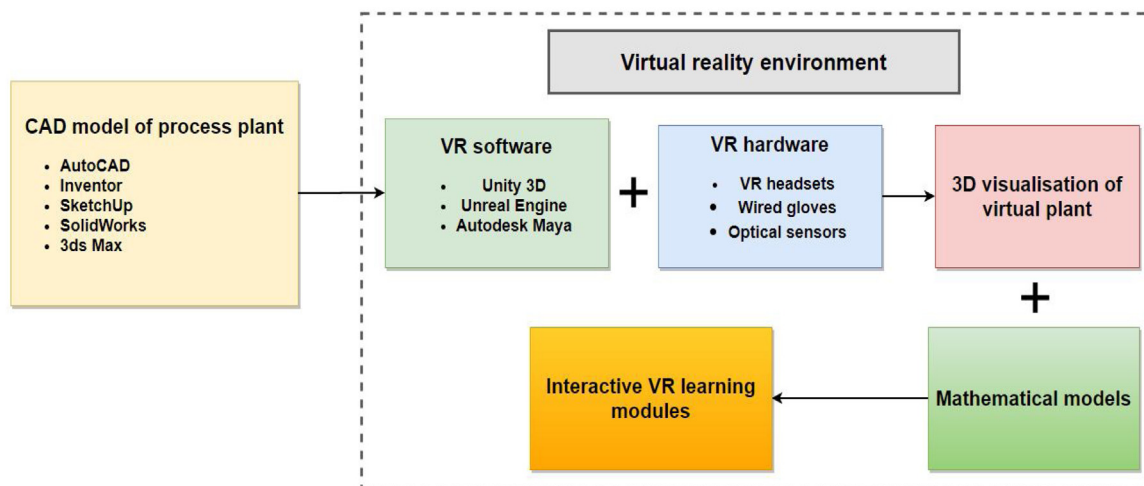
Fig. 2. Schematic diagram of virtual reality-based interface for chemical engineering education.
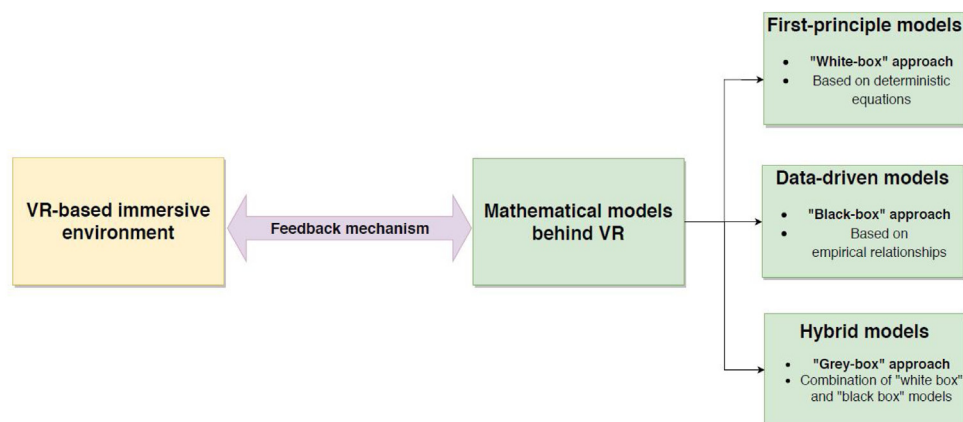
Fig. 3. Overview of different modelling approaches present behind virtual reality systems.

a virtual crude distillation unit plant. DYNSIM is a widely used software for modelling the dynamics of process plants with the help of first-principle models. The software includes mathematical equations representing the different unit operations, transport phenomena equations, and the thermodynamic models for the entire process plant.

3.1.2. Data-driven models

In recent years, there has been an increasing trend towards using data-driven models (also known as machine-learning models) in process engineering. One example of a data-driven model is a digital twin model. A digital twin is a virtual model of a physical process or a system, that can be used to monitor the physical entity in real-time (Wright and Davidson, 2020). Digital twins are widely used in industry as a process-monitoring tool for predicting faults and accidents, and for real-time optimisation of processes (Havard et al., 2019).

