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Immersive technologies for the training of operators in the process industry: A Systematic Literature Review

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Abstract

Immersive technologies aim to improve crucial process and safety training by increasing motivation, engagement and skills development. A Systematic Literature Review (SLR) was performed to identify immersive technologies applications that have been published in the past twenty years and aimed to enhance the training and learning of operators in the process industry, with special emphasis on the chemical industry. A set of 44 articles was obtained following the PRISMA framework with backward and forward snowballing. They were examined based on type of training, industry and technology. Only very few studies (10 out of 44) reported a comparison of immersive and traditional training. Six performance indicators (time; number of: mistakes, hints and instruction repetitions; events and equipment identification) were named to evaluate the immersive experience. To allow for a consistent analysis of the quality of immersive training in future studies, an effectiveness-efficiency model from the trainee viewpoint is proposed.

Keywords

Operator training; Process industry; Immersive technologies; Procedure and emergency training; Performance indicators; Effectiveness and efficiency.

1. Introduction

In the process industry, operators must receive appropriate and up-to-date process and safety training, as it is an industry with a permanent characteristic: risk (Srinivasan et al., 2019). This risk could jeopardize the safety of the operators, the plant, the general population of the surrounding area and the environment, but also the quality of the product and the productivity. Besides the need for safe operation and business continuity, the process industry is also recognized by the complexity of technology (Nazir et al., 2012). Therefore, there is a need for regular training that prepares the plant operators for their tasks. Operator training ensures business continuity and on the other hand, operator training should guarantee the safe operation of the installation and the correct response to unsafe situations.

There is a need for regular training that prepares the plant operators for their tasks, provides the necessary knowledge on how to perform their work safely, and on how to respond to unexpected events and to prevent them from escalating into accidents or incidents (Brambilla and Manca, 2011; Nakai et al., 2017; Rosero et al., 2018; Sangaran and Haron, 2017). Traditional training approaches include classroom lectures, e-learning packages, hands-on training in a pilot plant, and, in some cases, computer simulations (Kluge et al., 2014). Training based on lectures sometimes does not provide an engaging and challenging experience which could decrease the effectiveness of the content internalisation (Avveduto et al., 2017; Leder et al., 2019; Tatić and Tešić, 2017). In addition, the lack of realistic training when it comes to emergency situations is another important reason why the industry is changing the way training is conducted. The opportunity to conduct experiential learning with hazardous and abnormal situations could help operators to acquire a better understanding of the process and train for swift and adequate responses to (unsafe) process deviations and emergencies (Kluge et al., 2014). In order to better deploy inevitably limited resources for training and to direct them towards the most effective and efficient methods, it is important to understand the breadth of the training approaches in process industries, their advantages and limitations.

An increasing number of research projects, based on the process industry needs, is investigating the implementation of advanced immersive technologies in training as immersive technologies allow training to be conducted online or remotely. Immersive technologies give their users "the subjective impression that they are participating in a comprehensive and realistic experience" (Dede, 2009). As previously expressed in the CHARMING Policy Brief, "there are different types of immersive learning environments and they can leverage different types of immersive technologies. These technologies differ depending on how the user interacts with the experience: for example, augmented reality (AR) technologies overlay digital elements on top of the real world, and virtual reality (VR) on the other hand completely immerses the users in a virtual world with no parts of the real world visible" (Garcia Fracaro et al., 2021c).

The research reported here was conducted in the context of the EU Horizon 2020 CHARMING project, an inter-sectoral and interdisciplinary *European Training Network for Chemical Engineering Immersive Learning* (https://charming-etn.eu/), which is aiming to answer, as one of its research questions, how immersive technologies can support the chemical process industry to motivate and train employees. Specifically, one of the aims is to develop learning strategies, content, and immersive technology prototypes that can enhance the learning experience, supporting the workforce training crucial to motivate and teach current and future employees (Toyoda et al., 2021). This paper will thus limit its remit to training in process industries as related areas of education at various levels are explored in detail within other areas of the project and other literature reviews.

In order to develop immersive technology experiences that enhance the current training in the chemical industry, it is important to identify already implemented applications, to study their impact in the industry and to identify the conclusions of including immersive technologies for training. But, as Kumar et al. (2021) report, there is a limited number of studies that explore, among other aspects, the effectiveness and feasibility of immersive technology applied to training. That is why this paper aims to review the scientific literature on the use of immersive technologies that have been implemented and/or tested to enhance the training and learning of operators in the process industry. Immersive technologies are becoming more and more popular in society and industry, but often without proven evidence of performance. Therefore, this paper explores evidence that is published in peer-reviewed scientific literature.

A Systematic Literature Review (SLR) was conducted according to PRISMA (Moher et al., 2009). First, the immersive technologies are defined within the context of the work carried out here. To facilitate the discussion and to identify the evolution and current status, the selected publications are categorized based on the technology used, the content of the training, and the industrial sector considered. This overview answers the principal question "To what extent have immersive technologies been implemented?" The second question that arises is "Are immersive technologies increasing the effectiveness and efficiency of the training of operators in the industry?". To answer this question, effectiveness and efficiency indicators were identified from the selected papers. Based on these indicators, a novel effectiveness-efficiency model is proposed, which may serve as a baseline for future assessments of immersive technologies applied for the training of process operators.

The CHARMING project focuses on the chemical industry, but to report a broader analysis of the current state-of-the-art this Systematic Literature Review will include immersive technology training solutions reported in the process industry.

The paper is structured into six sections. The SLR methodology section explains in detail how the search for relevant publications was conducted, including the search terms, the inclusion and exclusion criteria. Section 3- SLR Results presents the search results, explaining the number of papers selected. Section 4- provides an analysis of the selected publications divided into categories: immersive experience, training, and industry. In section 5- the performance indicators presented in literature are collected and a proposed model to evaluate the effectiveness and efficiency of immersive training experiences is described, considering performance indicators and training phases. Finally, section 6- reports the review conclusions and highlight future research work.

2. Systematic Literature Review methodology

The Systematic Literature Review (SLR) presented in this paper follows the general structure of the PRISMA framework (Moher et al., 2009), including four main phases: identification, screening, eligibility, and inclusion. In Table 1, a definition of each phase is presented. As a result of the systematic review, *included papers* were identified, and a snowballing phase was performed to identify additional publications (Wohlin, 2014). The snowballing phase included a backward and forward search in Google Scholar ("Google Scholar," 2020). For the backward snowballing, the criteria were applied to the reference list of the *included papers*. In the case of the forward snowballing, the search included all papers that cited the *included papers.* In both procedures, the search was performed on a *Title & Abstract* basis, followed by a full-text analysis considering the inclusion and exclusion criteria applied to the original set of publications. The general methodology workflow is presented in Figure 1.

Table 1 – PRISMA phases used in systematic literature review methodology (adapted from (Moher et al., 2009))

Phases	Definition
Identification	String search in various databases, general inclusion criteria, and elimination of duplicates.
Screening	Title and abstract evaluation based on inclusion criteria.
Eligibility	Full-text evaluation based on inclusion criteria
Inclusion	Full-text papers selected plus snowballing papers selected.
Snowballing	Identification of additional papers from the citation of selected papers during the first search. This phase includes a backward and forward snowballing process.

