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Towards design guidelines for virtual reality training for the chemical industry

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Abstract

Operator training in the chemical industry is important because of the potentially hazardous nature of procedures and the way operators' mistakes can have serious consequences on process operation and safety. Currently, operator training is facing some challenges, such as high costs, safety limitations and time constraints. Also, there have been some indications of a lack of engagement of employees during mandatory training. Immersive technologies can provide solutions to these challenges. Specifically, virtual reality (VR) has the potential to improve the way chemical operators experience training sessions, increasing motivation, virtually exposing operators to unsafe situations, and reducing classroom training time. In this paper, we present research being conducted to develop a virtual reality training solution as part of the EU Horizon 2020 CHARMING Project, a project focusing on the education of current and future chemical industry stakeholders. This paper includes the design principles for a virtual reality training environment including the features that enhance the effectiveness of virtual reality training such as game-based learning elements, learning analytics, and assessment methods. This work can assist those interested in exploring the potential of virtual reality training environments in the chemical industry from a multidisciplinary perspective.

Keywords: Virtual reality; Chemical industry; Operator training; Learning analytics; Game-based learning; Assessment

1. Introduction

1.1. The problem statement

The chemical process industry is widely recognised as a high-risk industry where employees are at constant risk of injury and even fatality. These risks are mainly contributed by the use of chemical substances with hazardous properties (e.g. flammability, explosivity, toxicity) and by the extreme conditions (e.g. high temperature, high pressure, large volumes) that are required to process these chemicals (Srinivasan et al., 2019). Therefore, the health and safety of all chemical process industry stakeholders (i.e., employees, neighbouring communities) are of utmost importance. Huge improvements in terms of process safety design and operation technology have been rapidly developed in the past decades to ensure the safety of the stakeholders. However, despite these improvements and control measures, major accidents in the process industry are still occurring today and have not decreased significantly compared to even a few decades ago (Bhusari et al., 2020; Lee et al., 2019).

One of the main contributing factors of accidents in the process industry relates to human factors such as safety culture, emergency preparedness and situation awareness (Bhusari et al., 2020; Nazir et al., 2014). It was found that accidents in the oil & gas process industry were mainly (79%) caused by maloperations of the process operators who were responsible for stabilising emergency deviations (Antonovsky et al., 2014). Also, a recent report revealed that 76.1% of the chemical accidents in South Korea from 2008 until 2018 were caused by human error (Jung et al., 2020). These human failures can occur due to a lack of competence or even latent errors from the organisational level. Either way, adequate personnel training is crucial to develop a highly trained workforce that has a flawless competence in dealing with emergency situations.

However, currently used training approaches have some intrinsic limitations. While it is essential that the workforce understands, is prepared to follow the correct procedure and act fast in emergency situations to prevent the escalation of an event (Colombo and Golzio, 2016; Kluge et al., 2014), training of responses to non-stationary abnormal operations cannot be reproduced in the actual plant due to the dangerous nature of the event (Nakai et al., 2014). Current training methods in the industry vary from process to process, but they often could include a PowerPoint presentation, computer simulations, e-learning, learning of safety and/or production documents and/or practices in pilot or real production plants. The latter typically includes the need for a physical supervisor that provides guidance and detects mistakes during the training process (Ho et al., 2018). This methodology is very time consuming, especially for the supervisor who must repeat the sessions with different trainees. Such limitations render the current training methodology inefficient in some cases, and with room for improvement in most. The use of immersive technologies in technical training can provide an answer to these issues by allowing, for example, virtual reality emergency training without risks for the trainee or plant in real life (Manca et al., 2013; Norton et al., 2008), or the possibility of incorporating a virtual reality supervisor that simulates guidance and supervision reducing training periods (Ho et al., 2018; Norton et al., 2008).

This publication aims to present a multidisciplinary virtual reality (VR) prototype design for the training of operators in the chemical industry. The paper is divided into four sections, starting with an introduction about the framework of immersive technologies used for training in general and in the chemical industry, and specifically the use of VR in training. The second section details the multidisciplinary collaborative approach for developing the VR training simulation. In the third section, conclusions of the work are presented and finally planned future work is described in the last section.

1.2. The CHARMING project

CHARMING is an inter-sectoral and interdisciplinary *European Training Network*[1] *for Chemical Engineering Immersive Learning*[2], which aims to study how immersive technologies and games can teach chemistry and chemical engineering concepts to children and students, and train employees in chemical and process industries. Within the project, the key goal of Work Package 3 "Chemical engineering immersion for employees" is to support workforce training in the chemical industry in Europe. As it is crucial to motivate and teach current and future employees, Work Package 3 is developing learning strategies, content, and prototypes that can enhance the learning experience. This challenge is being addressed through a close collaboration of chemical engineers, chemist, computer science specialist, and educationalists that are working on a VR experience of a chemical industry environment (MARIE SKŁODOWSKA-CURIE ACTIONS, 2018).