Such models can also be coupled with virtual reality systems to develop reality-simulated learning and training modules. The combination of virtual reality and digital twin technologies enables real-time data exchange between the actual process and the virtual replica. Therefore, such a co-simulation environment captures the behaviour of processes and can be utilised for predictive modelling studies (Min et al., 2019).

3.1.3. Hybrid models

Moving beyond the conventional first-principle models and data-driven models, it becomes necessary to develop hybrid models so as to effectively capture the complexity and uncertainty of real-world processes (Nielsen et al., 2020). Such hybrid approach often makes use of a combination of first-principle models and data-driven models to enhance the modelling capabilities of immersive process plants. The combination of models can be used to develop various realistic learning scenarios for testing by using virtual reality-based educational systems.

It is to be noted that the output from mathematical models are often quite abstract in nature. In this regard, virtual reality can be augmented with mathematical models to enhance the immersive learning experience. It is worth noting that first-principle models can be used to simulate the real behaviour of process plants. On the other hand, simulating virtually unsafe scenarios and the prediction of process equipment faults can be better captured whilst using data-based models.

3.2. Technological challenges

Virtual reality technology is at an early stage of adoption in the domain of chemical engineering education. Some of the associated technological challenges are discussed below:

(1) Technical skills: The development of a virtual reality-based learning environment requires additional skills and resources, therefore, the implementation of such learning environments as part of undergraduate process engineering education necessitates human expertise in game design and development along with a background in chemical engineering.

(2) Technical maintenance: Long-term continued utilisation of such tools for the purpose of education would require regular hardware maintenance and software support. This necessitates the active engagement of chemical engineering educators with computer scientists and researchers, or with outsourced service providers.

(3) Technical functionality: Education using virtual reality technology requires advanced hardware and computer systems. Therefore, the unavailability or failure of such devices may hamper the intended learning experience designed by the teachers (Ismail and Hashim, 2020).

This section has emphasised the need for augmenting virtual reality tools with mathematical models for advanced educational applications, which would allow the users to view the model and the modelling output in a virtually immersive environment. It also highlighted few technological challenges, primarily related to system construction and maintenance, that may hinder the ability of an educational institution to deliver virtual reality learning solutions on an ongoing basis.

4. Educational implications

The wider pedagogical implications of virtual reality for chemical engineering education are discussed here. Virtual environments are being widely employed in educational settings, with studies showing potential teaching and learning benefits resulting from the utilisation of such environments (Quintero et al., 2019; Lanzo et al., 2020). Furthermore, interactive virtual reality-based environments can offer greater benefits due to the active rather than passive mode of learning (Schofield, 2012; Abdelaziz et al., 2014).

In the domain of chemical engineering education, the use of virtual reality is expected to have the following noteworthy benefits:

(1) Students or operators can access the virtual interface without any space and time related constraints. In addition, it allows the user to control the movement of the virtual camera within the interactive learning environment (Schofield, 2012). This permits the users to learn at their own pace unlike in a real process plant.

(2) In the case of a virtual process equipment (see Section 5), it is possible to 'cut' open and observe the internal operations of the equipment. This might not be practically feasible while using a real physical equipment. A real equipment is often insulated and thus, it can be viewed only as a 'black box' piece of equipment, as evident from Fig. 4.

(3) Virtual reality allows the users to learn in a safe, controlled and risk-free environment. This includes replaying and experiencing various unsafe and hazardous scenarios. This might not be practically feasible by using a real chemical plant.

(4) Process operators can experience various what-if scenarios that requires teamwork and coordination (Passos et al., 2016; Kolomaznika et al., 2017). This can be achieved by creating virtual avatars or digital representations of operators to experience teamwork during virtual plant shutdown, emergency, and evacuation scenarios (Lin and Wang, 2014; Ouyang et al., 2018). Similar multiplayer activities also make the undergraduate students more equipped to take up industrial positions after their graduation.