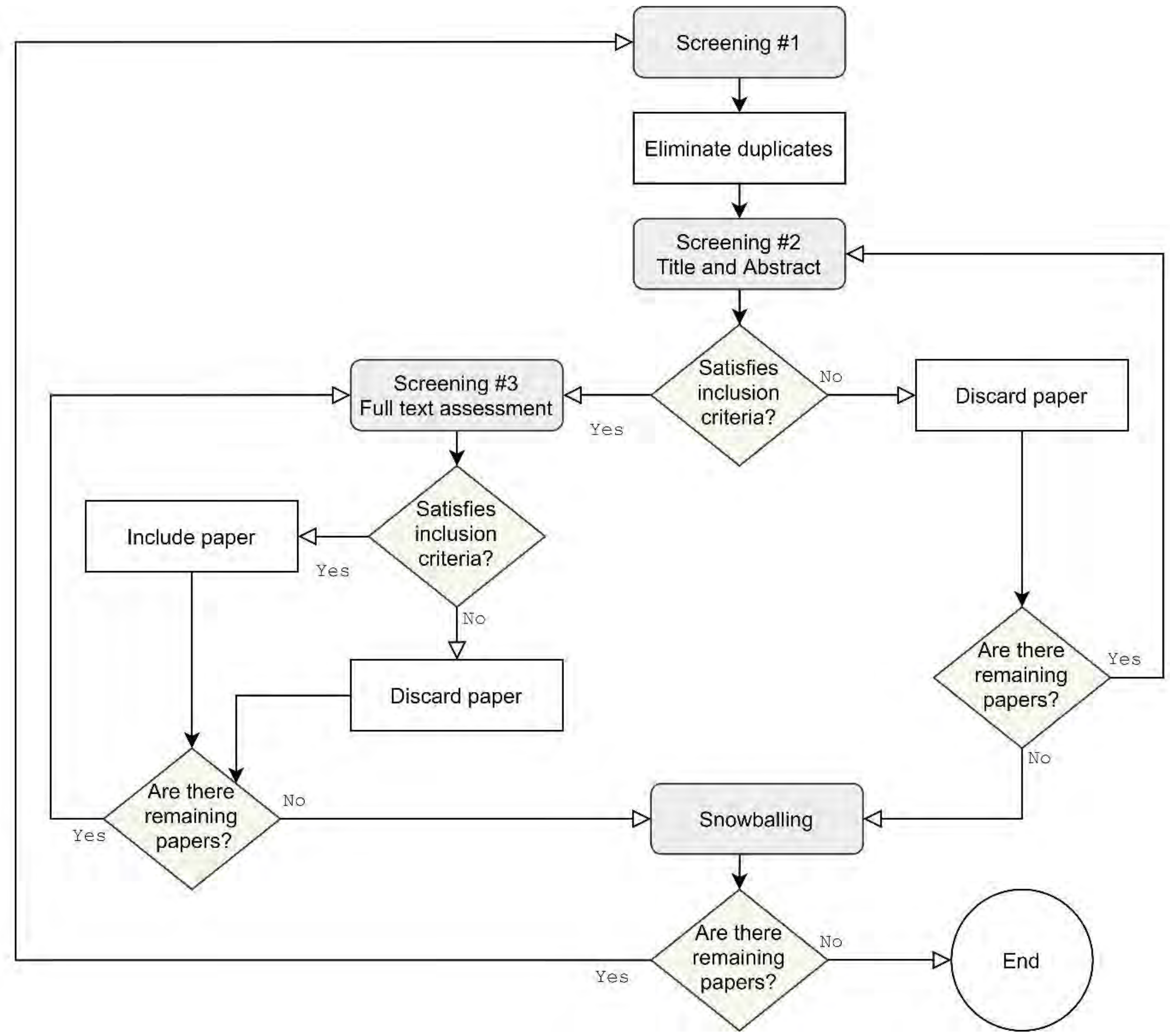

Figure 1. Methodology workflow followed in the Systematic Literature Review.

2.1 Formulation of the research problem

Two Main Research Questions (MRQ) were formulated (Table 2). The first Main Research Question (MRQ1) aims to define the state-of-the-art of immersive technologies implementation specifically for operator training in the process industry. This will also identify the context in which process industries are using immersive technologies during the operator training and what advancements have been made. The second Main Research Question (MRQ2) attempts to find evidence of any testing of immersive technologies to ascertain if this is actually improving the training of the operators, or if the new training proved to be equally or more effective and/or efficient compared to traditional methods. This will support the development of a robust phenomenological model for the evaluation of the effectiveness and efficiency of immersive technologies applied to the training of process industry operators.

To answer these research questions three major topics were identified as crucial, thus studied as a combination: immersive experience, training content, and industry. In the category 'immersive experience', five main subcategories were included which represent the solutions currently used in the industry. The subcategories are *Virtual Reality*, *Augmented Reality*, *3D Immersive Training*, *Simulators*, and *Serious Games & Gamification*. The reasoning behind these subcategories is explained in Section 4.1.

In the 'industry' category, the goal was to identify which specific branches of process industries are using immersive experiences for training. The following subcategories were included: *chemical*, *nuclear*, *manufacturing*, and *other process industries*. The last one is an aggregation of industries such as oil and gas, power plants, and food which were grouped into one category due to the limited number of publications. The nuclear industry is included as a subcategory due to the similarities with the chemical industries in terms of risk, process and waste management. Finally, the 'training' category was included to identify the content of the experiences. Two main subcategories were defined: *procedure training* and *safety and emergency training.* A summary of these classifications is presented in Figure 2.

Table 2 – Research questions of Systematic Literature Review.

Main Research Question (MRQ)	Sub Research Question (SRQ)
MRQ1: What is the role of immersive technologies/experiences in the training of operators in the process industry?	SRQ1: Are immersive technologies used in daily/frequent training? SRQ2: What type of immersive experiences are being used?
MRQ2: Are immersive technologies increasing the effectiveness and/ or efficiency of the training of operators in the industry?	SRQ3: Is there any evidence of the benefits of using immersive technologies? SRQ4: How are different learning methods evaluated and compared?

Figure 2. Concepts and categories considered for qualitative analysis of the *included papers* of the Systematic Literature Review.

2.2. Execution of the search

2.2.1. Search definition

The search was conducted in February 2020, in two different search engines: *Scopus* ("Scopus - ELSEVIER," 2020) and *Web of Science* ("Web of Science," 2020). These search engines meet necessary performance requirements, i.e. data retrieval capabilities and the reproducibility of searches, to perform a systematic review (Gusenbauer and Haddaway, 2020). In addition, they are the most frequently used search engines for physical sciences and engineering - the major focus of this study. The search was conducted on a title, abstract, and keywords basis. It is acknowledged that there have been several immersive experience developments due to the COVID-19 pandemic and there is literature published since the SLR was done that may be relevant, e.g. the work of Ko et al. (2021), but for the purposes of the structured SLR analysis, date boundaries had to be set so the work can be completed. The reader should continuously update themselves within the fast-moving area of research.

The search string was constructed, including the three major concepts: immersive experience, training, and industry. A conjunctive operation was performed for those categories, while each of them includes a disjunctive combination of elements, presented in Table 3. The exact string search used in the databases is presented in Table A. ii in the Annex.

Table 3 – Categories and elements included in the initial search of the Systematic Literature Review.

AND					
Immersive Experience		Industry		Training	
OR	- Immersive technology	OR	- Chemical	OR	- Process

	- Virtual Reality (VR) - Augmented Reality (AR) - Cave Automatic Virtual Environment (CAVE) - Escape Room - Mixed Reality (MR) - Serious Game - Game-based learning		- Pharmaceutical - Petrochemical - Nuclear - Process		- Safety - Health, Safety & Environment (HSE)

2.2.2. Inclusion and exclusion criteria

Three levels of inclusion criteria were used during the selection of the relevant publications (Table A iii in the Annex). The general criteria aimed to identify studies in the English language submitted to international peer-reviewed journals during the time frame 2000 to 2020 (end of February). Conference proceedings were excluded from the SLR because it was difficult to evaluate the quality of conference proceedings. The impact and metrics of conference proceedings found during the search were not sufficient to be listed in the rankings provided by the used databases. Furthermore, it was expected that valuable concepts would be expanded into full journal publications and would be picked up in the SLR in that way.

First level inclusion criteria filtered for publications that answer *Main Research Question 1* (MRQ1), i.e., retained papers including workplace training, with a thematic of process or safety, applying immersive technologies in a process industry. To answer *Main Research Question 2 (MRQ2)*, a second level of inclusion criteria was included, to focus and select publications that include an evaluation of the application in terms of performance (effectiveness or efficiency). After reviewing the results, it was decided that this inclusion criterion was not going to be a reason for immediate exclusion of the publication, but further qualitative analysis will be developed, which is presented in section 5.

This Systematic Literature Review wants to identify original papers on immersive experiences and other reviews summarising examples of such reports were thus not included. For example, the review by Patle et al. (2019) presents applications, which have met the inclusion criteria and are included in their original form in our SLR, but the review itself was not included (Table A iii in the Annex).

Two additional inclusion criteria were incorporated in the inclusion criteria that were originally not part of the search terms, i.e., "simulators" in the technology category and "manufacturing" in the industry category. Only simulators in the chemical industry were considered (see section 4.1.4. Simulators), and the manufacturing industry was accepted in cases where the relevance of the procedure was close to the process industry (see section 4.3). The term "maintenance" was also not considered in the initial search, but it was included in the inclusion criteria due to relevant examples of procedures in the process industry that had used immersive technologies for maintenance tasks.

3. Results

The first search step (Table 3) identified 964 publications, which were reduced to 409 after the screening for general inclusion and exclusion criteria (Table A iii in the Annex). From this set, duplicates were eliminated, giving a total of 389 publications to analyse initially. This concluded the *Identification phase* of the research.

In the *Screening phase, Title & Abstract* were screened applying the First Level inclusion and exclusion criteria (Table A iii in the Annex). This analysis revealed 82 potentially eligible references, which were assessed on full-text basis to verify if they should be included in the review (*Eligibility phase)*. After reading and applying the criteria, 23 publications were selected and included in the initially *included paper* category. The 23 publications were the initial group used for the snowballing procedure. This procedure included the same search and selection phases as the original search (Table 1). The resulting search included 1587 additional papers, following backward and forward snowballing. After the General and First Level inclusion criteria were evaluated, 66 papers were assessed on full-text basis, from which 21 studies were retained and included in the final collection of papers in the SLR.

A total of 44 studies were included in the qualitative analysis of this Systematic Literature Review. The results of each phase of the selection process are presented in Figure 3. Some publications could have been included based on the inclusion and exclusion criteria, but as the authors of the publication were the same and no new technology, concept or evaluation was presented, it was decided to only include one of the repeated articles. In the *included papers*, it was observed that eleven papers were from two research groups. Eight publications were from a research group of the Polytechnic University of Milan (Brambilla and Manca, 2011, 2009; Colombo and Golzio, 2016; Manca et al., 2014, 2013; Nazir et al., 2015b, 2013; Nazir and Manca, 2015). Some of these papers were the work of the VIRTHUALIS project (https://cordis.europa.eu/project/id/515831): Virtual reality and human factor applications for improving safety (2005-2010), a European Union project coordinated by this university. Three papers were authored by one research group from the Okayama University (Nakai, 2015; Nakai et al., 2014; Nakai and Suzuki, 2016). This means that 25% of the included papers belong to two research groups. This is a significant number, but there is still research diversity on the reported results to proceed to the analysis. It is also demonstrated that only a few groups focus on this domain of research.