1.3. Immersive technologies and training

Numerous studies have demonstrated that immersion has the potential to increase learning experiences (Huang et al., 2016) and improve creativity and engagement (Huang et al., 2010), which is essential for training. According to Chris Dede's definition, "Immersion is the subjective impression that one is participating in a comprehensive, realistic experience" (Dede, 2009). For example, reading an interesting book can make us immersed in the storyline and imagine the actions in our heads. Although we know that this is not reality, in our minds, we are creating a whole scene while reading the book and accepting the fiction. Thus, an exciting book has the potential to immerse us mentally to some extent. Similarly, through immersive technology, mental immersion can be achieved and/or increased when physical immersion is created (Sherman and Craig, 2003). The imagination of a person

[1] https://ec.europa.eu/research/mariecurieactions/actions/research-networks_en
[2] https://charming-etn.eu/

is then supported by physically delivered sensations of another world which is not the real world. Immersive technology blurs the boundary between virtual and real worlds (Lee et al., 2013), making the user perceive physical presence in a virtual environment (Jasoren, 2018). Thus, immersive technologies can create an artificial situation to train people for the best and worst scenarios.

1.3.1. Immersive training in the chemical process industry

Immersive technologies are an innovative element in trainings of employees in different industries and sectors. Specifically, in the process industry, immersive technologies are gaining popularity, for the procedures and safety training of employees. In the past ten years, there has been a significant increase in the number of publications that report an immersive solution applied to training in this industry (Garcia Fracaro et al., 2020, n. in submission process). These solutions explore different aspects of training, where one of the common goals is to achieve a high transferability of the knowledge or skills acquired to the real plant (Gallegos-Nieto et al., 2017). Immersive technologies, in general, allow the trainee 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 (Gallegos-Nieto et al., 2017; Mól et al., 2009; Nakai, 2015)

A recent review found that almost 70% of the reported immersive training experiences available in the process industry have included a procedure training application (Garcia Fracaro et al., 2020, n. in submission process). 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)]. Safety or emergency training functionalities are a specific part of the procedure training. As this type of dangerous training cannot be done in real life to its full extent, there is a higher motivation to include them in immersive technologies due to the importance of the training and the benefits of the technology (Nakai, 2015). However, including emergency situations in the experiences has not been explored to a great extent, as these scenarios were included in 30% of the reported immersive solutions.

1.3.2. Virtual reality for immersive training

There are different kinds of immersive technologies. For example, augmented reality (adding digital elements in real-world), virtual reality (making digital world completely cut off from the real world) and mixed reality (combining both real and virtual worlds to interact with each other). Here, we will discuss VR which can create full immersion and disconnect us totally from the real world. This is because VR is a computer-generated interactive simulation of reality. This simulation is a 3D environment in which a user can look around, navigate, and interact with virtual objects in an almost natural way (Sherman and Craig, 2003). So, VR can allow the user to see, hear, touch, and even smell in a virtual world causing a sense of full immersion (Berg and Vance, 2017). Taking the advantage of this full immersion, VR has the potential to create dangerous or emergency situations in training so that a user can experience the moment of decision making and the consequences of wrong actions in a virtual simulation. Thus, VR training is often used in healthcare (Harrington et al., 2018), military (Liu et al., 2018), physical skills, education (Kang and Kang, 2019), psychology (Formosa et al., 2018) and industrial training (Manca et al., 2012b).

For training in VR, selection of hardware also matters regarding cost, portability and quality. Head-mounted-displays (HMDs) are currently considered to be the most suitable visual devices (Zhang, 2017). With the help of HMDs, input sensors and a 3D virtual environment, users can easily accept the virtual world as reality. Some challenges, such as collaborative face-to-face training, still remain when using HMDs because the users get completely cut off from their surroundings, but this problem could be solved by connecting users with HMDs into one VR environment over a network where they collaborate (all in the virtual world) (Bednarz et al., 2015). VR is not a new concept (Mazuryk and Gervautz, 1999). It started around 1962 but gained success after 2012 when the affordable and portable VR headsets came into the market (TechCrunch, 2014). The improvements in hardware, display resolution and cost made HMDs preferable for companies and research centres. At the time of writing, numerous HMDs from Oculus, HTC, Valve, Lenovo, etc. and many smartphone-based solutions are available on the market (as shown in Figure 1). New features are being developed by a large online community due to freely available game engines. Thus, the improvements are not only in making good VR applications but also more advanced HMD devices to overcome the motion sickness, sense of isolation and other remaining limitations soon (Nunes De Vasconcelos et al., 2019). This rapid evolution of VR headsets makes it easier to create efficient training environments regarding quality, cost, and portability.