(5) Development of the learning content can be better, faster and continuously updated by using active student involvement not only as users, but also in planning and creating the necessary content. This allows the teaching activities to reach significantly higher levels of Bloom's taxonomy (Bell and Fogler, 1997; Churches, 2008). The skills acquired from learning at higher levels of Bloom's taxonomy are increasingly important in the present context, where information is easily accessible, while active planning and creative utilisation of that information are even more desirable skills, not least in a chemical engineer. For example, developing a library of chemical process design attempts in the virtual environment, including successful and failed attempts, would be beneficial to both the student and the teacher.
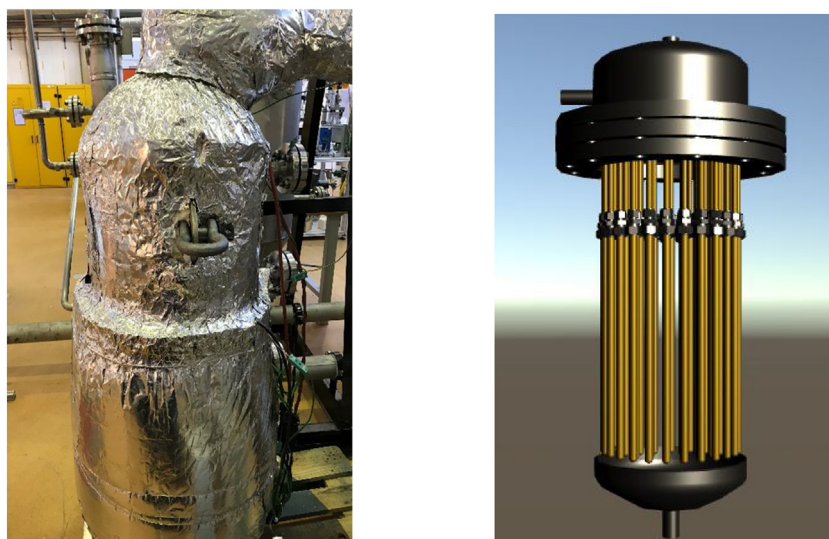
Fig. 4. Students' view of the (a) real membrane reactor and (b) virtual membrane reactor.

(6) A VR environment provides excellent opportunities to make use of peer instruction (Mazur, 1997), as students' VR creations (e.g. a chemical process design) can be made completely anonymous and evaluated by the student peers. This reduces the teacher load while increasing the student learning, e.g. as assessed by higher levels on Bloom's taxonomy (Churches, 2008). Peer instruction has also been demonstrated to minimise differences between students with different educational backgrounds (Lasry, 2008), which enables an efficient mode of teaching particularly at the postgraduate level, where the student base is typically quite varied and international.

At the same time, there are certain drawbacks associated with virtual reality-based education, as discussed below:

(1) VR might not be an appealing educational platform for all users. For instance, it might not be feasible for those users who are unable to appreciate any type of learning that involves interactive educational activities (Seifan et al., 2020). For such users, immersive VR might only be able to create situational interest on a topic and may not encourage deeper learning (Makransky et al., 2019)."

(2) Another drawback is that the use of virtual reality devices such as HMD could cause physical discomfort including cyber sickness, nausea, headache, and eye strain to the users (Lanzo et al., 2020; Weech et al., 2020). This might also distract the users and could negatively impact the immersive pedagogical experience.

The review of the existing case studies in the literature has exposed the following pedagogical issues:

(1) Most of the case studies do not analyse the educational impact of virtual reality on the undergraduate student users. Similarly, the existing studies do not propose a training assessment methodology to evaluate the industrial operators. As evident from Section 2.1, most of the studies only discuss the short-term benefits of using virtual reality and try to overlook the wider implications. Therefore, novel methodologies are necessary to evaluate the educational impact of virtual reality on the user community. The long-term learning benefits and the limitations of using immersive environment in comparison to traditional classroom-based education needs to be examined further.