Figure 4 shows an increasing trend in the number of publications (by year of submission) in the past 20 years. Taking the first eleven years (2000-2010), there are only 8 papers discussing applications of immersive technology in the process industry, but since 2011, there is a clear increase in the number of papers in internationally peer-reviewed journals, adding 36 publications. This increasing tendency was also observed and reported by Kumar (2021). However, the rather small total of 44 papers fulfilling the strict criteria of this SLR also demonstrates that there is still limited research carried out on this topic (SRQ1, Table 2).

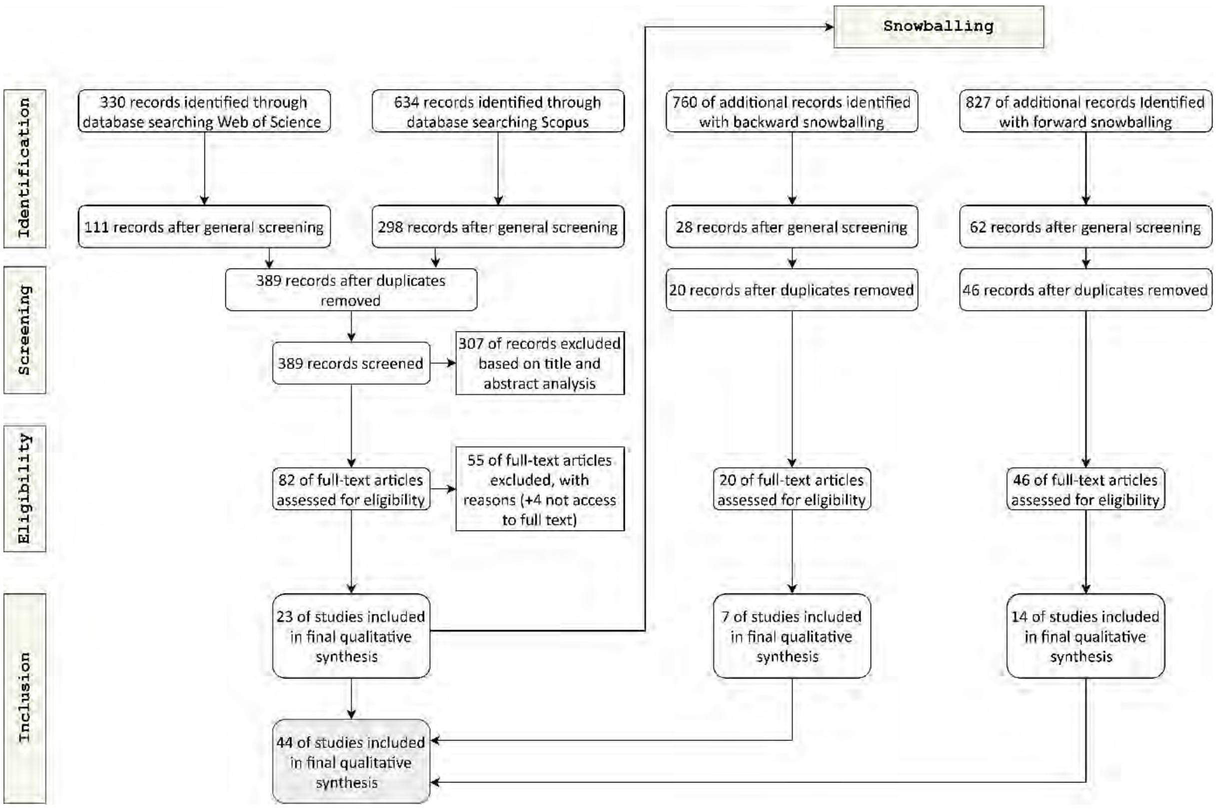

Figure 3. Result of the Systematic Literature Review according to the PRISMA methodology.

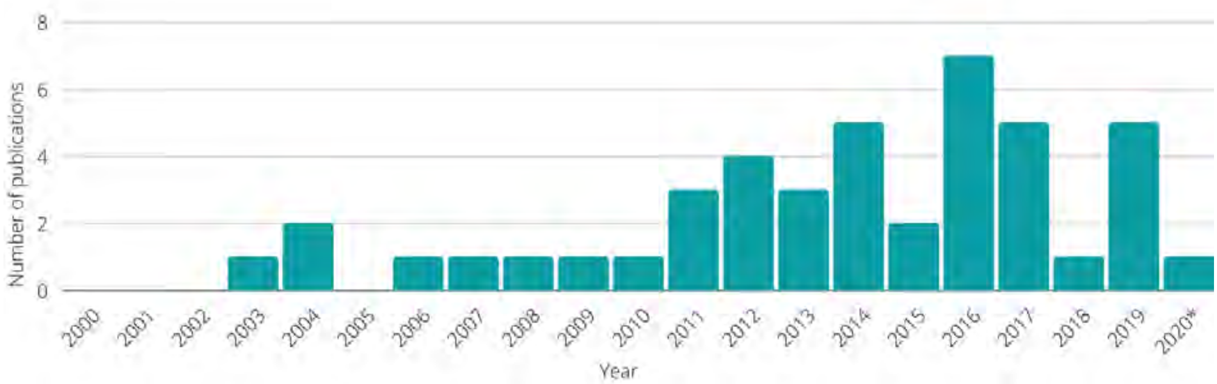

Figure 4. Number of publications resulting from the SLR shown by year of submission to the journal. *The Year 2020 is only considered partially due to the date of the search (February 2020).

4. Analysis according to immersive technology, training content, and industry.

The 44 *included papers* are categorized in the following subsection according to the immersive technology used, the training content of the experiences and the industry in which the solution was applied, as presented in Figure 2. The cross-reference by technology and industry is presented in Table A. i in the Annex to facilitate the retrieval of the references to the reader.

4.1. Trends in immersive experience and technologies

Training in the process industry is changing, adapting to the new Industry 4.0 era (Wilk et al., 2020). Digitalization of the workplace is a trending topic that is impacting different aspects of the industry, i.e. digitalizing data during manufacturing operations (Klei, 2017). One of those main aspects is training, which underwent a transformation in the past twenty years, with the introduction of e-learning (Akansha, n.d.). This example could be considered the standard type of training now, but would have been a revolutionary concept not too many years ago. Reduction in cost, easier availability, and technological progress, among others, indicate that digitalisation is enabling more wide-spread inclusion of immersive technologies for training of employees (Manca et al., 2014; Nazir and Manca, 2015; Zewei et al., 2011). In their VR review, Kumar et al. (2021) reported that VR has completed a “phase of technology adaptation and shows good potential as a training tool” in a professional environment.

In this Systematic Literature Review, five categories of immersive technologies can be identified (SRQ2, Table 2): *3D Immersive Training*, *Virtual Reality (VR)*, *Augmented Reality (AR)*, *Simulators,* and *Serious Games & Gamification*. The first three immersive technologies categories are leading in terms of number of publications, i.e., in order of prevalence 3D Immersive training, Virtual Reality, and Augmented Reality (Figure 5).

One main and common objective of immersive experience is that the acquired knowledge or skills easily transfer to real plants and equipment (Gallegos-Nieto et al., 2017), and therefore help with the reduction of human errors that can develop into industrial accidents (Nazir et al., 2015b). Immersive technologies allow the trainees to practice tasks safely in a virtual environment which in the real world would be too dangerous, not possible to perform, too expensive to organize, or not reproducible (Gallegos-Nieto et al., 2017; Mól et al., 2009; Nakai, 2015). They also enable the understanding of equipment and processes, setting the point of view from inside the equipment or adding animations, which could help to visualize danger and safety zones (Szke et al., 2015).

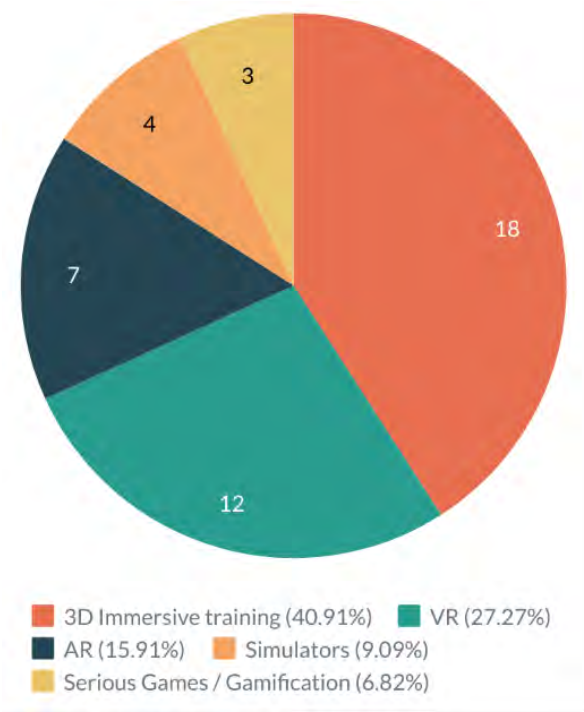

Figure 5. Five immersive technology categories with the number of papers in each category indicated in the pie chart and the percentage in the legend (a total of 44 papers were included in SLR). Table A. i gives the paper references per immersive experience category.

4.1.1. 3D Immersive training

The category *3D immersive training* is introduced in this SLR to group all developments which create a 3D representation of an environment or situation within which certain tasks can be executed. 3D visualisations and simulations were the early developments of virtual reality, and therefore, the terminology of virtual reality (or alike) is often adopted in these papers, i.e. “3D virtual environment” (Manca et al., 2013; Nazir et al., 2015b, 2013), “3D immersive display” (Fillatreau et al., 2013), “virtual environment” (Mól et al., 2009), “virtual system” (Sun and Tsai, 2012), “virtual simulation platform” (Zewei et al., 2011), “immersive virtual environment” (Nazir and Manca, 2015), “virtual reality studio” (Gallegos-Nieto et al., 2017), and “VR environment” (Nakai, 2015; Nakai et al., 2014). Clearly, the terminology used to name the technologies was not completely defined at the time, and there is a great diversity of names that the authors chose to name the technology used. Most of these concepts appeared in publications between the years 2011 and 2016. However, nowadays virtual reality refers to the technology where the user is wearing a head-mounted display and uses controllers to perform tasks (see Section 4.1.2. Virtual Reality).

The 3D representation of a location and situation can be visualized (within increasing levels of immersiveness) on a computer screen, on a Powerwall or in a Cave Automatic Virtual Environment

(CAVE)(de Back et al., 2020). CAVE technology was not retrieved in any of the SLR papers (Table A iii in the Annex). Only three studies reported a virtual experience on a computer size screen (Norton et al., 2008; Ródenas et al., 2004; Zewei et al., 2011). One main technology, namely Powerwall, was used in most of these *3D immersive training*. The Powerwall can be built in different ways and depending on the year in which the research was conducted the technology varied. For example, in some cases, the methodology to project the experience is modified to allow the user to move and get close to the screen, without blocking the projection (Mól et al., 2009). Other cases use a big screen or a large scale display that reproduces the information, some use projections on the wall (for example a stereoscopic projection by two polarized projectors (Skripcak et al., 2013)), and some use a stereo screen with video projectors (Fillatreau et al., 2013). Most cases have in common the use of 3D glasses adapted for passive or polarized visualization (Mól et al., 2009). Some of them included also 3D spatialized audio features for a higher level of immersion (Nazir et al., 2013).

Early *3D immersive training* experiences provided opportunities to explore the plant with 360° spherical images, and to perform procedures by "mimicking" actions, such as opening drains or valves from a computer screen (Norton et al., 2008). Modern experiences in *3D immersive training* include simulations of industrial plants, where operators are able to move around the plant to learn about the different plant sections (Manca et al., 2013; Nazir et al., 2013; Skripcak et al., 2013). These simulations allow the plant procedures to be presented with the realism of operations in the industry (Nazir and Manca, 2015). In the area of accident simulation, for example, a pipe rupture in a conventional refinery which causes the emission of a flammable liquid was reported (Nazir et al., 2015b). This represents a very important benefit, common to all immersive methodologies, as it allows the operator to experience repeatedly dangerous and non-stationary situations that are not safe to reproduce in the real chemical plant (Nakai, 2015; Nakai et al., 2014). Furthermore, several situations can be simulated to happen at the same time, creating the need to react quickly and accordingly to find the root cause and solve the problem (Manca et al., 2013).

Colombo and Golzio (2016) indicated that using *3D immersive training* for training in the process industry domain, trainees learned more compared with trainees that learned in a traditional lecture. Other researchers observe that training in immersive environments can enhance safety learning as operators can visualize hidden safety aspects more clearly (Nakai, 2015; Nazir and Manca, 2015) and situational awareness was obtained with higher efficiency compared with traditional training (Nakai, 2015; Nazir et al., 2015b). Also, preliminary results have shown that *3D immersive training* enhances the understanding and involvement of the operators (Nazir et al., 2013). One benefit of *3D immersive training*, for example using Powerwalls, is that participants have more flexibility to train and discuss in teams (Colombo and Golzio, 2016). They can visualize the same experience at the same time, create interactions, perform tasks and collaborate within a virtual representation of their workplace, a crucial skill that operators should develop (Nakai, 2015). This is a big advantage of Powerwall over Virtual Reality- head-mounted display experiences. Moreover, the SLR also showed that training environments were not only developed to train new employees but also to keep the skills of operators up to date over time (Manca et al., 2013).

4.1.2. Virtual Reality

Virtual Reality (VR) refers to virtual environments reproduced by using a head-mounted display (HMD) or VR headset. Most (75%) virtual reality applications were reported between 2016 and 2020, which indicates the recent development of the technology in the process industry. The virtual environments are computer-generated and create the illusion of physical presence in the virtual world (Shamsuzzoha et al., 2019). This technology has been used to create training experiences that can help to improve several aspects of training, such as location, time demand, dangerous nature, or supervision. Many of the benefits are similar to those of *3D immersive training*, regarding the possibility of training in hazardous situations; but VR incorporates a higher level of immersion as the user loses the reference to real-world, creating the feeling of “being there” (Hou et al., 2017), being able to “walk” the 3D space and manipulate virtual objects (Shamsuzzoha et al., 2019).

Training in the process industries currently relies heavily on one-to-one training with instructors, which is very time-consuming. One of the most innovative benefits of VR is the possibility of conducting the complete training with no physical supervision, as the trainee can be guided through the steps by instructions presented in different modalities such as audio, written, or by simulated characters (Garcia Fracaro et al., 2021a), and simultaneously receive feedback on mistakes or alerts. The operators can repeat sessions without the physical presence of the trainer. The training sessions can include dangerous situations that can be experienced from the safety of a virtual environment (Kao et al., 2011), reducing the need for expensive training centres, reducing cost and increasing the diversity of design of experiences that can be included (Soós et al., 2019). Several papers on VR training highlight that VR increases the performance, as the learning time required by the trainees can be reduced (Brough et al., 2007; Hou et al., 2017; Moltó Caracena et al., 2017; Nash et al., 2018). This can be translated into increased efficiency in training with VR (Ho et al., 2018). Moreover, it can lead to a reduced probability of user errors in the procedures during the training (Brough et al., 2007; Hou et al., 2017) and to an improvement of worker safety awareness (Nash et al., 2018).

The benefits of VR experience are numerous, but there are also some challenges that the industry needs to overcome. One of the most impactful is motion sickness (Shamsuzzoha et al., 2019). Brough et al. (2007) reported 15% of the participants did not complete the experiences due to motion sickness, but not all publications included in this literature review mention this challenge. Another challenge of VR, when compared to training in real environments, is the fact that most of the VR experiences use controllers to simulate the action of the hands, which cannot represent every hand movement (Soós et al., 2019). Being immersed with a headset also means that users are not able to see the real space around them which could lead to physical danger within the real space (e.g., trips and falls). Also, some headsets work with lighthouses and cables. To avoid accidents of walking into walls or furniture, protective virtual limits are included in the experience to alert the trainee that they are near the limits of a safe area. This means that the actual walking space of the user is reduced, but to cover the whole space of a chemical plant, for example, some features are included such as teleportation (Shamsuzzoha et al., 2019) or standing nodes in the simulation (Dewhey et al., 2020). This allows the user to virtually jump from one position to another. Some researchers have tested the combination of VR with a special treadmill, which allows the user to walk and travel in the virtual experience while staying in the same physical real position (Soós et al., 2019).

In addition to those challenges, Kumar (2021) outlines three main drawbacks of virtual reality: technical skills (the need to pre-learn how to use virtual reality before learning the content); technical maintenance (the need for long-term regular hardware maintenance and software support); and technical functionality (the possible situation in which there is unavailability or failure of the device). It has been also reported, that there is a need for a re-design of the training sessions (as opposed to traditional long hours sessions) when using VR for learning and training, as it is recommended to take several frequent breaks while using VR (Kumar et al., 2021). The traditional training approaches should also be revised from this point of view, as the pedagogical literature has been emphasising the need for shorter and more engaging sessions in order to ensure effective learning (Molloy et al., 2012).

Finally, depending on the type and content of training, some conditions are difficult to reproduce from the realism point of view. The sense of liquid flowing in pipes, heat, or smells are challenges in the development nowadays and can make the task harder to perform in the virtual world for the operators (Manca et al., 2013). But this is an opportunity to include features that do not exist in real life to practice learning concepts such as dispersion of radioactivity (Hagita et al., 2020), which is not visible, but within the VR, training can be modified to understand the physical concept (Dewhey et al., 2020). The development of a VR learning experience takes time and is expensive (Shamsuzzoha et al., 2019), but it brings to the table flexibility regarding the scenarios, content, and training independence (Hagita et al., 2020; Nash et al., 2018; Soós et al., 2019).

4.1.3. Augmented Reality

Augmented Reality (AR) overlays virtual information with the real world (Fiorentino et al., 2014; Gimeno et al., 2013) and shows it simultaneously as a real-time interaction (Nakai and Suzuki, 2016). This functionality is the main advantage of using *Augmented Reality* for training (Webel et al., 2013). The digital information introduced in the training or the procedure aims to help the user perform actions safely and efficiently. For example, AR can help the understanding of a problem (Fiorentino et al., 2014), understanding what are the next steps, or providing additional relevant information (such as warnings or alerts) (Vignali et al., 2018). This information can be, for example, photos, videos, flow diagrams, instructions, voice assistance, 3D models or representations or anything that can simplify or complement the understanding. This indicates that AR training is primarily used for providing virtual guidance in the industry (Tatić and Tešić, 2017). This information can be observed with displays such as smartphones or tablets (Vignali et al., 2018) which are the most popular solutions (Fiorentino et al., 2014), or head-mounted devices (Gimeno et al., 2013). In some cases, the user will “activate” the functionality by using markers or tracking systems (popular examples are the QR-codes), and in another, the software can be designed to identify the shape of equipment, for example (Vignali et al., 2018).