(2) It is necessary to examine the impact of case study applications on specific groups of learners with different learning goals. For example, undergraduate chemical engineering students generally have a good theoretical background but often cannot visualise the scale and complexity of actual process plants. Meanwhile, process operators have a good knowledge of operations but lack a deeper theoretical understanding of the reasoning behind the processes. It can also be noted that most of the studies overlook the prospects of utilising the same immersive virtual environment that can cater for the educational needs of both academia and industry. For instance, both undergraduate chemical engineering students as well as process operators have a general liking towards visual explanations rather than traditional text-based learning (Norton et al., 2008).

Thus, virtual reality, being an emerging technology, has pedagogical challenges that needs to be addressed. At the same time, education using such virtual environments can prevent damage to real process equipment and avoid wastage of materials during the process of learning. Moreover, virtual reality allows training in hazardous situations without jeopardising the well-being of students and plant operators.

The educational impact of VR learning tools has only been partially explored so far. It is worth mentioning that traditional learning design has been used for decades and indeed centuries, while VR educational design is still in its infancy. In addition to enabling training in situations that would otherwise be harmful and/or entail material wastage, VR educational design enables interactive visual learning experiences, which are almost impossible with traditional learning design for various reasons. For example, in virtual environments students can have experiences that are physically impossible such as visualising and manipulating very small objects (e.g. molecules or cells) or very large objects scaled up or scaled down (e.g. a full scale chemical process plant) so that it becomes easier to explore and to understand. In addition, such environments allow the students to have unlimited repetition of procedures and tasks to be learned, such as standard operating procedures (SOPs) or safety procedures, which is not possible in traditional learning design due to practical constraints. Finally, virtual and digital learning environments can cater to a wide range of student users unlike traditional learning environments. For example, while traditional learning environments in engineering primarily accommodate engineering students, virtual reality learning can

Table 3
Cost breakdown for the virtual reality hardware.

Component	Model description	Unit Price (in Euros)	Reference
Virtual reality system	HTC Vive Pro Full Kit (includes Vive Pro Eye headset, link box, two Vive hand controllers and two SteamVR base stations)	1219	(HTC, 2021)
Gaming desktop CPU	Dell Aurora R8 Base - Core i9 9900 K, (3.6 GHz,8C) - 64GB - 1TB SSD - 2TB	3695	(DELL, 2020)
Desktop monitor	Dell Alienware 25 Monitor - AW2518 G - 63.5CM	425	(DELL, 2020)

also accommodate younger students, lifelong learners, as well as students that cannot physically access, or cannot afford, traditional learning environments. The societal impact of this democratising feature of the virtual learning experience is yet to be assessed. Therefore, further research is needed to evaluate the wider educational impact of virtual reality on the student user community.

5. Economic and social challenges

The inclusion of virtual reality for education is expected to provide additional learning and training benefits, as discussed in the previous section. However, the additional benefits come along with additional costs for developing the virtual environment (Patle et al., 2019). Since virtual reality is an evolving mode of education, it becomes necessary to discuss the wider social and economic implications on the user community.

This section touches upon the social and economic implications of virtual reality for education with the help of an ongoing case study application. In work progressing at the Eindhoven University of Technology in the Netherlands, a virtual reality model of an existing fluidised bed membrane reactor is being developed as an executable program that can be run on a personal computer. The key objective of this case study is to develop a virtual reality platform that can be used for teaching and training of undergraduate chemical engineering students at the university. Further, virtual reality headsets along with hand controllers are used to experience the immersive learning environment. An overview of the existing real membrane reactor at the university laboratory and its corresponding virtual reality twin is shown in Fig. 4.