Vignali et al. (2018) showed that AR solutions resulted in an error reduction in cases where AR functionalities were added into safety training, and Gimeno et al. (2013) observed a 75% error reduction in training in sequential instructions. Reducing the number of mistakes is directly related to reducing the risk of accidents caused by operators (Nakai and Suzuki, 2016; Tatić and Tešić, 2017). Operators can also easily identify the correct equipment to use with the guidance of AR technology (Nakai and Suzuki, 2016), and reduce the amount of time needed to complete tasks (Fiorentino et al., 2014). Some examples included the need for action confirmation from the user, which makes it interactive and increases the awareness of the actions performed (Tatić and Tešić, 2017).

Challenges with AR training are, e.g., the time needed for the trainee to adapt to the new learning methodology (Tatić and Tešić, 2017). Particularly for AR, there is a need for wireless internet connection in the working environment to provide real-time feedback to the user (Tatić and Tešić, 2017), or the feasibility of using QR codes in some section of a plant where space is reduced (Nakai and Suzuki, 2016).

4.1.4. Simulators

Simulators, commonly known as Operator Training Simulators (OTS), are software tools that use a computer-based virtual realistic representation of a real process plant and the control room for training purposes (Gerlach et al., 2016, 2015). This technology is used, and has been for many years (Kluge et al., 2014), as a tool for training in several industries such as aviation and nuclear power (Gerlach et al., 2015). In this review, neither nuclear power nor aviation industry training simulators have been included, only simulators used as a training tool in the chemical industry were included (9% of the *included papers*). It is important to mention that not all publications describing simulators in the chemical industry were included, as this Systematic Literature Review is aiming to address how immersive technologies have an impact on the training aspect. The included publications explored the scope of the training from the point of view of the improvements in efficiency and understanding that Simulators provide.

Some features of the different Simulators presented in the research included a real-time tool for the operators to understand the time frame in which the events developed (Brambilla and Manca, 2011). However, fast-track functionalities are a useful addition to understand how, for example, initial deviations from normal conditions can quickly grow into emergencies; or to practice efficiently start-up and shut down procedures, as it could allow moving forward through long transient stages more rapidly. This functionality has been included also in the other immersive experiences discussed above.

Research has shown that training with Simulators is an effective method to train standard operating procedures (Gerlach et al., 2016) and that combining operator standard training with simulated accident scenarios can improve the effectiveness of the training, offering a more realistic representation of the accident event (Brambilla and Manca, 2011) introduced in normal operation training. This will lead to trainees being better prepared to solve unexpected situations (Brambilla and Manca, 2009; Lee et al., 2017). Results have shown an increase in safety awareness, and the understanding of cause-consequence dynamics of the process (Gerlach et al., 2016). Simulators provide time-efficient training of operators within a safe virtual environment, and an increase of initiative and independence of the operators when training with simulators (Gerlach et al., 2016, 2015), this was also observed in other immersive experiences created coincidentally using simulation as a technological base. This shows that training methodology is evolving, building from foundations proven to be useful.

4.1.5. Serious gaming & gamification

The use of immersive technologies is not the only methodology by which a training can be defined as “immersive”. Incorporating game design elements into training can stimulate the employee, and enhance their performance and engagement (Liu et al., 2018). This "gamification" process can be added to the different experiences to motivate the participants, such as competition and challenge elements in a manufacturing experience (Liu et al., 2018) or time limitations in emergency training simulators (Ferretti et al., 2018; Patriarca et al., 2019). In different industries, the question has been raised as to whether the gamification element in the workplace can improve job motivation. For an application in the manufacturing industry, Liu et al. (2018) developed a gamified experience to test whether job satisfaction and performance are improved. Their data indicated the implementation of gamification elements can indeed increase the satisfaction, motivation and performance of the industry employees.

In some cases, gamification elements can transform the experience into a game, and as the employees play the game, they also learn the content. These experiences are called Serious Games and combine with computer-based simulators that can complement, for example, the training of employees for emergency situations (Ferretti et al., 2018). These traditional safety training solutions and procedures sometimes consist of checklists and questionnaires that the employee must follow and complete. This can include several required repetitions, that can transform the responsibility of the employee into monotonous and uninteresting obligations. Here is where researchers have found an opportunity to explore how gamification elements and serious games can provide a boost of motivation.

Time constraints, as the most critical aspect in a real-life emergency, are the main gamification element included in two serious games developed for the chemical industry and an industrial plant. In the first example, researchers have developed a serious game (Patriarca et al., 2019) that takes the employee through the safety steps in a mission-like game, where the player-employee is presented with an emergency and must check the initial state of the plant, find accident locations and deal with them. The player-employee loses the game if the location of the accident is not found or if the mitigation actions are not taken within the specified time. In this 2D map simulation, simultaneous conflicting objectives are presented to the player-employee, encouraging the development of adaptive capacity and emergency response. The second example is a game for industrial plant emergency training (Ferretti et al., 2018) designed to grow experience and preparation in case of an accident. In the serious game, the player-employees have to test their capability in terms of planning, preparation of equipment and coordination of operators, improving their own emergency management abilities. Indications of improvement in decision-making abilities in emergency situations were identified.

4.2. Content of training

Besides the analysis of the immersive experiences and technologies, the content of the immersive experience training was evaluated using two categories: process operation training (i.e. executing of tasks on the plant) and safety training (i.e. emergency response training). Safety or emergency training functionalities are basically an evolution of a procedure training, but the categorization shows that these features are not included in all the experiences. Almost 70% of the reported immersive training experiences for the process industry have included only procedure training applications (Figure 6). Procedure training is key to perform the complex steps of a process in the correct order [e.g., standard operating procedure of the hydrodesulfurization process (Nakai and Suzuki, 2016)], understanding the meaning of actions (Colombo and Golzio, 2016), and the possibility of practice repeatedly the training allows a standardized and validated formation of the operator (Nazir et al., 2013).

Some solutions reported in the *included papers* presented a standard operation training, with features of emergency operations that will appear after the operator makes a mistake in the procedure (Nazir et al., 2013). Training in non-stationary conditions is crucial to prepare the operators to handle rapidly developing unexpected situations, as these conditions could evolve in accidents or incidents very quickly (Nakai, 2015). It would be ideal to have the possibility to create these situations during the training in the plant, rather than classroom training, but it is not conceivable to generate unsafe conditions in the real equipment due to its dangerous nature (Nakai, 2015). Here the use of immersive technologies takes a prominent role in the training experience of the operator in the process industry. Safety and emergency trainings in VR are reported to be a “realistic, safe and cost-effective alternative for traditional training methods”(Kumar et al., 2021).

In the virtual world, it is possible to generate any kind of dangerous situations allowing the operator to experience the consequences of unsafe behaviour. Moreover, the experience could trigger psychological pressure on the operator and provide the possibility to learn how to handle these situations in those conditions (Soós et al., 2019). Also, for example, an Augmented Reality application could provide the operators with the relevant information they need during the emergency, helping them to make the required quick decisions (Nakai and Suzuki, 2016). These qualities show why there is a high motivation to include these features in virtual training sessions (Nakai, 2015). However, even though the benefits of emergency training are clear and evident, the categorization shows that this has not been explored widely, as these scenarios were included only in an approx. 32% of the reported immersive solutions.

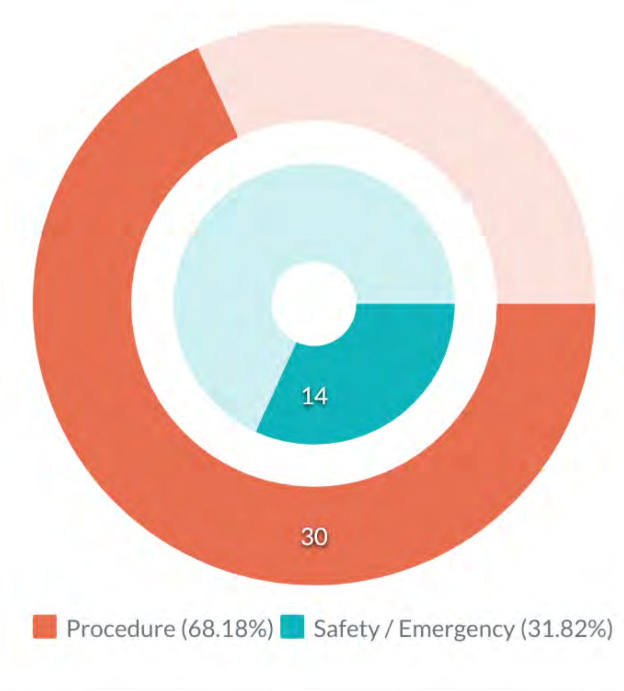

Figure 6. Content of training of immersive experiences of 44 *included papers.* The number of papers in each category is stated in the chart, the percentages are shown in the legend.

4.3. Distribution of immersive experiences by process industry

Although the main interest of this research is the chemical industry, other industries are included due to the relevance and closeness of type of training, content, and methodological operation. All the selected publications were divided into four industrial categories: *chemical, nuclear, manufacturing*, and *other process industries*. The last one contained all the publications that presented an immersive experience solution for training but did not belong to the previous categories, for example, food (Vignali et al., 2018), refinery (Zewei et al., 2011), or simply "industrial environment" (Ferretti et al., 2018; Tatić and Tešić, 2017). A specific example of this category is research that was conducted to study a VR assembly of medical devices (Ho et al., 2018), but the environment was a laboratory, with equipment present in the chemical laboratories, and the evaluation of skills that are directly extrapolated to any other chemical procedure. The number of publications by industry is presented in Figure 7.

Despite the different end-products of the industries, all of them have elements in common, such as the hazardous working environment (Soós et al., 2019) and technical-functional complexity (Nazir et al., 2015a). The hazardous environments in the process industry can include risks such as high temperatures, chemical hazards, radiation, explosion, and high pressures. The possibility of training without being exposed to these risks (Soós et al., 2019) (if it can be avoided), and the possibility of building lower-cost virtual plants (Nakai et al., 2014), led to immersive experiences gaining popularity as employee training.

One of the challenges of the process industry is the training of employees to prepare them to work in the plant, without compromising safety (Soós et al., 2019). In the nuclear industry, tasks, such as maintenance or decommissioning, are highly risky (Nash et al., 2018; Soós et al., 2019). The operators need to know what to do, with no time to spare, and an accident or even a small error could be catastrophic. Considering the differences in the nature of the hazardous materials, this is also true in the chemical industry (Nakai, 2015; Nakai and Suzuki, 2016). Management of waste is another common feature in the process industry with particular importance in the *nuclear industry*. In this industry training with immersive technologies that avoid real radiation but include realistic radiation dose feedback is being implemented (Freitas et al., 2014; Moltó Caracena et al., 2017).

In the *manufacturing industry* category, research in which the experiences and skills trained could be transferred to procedures in the chemical or pharmaceutical industry was included. For example, researchers studied a virtual reality application and as a case study, they used the task of assembling a pump (Yao et al., 2006). Maintenance tasks are common in the manufacturing industry and require sequential procedures and training, which are complicated and maybe risky tasks. This is also another point in common with the chemical industry. For example, when changing filters (Shamsuzzoha et al., 2019), incorporating immersive technologies for training and performance of this type of task can decrease mistakes and make them more efficient (Shamsuzzoha et al., 2019).

Figure 7. Four Process Industry categories and their percentage of occurrence in the SLR. Table A. i gives the paper references per immersive experience category.

5. Efficiency and effectiveness of immersive technologies

Is immersive experience an effective way of training operators in the process industry? Does the applied technology influence the efficiency and effectiveness? Is the trainee able to learn and retain a procedure long-term? Does the trainee understand the principles of this procedure? Is the trainee able to perform the procedure afterwards? How many mistakes does the trainee make when performing the procedure? Are immersive experiences also efficient when it comes to the process of training? Is the training shorter compared to traditional methods? How many repetitions should the trainee perform to learn the process? These (amongst many others) are the typical questions that potential trainers/trainees have when deciding on the training approaches. Given that immersive technologies for training in the process industry have become more and more prevalent in the past twenty years (Section 3), the question if these immersive technologies are truly improving the efficiency and/or effectiveness of the training compared to traditional training (MRQ2, Table 2), needs to be answered. Therefore, Section 5.1. analyses the SLR data for reported indicators and studies on efficiency and effectiveness. Efficiency is defined as the relation of resources, e.g. time, to successfully achieved results, while effectiveness refers to “accuracy and completeness with which users achieve specified goals"("ISO 9241-11:2018(en), Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts," n.d.). Based on this analysis, we propose a conceptual model for both features.

5.1. Performance indicators reported in *included papers* of SLR

Even though there is a growing tendency to use immersive experiences in training, there is limited evidence on their effectiveness and efficiency as compared to traditional methods of training (e.g. e-learning, PowerPoint, etc.). Only 22.72% of the *included papers* (ten papers, references can be found in Figure 8) in this SLR reported measurement of indicators that provide some evidence of the effectiveness and/or efficiency for training based on immersive technologies (SRQ3, Table 2). All ten papers report some kind of quantitative comparison between immersive technology training and traditional training, but a specific standardized framework is not reported to date.

The statistical analyses reported in the ten papers show a low number of participants in the comparisons, with traditional training and different version of the immersive technology in some cases: two groups of 10 participants (Hou et al., 2017; Webel et al., 2013), two groups of 14 (Fiorentino et al., 2014), three groups of 5 (Gallegos-Nieto et al., 2017), four groups 6 (Vignali et al., 2018), three groups of 10 (Ho et al., 2018), two groups of 12 (Colombo and Golzio, 2016; Nazir et al., 2015b), two groups of ~7 (Gimeno et al., 2013), one group of 29 and one of 40 (Liu et al., 2018). These numbers demonstrate that the current evidence of immersive training vs. traditional is in most cases an indication (SRQ4, Table 2). Further research must be conducted to statistically validate the efficiency and effectiveness of immersive training.

Each author has chosen different indicators to evaluate. In the present SLR, we refer to them as *performance indicators*, as they are measurements that reflect efficiency and/or effectiveness. These *performance indicators* are categorised as: time, number of mistakes, number of hints, number of instruction repetitions, events identification, and equipment identification. Some of the parameters are reported in the same publications and to provide a clear view of their overlap Figure 8 is included, showing which of the ten publications reported which *performance indicator.*

Figure 8 also shows how often these parameters were reported and evaluated in the literature. In all ten publications time was reported; in half of them a measurement of the number of mistakes was made; and the other four performance indicators (number of hints, number of instruction repetitions, events identification, and equipment identification) were only reported by two publications. Especially the last three were reported by the same two publications. Ten publications reporting performance indicators, and comparison with traditional training for immersive training in the process industry in the past twenty years is rather limited. Taking into account that two-thirds of those performance indicators are reported by only two papers, the evidence of further research to evaluate the immersive training becomes even more obvious.

The *performance indicator* "time" was reported in the ten publications as a key parameter. Different definitions of time were used and measured by the authors: time spent to complete the task/trial/required work pieces (Fiorentino et al., 2014; Gimeno et al., 2013; Hou et al., 2017; Liu et al., 2018; Nazir et al., 2015b), total competition time (Colombo and Golzio, 2016; Vignali et al., 2018), training time (Webel et al., 2013), time to resolve the accident (Nazir et al., 2015b). Time is a reasonable simple parameter to measure, using external equipment such as chronometers (Vignali et al., 2018) or including the feature in the design of the learning experience. This parameter can provide a direct sense of the efficiency of immersive training when compared with traditional training (Fiorentino et al., 2014). In some cases, this parameter has been reported as a way of measuring the effectiveness of the immersive training, arguing that a reduction in task time after virtual training is a way of quantifying it (Gallegos-Nieto et al., 2017). However, this may be a rather misleading parameter of effectiveness measurement, given its complex relationship and various other influences upon effectiveness.

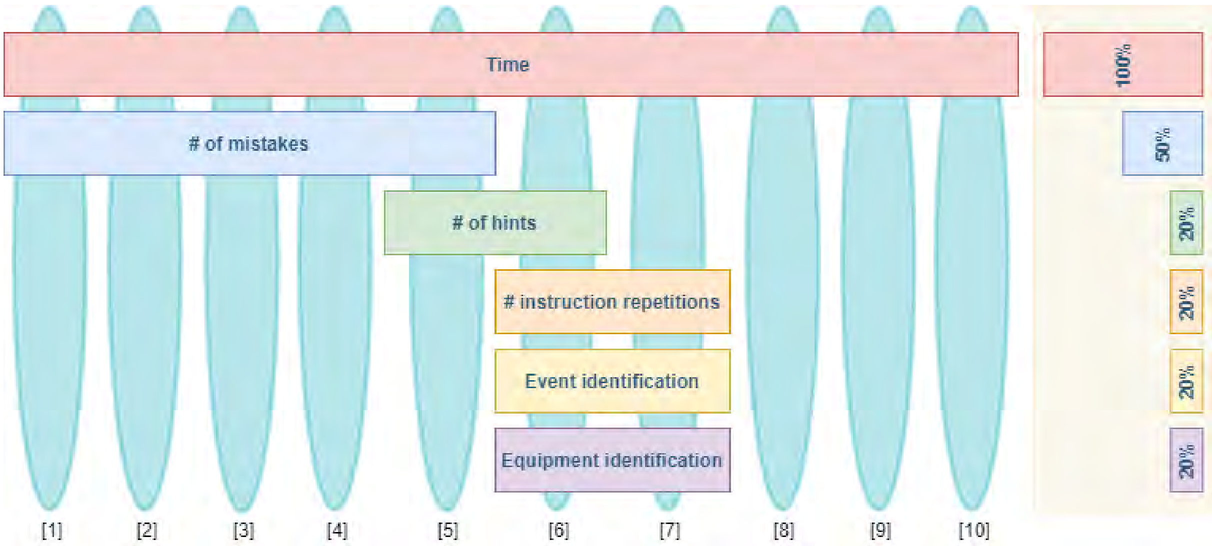

Figure 8. Summary of *performance indicators* to measure efficiency and effectiveness and retrieved from ten papers of the Systematic Literature Review reporting a quantitative assessment of immersive-technology-based training versus traditional training. Each oval represents a paper. Five *performance Indicators* are represented by the boxes. This illustration shows which paper reported which

performance indicators, and on the right of the figure the percentages of each reported performance indicator in the subset of ten papers are included. [1](Hou et al., 2017), [2](Fiorentino et al., 2014), [3](Vignali et al., 2018), [4](Gimeno et al., 2013), [5](Webel et al., 2013), [6](Colombo and Golzio, 2016), [7](Nazir et al., 2015b), [8](Ho et al., 2018) [9](Gallegos-Nieto et al., 2017), [10](Liu et al., 2018). Note: time can have different meanings (see text)