The development of the virtual membrane reactor requires advanced hardware as well as gaming software. The associated capital expenses can be split into three components as follows:

(a) Cost for virtual reality hardware
(b) Cost for virtual reality software
(c) Human resource costs

The hardware for this study primarily consists of the desktop and virtual reality headset. The cost breakdown for the different hardware components is shown in Table 3. The interface is being developed using the *Unity 3D* game engine with the back-end programming done in C# language. Further, the *SteamVR Unity Plugin* is used to setup the hardware and software interface (Unity Technologies, 2021). The personal free version of *Unity* that is available for educational and non-business purposes is used for the interface development. It is to be noted that the license terms for the personal free version are very restrictive and becomes inconvenient particularly when a large team is involved in the development. Moreover, anyone else who wishes to work on the virtual interface would also need *Unity*. In this context, *Unreal Engine* can be regarded as an alternative to *Unity3D* for the interface development (Unreal Engine, 2021). Further, human resource is necessary to develop the virtual reality environment. For this purpose, a post-doctoral researcher and a research assistant are employed at the

Table 4
Human resource costs involved in developing the virtual reactor.

Component	Approx. total salary(in Euros)
Salary for post-doctoral researcher	65000
Salary for research assistant	3400

Table 5
Expenses associated with the case study application.

Component	Expenses(in Euros)
Overall cost for developing the VR environment	95095
Costs per student	4755

Eindhoven University. The associated human resource costs are provided in Table 4.

The long-term uninterrupted utilisation of virtual reality tools would also require operating expenses in the form of technical maintenance and software support. However, these expenses are difficult to quantify and are not presented in this paper.

This case study application assumes that there are 20 students in a classroom, divided into groups of 4 people. This would require five sets of VR hardware and five gaming desktops as shown in Table 3. The availability of multiple VR systems allow the student groups to experience and interact with the immersive virtual environment at the same time. The resulting overall expenses and the costs involved per student are presented in Table 5.

The virtual exercises that are being developed include a self-guided tour of the fluidised bed membrane reactor for hydrogen production, a piping and instrumentation diagram (P&ID) referencing interface, a virtually unsafe reactor scenario, and a technical quiz for learning evaluation. Further, teachers could gather the students' opinion about the developed virtual interface with the help of a survey. The different questions proposed as part of the survey are listed in Table 6.

It is worth noting that this is a generic case study application and the estimated costs would change on a case to case basis. Nevertheless, it provides an overview of the additional expenses involved in developing an immersive VR environment for chemical engineering education.

From an economic perspective, the availability of financial resources continues to be a major barrier for the massive adoption of VR for education. Most of the educational institutions have limited funding and are mostly reluctant to invest in expensive VR gadgets when compared to traditional classroom or laboratory-based learning (Fransson et al., 2020). Moreover, the cost-effectiveness of using VR for education is difficult to quantify and needs to be evaluated in terms of additional costs to additional benefits. However, the benefits or the returns of investment for education are yet to be quantified (Patle et al., 2019). One possible benefit is that learning with a virtual reactor, for example, does not require the use of actual chemicals. Therefore, such education helps to avoid undesirable wastage of chemicals. In addition, the users can interact with the virtual model multiple times, making it ideal for the purpose of operator training.

Table 6
List of questions proposed in the feedback survey.

Question	Opinion (Strongly agree = 4, Agree = 3, Neutral = 2, Disagree = 1, Strongly disagree = 0)
Could you clearly visualise and understand the different parts of the membrane reactor that was taught earlier in the classroom?	
Do you believe that the VR interface improved your understanding of the membrane reactor when compared to the real reactor in the laboratory?	
Do you feel that audio narration would improve the learning during the self-guided tour?	
Did you experience any sort of physical discomforts such as nausea, headache, or eye strain while using the VR hardware?	
Do you think that VR can be used as an alternative mode of education at the Eindhoven University during the COVID-19 pandemic?	
Do you believe that a hybrid model involving traditional classroom learning, hands-on experiments, and VR exercises would be the best possible approach for education?	

There is a lot of cross over in terms of the social and pedagogical benefits of VR-based education interfaces. The ready accessibility and availability of VR teaching interfaces is one such example.

At the same time, there are certain social challenges associated with the slow adoption of VR tools for education.