The second most reported *performance indicator* is the “number of mistakes” made during the execution of the tasks in the immersive training (Hou et al., 2017; Vignali et al., 2018). This number, which should be defined before the evaluation, represents a mistake in the sequence or the selection of a tool or valve (Hou et al., 2017; Vignali et al., 2018; Webel et al., 2013). The nature of the task evaluated in the five examples that report the number of mistakes is procedural. As stated, skipping one step in the sequence (in some examples consisting of 25 steps (Webel et al., 2013)) is considered a mistake, but none of the examples explored the concept of severity in the mistakes. Minor mistakes could develop into a dangerous consequence, just like a single fatal mistake can. This should be explored in-depth in future models of evaluation of immersive training sessions.

The next four performance indicators were only reported by two papers (Figure 8); particularly the last three were reported by the same two papers (Colombo and Golzio, 2016; Nazir et al., 2015b), which were not written by the same authors, but the work was carried out in the same research group from the Polytechnic University of Milan. The *performance indicator* “number of hints” refers to the moment the trainee does not know the next step and requires help to avoid making a mistake or is unable to solve the problem and requires a hint. These two research groups considered the “number of hints” as a separate indicator, instead of counting it as a mistake. In (Colombo and Golzio, 2016), the number of helps was registered without considering errors separately, and in (Webel et al., 2013), it was registered as the number of aids and mistakes.

The *performance indicator* “number of instruction repetitions” could be also associated with the “number of hints” indicator, but they are considered as two different categories because the number of helps can be registered during the evaluation/performance phase, while the number of instruction repetitions can be registered during the learning/instruction phase of the experience. If there is a possibility of repeating the instruction during the evaluation/performance phase it should be clear which *performance indicator* would be included. The need for an instruction repetition could appear when the trainee does not know what the next step is or is lost in the environment (digital or real); in order to complete the tasks, a refreshing instruction would allow the trainee to keep going.

The *performance indicator* "event identification" refers to the action of acknowledging and reporting events like fire or leakages, situations that can be included in emergency training (Colombo and Golzio, 2016; Nazir et al., 2015b). It is closely related to the other *performance indicator* "equipment identification", which has been used to evaluate the actions performed in the plant, for example, deciding and identifying which valve to open/close (Colombo and Golzio, 2016; Nazir et al., 2015b). The actions evaluated are selected based on the procedure that the trainee must perform. These last two *performance indicators* can complement the *performance indicator* "number of mistakes", since, for example, identifying a small spillage or not can determine the final result of an abnormal situation (Colombo and Golzio, 2016).

Based on the papers reporting comparative studies between immersive technologies and traditional training (Figure 8), we now want to answer the question of whether there is any evidence of the benefits of using immersive technologies (SRQ3). Several studies reported a reduction in the execution time of the task when using immersive technologies (*AR* (Fiorentino et al., 2014; Gimeno et al., 2013; Norton et al., 2008), *3D immersive training* (Gallegos-Nieto et al., 2017)) but this is also contradicted by studies that reported no significant difference in execution time when using immersive technologies (*AR* (Vignali et al., 2018; Webel et al., 2013)). In (Gallegos-Nieto et al., 2017), the learning process in a *3D immersive training* was reported to be slower than the traditional methods. Given the contradicting results and the low number of studies, the positive effect of immersive training on the *performance indicator* "time" remains undetermined for now.

When looking at the *performance indicator* "number of mistakes", there is a consistency in reports asserting that immersive technologies (*AR* (Fiorentino et al., 2014; Gimeno et al., 2013; Vignali et al., 2018; Webel et al., 2013)) are improving the task performance by reducing the error. In some cases, a "highly noticeable trend in error reduction" (Vignali et al., 2018) was reported, in concordance with "reduction in cumulative errors rate by more than 75%"(Gimeno et al., 2013). The recurrence of reported error reduction when training/performing tasks using AR, could imply that this immersive technology is the most promising for this objective, but the current lack of reporting data does not provide enough certainty for this conclusion. It was also reported that participants that trained with immersive technologies outperformed the traditional method trainees in the performance indicators evaluated (Colombo and Golzio, 2016). Also, an increase in motivation, satisfaction (Liu et al., 2018), and performance (Colombo and Golzio, 2016) was reported.

However, it should be noted that the research reviewed was often carried out with the specific aim of introducing the new technology described in the paper and may selectively report favourable comparisons with traditional methods of training which skew the conclusions. This increases the importance of introducing a consistent set of performance indicators that would enable unbiased comparison of various training methodologies and an objective comparison amongst studies.

5.2. Formulation of a conceptual novel effectiveness and efficiency model

To answer the question "are immersive experiences better than traditional training?", a quantitative and uniform assessment framework should be adopted. It is also essential to specify the definition of "better". Both efficiency and effectiveness are important. In some cases, researchers could equate "better" with "more efficient", when comparing only the performance time. But completing a training faster does not provide any insight as to the quality of what was learnt. The training should also be evaluated from an effectiveness point of view. In short, immersive training could be considered "better", if it is more effective and efficient compared to traditional training.

Based on the review of reported *performance indicators* in Section 5.1, the following minimal conceptual model for objectively measuring the effectiveness and efficiency of any training methodology is proposed (Figure 9).

This model is a starting point intended to provide guidelines on which parameters should be measured to determine the effectiveness and efficiency of an immersive experience designed for training in the process industry. The conceptual model only evaluates the effect on the learner. A more involved question of effectiveness and efficiency of training provision from the viewpoint of the institution (company) providing the training will require other parameters to be included, e.g., investment costs, operating costs, number of learners in the training sessions and frequency of usage.

The *performance indicator* "time" will be measured in the learning and evaluation process, providing input to assess the *Efficiency Parameter*. With the performance indicator "time", we will be able to compare the time used by the trainee to learn and perform successfully the task in the immersive environment, with time spent in the traditional methodology. During the learning phase, the number of instruction repetitions will be registered and will be indirectly considered for this parameter.

The *Effectiveness Parameter* is determined during the evaluation phase, with three main *performance indicators*: number of mistakes, equipment identification and event identification (Figure 9). This parameter indicates how the operators perform in an evaluation after learning the content. The number of hints will be considered indirectly, through the number of mistakes. The three performance indicators will determine the successful learning of the training in immersive technology, which will also be compared with traditional methodology.

Pre-print version of *Garcia Fracaro S., Glassey J., Bernaerts K., Wilk M. (2022). Immersive technologies for the training of operators in the process industry: A Systematic Literature Review. Computers & Chemical Engineering,V:160, 2022, 107691, https://doi.org/10.1016/j.compchemeng.2022.107691*

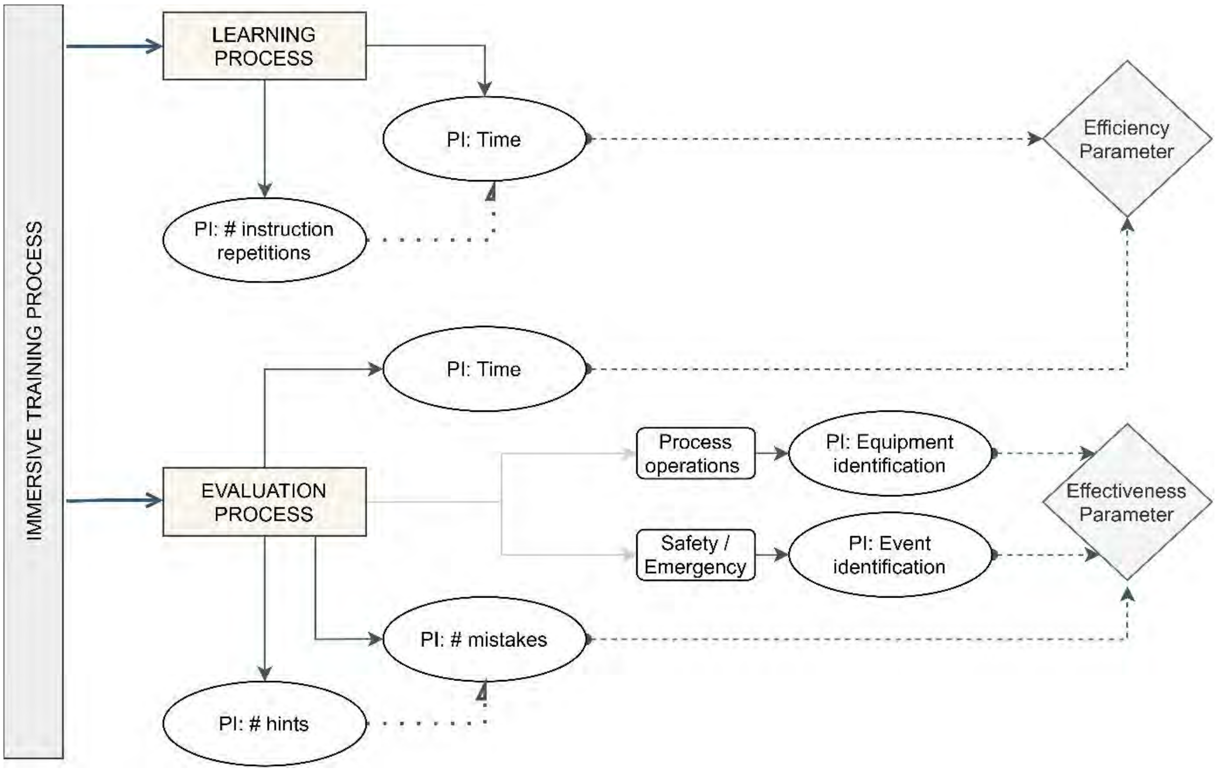

Figure 9. Model of Efficiency and Effectiveness evaluation parameters in comparative assessments of immersive experience training. The ovals represent the performance indicators (PI) that are considered in the model; the continuous arrows indicate in which stage of the immersive training process will each performance indicator be evaluated; the dotted arrows indicate that the connected performance indicators are associated, for example, the number of hints will influence the number of mistakes; the dashed arrows indicate which performance indicator influences which parameter.

6. Conclusion and future work

There is a need for more engaging training approaches in the industry and immersive experiences may provide part of the solution. In addition, training with immersive technologies provides an opportunity to incorporate dangerous emergency situations into the training that could not be performed in real-life classroom settings. This study has identified 44 publications that presented an immersive experience in the training of operators in the process industry in the past twenty years. Overall, the findings strengthen the perception that there is an increasing number of immersive solutions being applied to the training of operators. This increasing trend is also observed by Chan et al. (2021) in the field of immersive virtual labs and by Checa et al. (2019) in the field of Virtual Reality Serious Games. It can be expected that in the years to come the number of immersive training applications will further increase.

Before this study, evidence of how many training immersive experiences were implemented in the process industry was mainly anecdotal. Now, there is a clear view of the state-of-the-art research and the trends in the applications. The research has shown that three main technologies are being used for the training of operators: 3D immersive training (with a large majority of Powerwall examples), virtual reality and augmented reality. In the earlier years of the analysed period, there was a high proportion of examples of 3D immersive training, but it was observed that in the past five years the training solutions in the industry are mostly in virtual reality. The categorization of the type of training proved useful in expanding the understanding of what immersive training methods are being used for, and how there is a lack of implementation of useful and promising features such as emergency and dangerous situations. In terms of industry where immersive experiences have been implemented, this paper has included chemical, nuclear, manufacturing and industrial environment as part of the analysis. Despite the differences in terms of the final product of all the industries, all of them have elements in common, such as the hazardous working environment and technical-functional complexity. The possibility of training without being exposed to these risks and to practice tasks safely (in the virtual environment which in the real world would be too dangerous or not possible to perform, and very expensive to organize or reproduce), led to immersive experiences gaining popularity as employee training.

This study raises the important question of the assessment of the training experience. Only a small fraction of the researchers considered and reported a comparison of immersive training with traditional methodologies, describing performance indicators measured. These findings suggest that greater efforts are needed to ensure a clear analysis of the effectiveness and efficiency of immersive experiences applied to the process industry. The study of the performance indicators facilitated the development of an effectiveness-efficiency model from the learner's perspective to assess immersive experiences in the process industry. This model is a starting point intended to provide guidelines on which parameters should be measured to determine the effectiveness and efficiency of an immersive experience designed for training in the process industry. The model should also be evaluated in terms of characteristics of the trainees, e.g. age, work experience, digital expertise. The insights gained from this study may be of assistance to other researchers developing immersive training experiences for the process industry, who want to validate their results with others.

As Toyoda et al. (2021) argue, it is vital to identify the factors that affect the intentions and the eagerness of the learners to use immersive technologies. The modified Unified Theory of Acceptance & Use of Technology 2 (UTAUT 2) facilitates the "examination of the effect of factors such as performance expectancy (PE), effort expectancy (EE), social influence (SI), and hedonic motivation

(HM) that may motivate operators and employees" into using immersive training in their training sessions. A perception study conducted by Udeozor et al. (2021) showed evidence that professionals (and chemical engineering students) find virtual reality games as a useful way to learn health and safety content and that they will use it.

One of the lessons learned in the ongoing COVID-19 pandemic is that learning in a classroom or an office is not always possible under extraordinary situations, increasing the urgency for online education (Caño de las Heras et al., 2021) and leaving distance learning as the only alternative (Chan et al., 2021). Immersive technologies can provide a practical experience for the learners from the safety of an office, facilitating the training (Caño de Las Heras et al., 2021). For example, chemical operators can gain practical experience in a virtual chemical plant (Garcia Fracaro et al., 2021a)).

In addition, given the COVID-19 circumstances, the researchers and industries implementing immersive technology in their curriculum or conducting research, have to consider such a methodological approach to keep the participants/users, as well as the researchers, safe and healthy (Garcia Fracaro et al., 2021b).

Future research will further develop the conceptual model, which is created from the Systematic Literature Review point of view, and it is not a complete model from the perspective of Learning Analytics. This is a starting point of further research, where studies need to be carried out to validate the proposed model and to include a model from the institutional point of view.

7. Annex

Table A. i – Cross-reference of the 44 *included papers* by technology and industry.

	Industry			
Immersive experience	Chemical	Manufacturing	Nuclear	Other process industries
3D immersive training	Colombo and Golzio (2016) Manca et al. (2013) (2014) Nakai et al.(2014) Nakai (2015) Nazir and Manca (2015) Nazir et al. (2013) (2015b) Norton et al. (2008) Skripcak et al. (2013)	Dangelmaier et al. (2005) Fillatreau et al. (2013) Gallegos-Nieto et al. (2017) Sun and Tsai (2012)	Mól et al. (2009) Ródenas et al. (2004) Szke et al. (2015)	Zewei et al. (2011)
Virtual Reality (VR)	Shamsuzzoha et al. (2019)	Brough et al. (2007) Pérez et al. (2019) Yao et al. (2006)	Freitas et al. (2014) Hagita et al. (2020) Lee (2020) Moltó Caracena et al. (2017)	Ho et al. (2018) Hou et al. (2017)

			Nash et al. (2018) Soós et al. (2019)	
Augmented Reality (AR)	Nakai and Suzuki (2016)	Fiorentino et al. (2014) Gimeno et al. (2013) Morkos et al. (2012) Webel et al. (2013)		Tatić and Tešić (2017) Vignali et al. (2018)
Serious game/ gamification	Patriarca et al. (2019)	Liu et al. (2018)		Ferretti et al. (2018)
Simulator	Brambilla and Manca (2009)(2011) Gerlach et al. (2016) Lee et al. (2017)	*	*	*

* not included in the inclusion criteria

Table A. ii – Search string used in the initial search in Database Scopus and Web of Science. The search was conducted under Newcastle University license.

String search	Database	Date
(TS=(Plant OR Industry OR Company) AND TS=(chemical OR pharmaceutical OR process OR petrochemical OR nuclear)) AND (TS=(Training) AND TS=(process OR Safety OR HSE OR Occupational Health)) AND (TS=("immersive technology" OR "virtual reality" OR "augmented reality" OR "CAVE" OR "Escape Room" OR "Mixed Reality" OR "Serious Game*" OR "VR" OR "MR" OR "AR" OR "Game-Based learning"))	Web of Science	04.02.2020
TITLE-ABS-KEY((plant OR industry OR company) AND (chemical OR pharmaceutical OR process OR petrochemical OR nuclear)) AND (training AND (process OR safety OR hse OR occupational AND health)) AND ("immersive technology" OR "virtual reality" OR "augmented reality" OR "CAVE" OR "Escape Room" OR "Mixed Reality" OR "Serious Game*" OR "VR" OR "MR" OR "AR" OR "Game-Based learning")	Scopus	04.02.2020

Table A. iii – Inclusion and exclusion criteria of Systematic Literature Review.

		Include	Exclude
General	Time frame	From 2000 - 2020	Before 2000
	Document type	Journal Article	Conference proceedings
	Language	English	Not English
First Level MQR1	Who is trained?	Adults	Age < 17
	In which environment is the training carried out?	Workplace training Apprenticeship training	University/undergrad training Non-workplace environment
	Is there training involved?	Yes	No
	What is trained?	Control Room	Automatization

		Process HSE Safety Maintenance	Soft skills
	Is immersive experience used?	Virtual Reality (VR) Augmented Reality (AR) Mixed Reality (MR) Cave Automatic Virtual Environment (CAVE) Escape Room Serious Games Simulators*	e-learning
	In which industry is the training used?	Chemical Pharmaceutical Process Petrochemical Nuclear Manufacturing§ Oil and gas Food Industry	Medical Automobile Mining Construction
Second Level MQR2	Which types of evaluation criteria are presented?	Shows evidence of evaluating immersive technology. Reports test results	Does not perform a test. Does not report results

*when used in the chemical industry; § when linked to the process industry

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