1. The readiness of teachers and students to embrace new technologies for education is a key challenge. An assessment of user readiness for technology-based classroom learning is necessary before the implementation of immersive virtual environments for education. This is also important to ensure long-term motivation for using virtual reality among the learning community.
2. The embracement of such technologies might also require redesigning of courses/ modules, changing content delivery methods, and learning of new digital skills by the educators.
3. The easiness for addition, modification and replication of educational content will determine the successfully implementation of the VR platform across different courses.

This section has touched upon the social and economic implications of virtual reality for education with the help of an ongoing case study. The development of any virtual learning environment for training incurs additional expenses. At the same time, there are noteworthy benefits associated with the deployment of virtual reality for education. In this regard, case studies to assess whether the benefits outweigh the cost would offer additional insights. There are also associated social challenges, including the need for on-boarding strategies and additional skills, that might otherwise prevent the adoption and utilisation of virtual reality tools for education.

In the near future, the virtual membrane reactor, referred to above, will be tested with a view to qualifying its value for undergraduate chemical engineering education. During testing, it will be compared with laboratory experiments performed in a real reactor, which can be documented using the traditional laboratory notebook concept. The level of learning will be assessed by conducting a technical quiz on the membrane reactor before as well as after performing the virtual exercises. Further, a methodology will be developed to evaluate the educational impact of virtual reality on the undergraduate student community.

6. Conclusion and future directions

The paper reviewed the state of the art in virtual reality technology for chemical engineering education. The review highlights that there is an increasing scholarly interest towards utilising virtual reality in chemical engineering academia and in industry. Various studies have made efforts to develop virtual process plants that can cater to the educational needs of both industry and academia. The paper identified opportunities and shortcomings in the fundamental areas of technology, pedagogy and socio-economics for virtual reality-based education. The paper emphasised the need for augmenting virtual reality interfaces with mathematical models and discussed the modelling approaches present behind such systems. Further, the paper identified the major pedagogical strengths and limitations associated with such education. The paper also stressed upon the need for novel educational impact assessment methodologies to evaluate virtual-reality-based learning. Further, a case study was presented to discuss the social and economic implications, and to identify the bottlenecks associated with the slow adoption of virtual reality tools across chemical engineering education.

The review has the following limitations due to the reduced scope. Firstly, the review focussed on virtual reality-based case studies rather than just virtual laboratories. This was done due to the overall research motivation for this paper. Another weakness is related to the quantification of learning outcomes for the different case studies. Almost all the studies evaluated the learning only in terms of user feedbacks on different virtual reality accessories and the virtual environment. Finally, all the studies had a strong bias towards the positive aspects of virtual reality in chemical engineering education. Therefore, it was difficult to discuss the drawbacks of existing case studies. Nevertheless, the above limitations do not diminish the value of this paper, and in fact, highlight the opportunities for future research in this field. As part of the future work, the following recommendations are made.

Firstly, a quantitative cost versus benefit analysis could be carried out. In this regard, the training benefits can be quantified in terms of the avoided financial costs resulting from plant failures and shutdowns owing to poor training of the users. The capital expenses and the monetary benefits can be used to determine a cost to benefit ratio for the virtual process and for the real process. This ratio would aid in decision-making between the two modes of education from a socio-economic perspective.

Secondly, virtual reality-based education has certain strengths and limitations as discussed in Section 4. For example, it cannot be used to directly display and visualise mathematical formulations. In such situations, traditional classroom-based approach becomes more effective. On the other hand, traditional learning might not be engaging and inspiring enough for students to attend classroom lectures. Therefore, future case studies should explore options that utilise a combination of traditional classroom-based learning and virtual reality-based learning. This kind of a hybrid approach would help to reap benefits from both modes of education.

Finally, it can be concluded that virtual technologies have become more promising during the COVID-19 pandemic (Magalhaes, 2020). In this regard, virtual reality can be regarded as a powerful tool for remote learning in chemical engineering education. For instance, Seifan and co-workers (Seifan et al., 2019) developed a virtual field trip for the undergraduate students of

engineering biotechnology course at the University of Waikato. It is acknowledged that such experiences cannot replace physical industrial field trips. However, such virtual technologies are the best possible alternatives during situations where the real experience is not practically feasible.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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