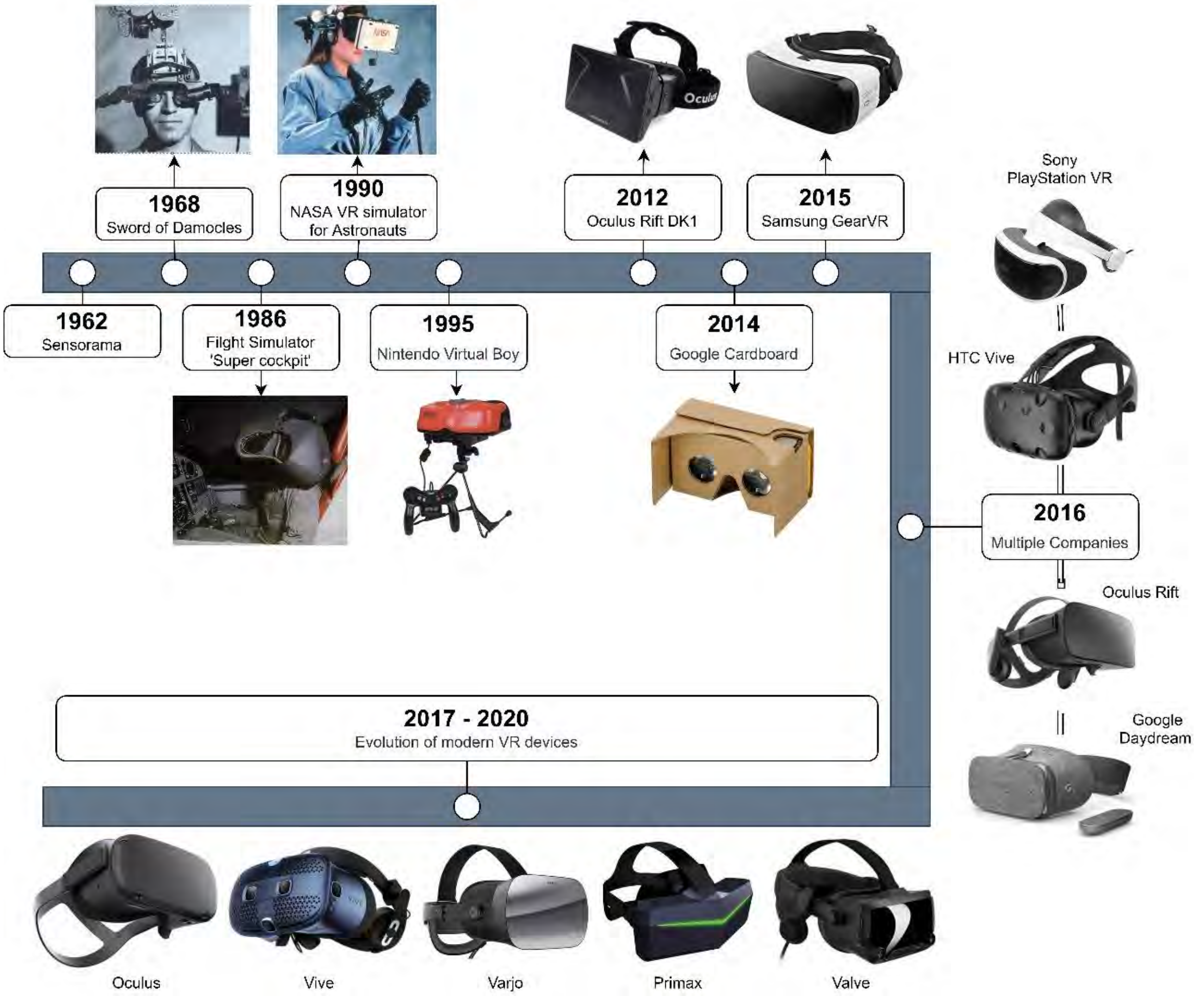

Figure 1. Evolution of modern VR headsets.

2. Developing VR training simulations: a multidisciplinary collaborative approach

VR has for a long time been a specialization of computer scientists, yet for a successful learning experience, VR training requires a broader view than just focusing on technical elements. It cannot be assumed that just by using VR the trainee will learn automatically (Makransky et al., 2019b). An effective VR training system involves content, technical and educational expertise that transform the experience to be motivating, providing feedback and guidance that allows the trainer and trainee to easily use the system. Thus, for VR training design, the viewpoints of instructor, trainee, educator and developer should be synchronized for a complete learning experience (Lövquist et al., 2012). To this end, a collaboration between a team of researchers from multiple disciplines is essential. The CHARMING Work Package 3 collaborative team consists of two chemical engineers, a chemist, an educational specialist and a computer science specialist (Mikropoulos and Natsis, 2011). Each researcher is contributing to a specific aspect of the VR training experience, covering content requirements of the training, assessment tools, game-based learning elements, learning analytics, and the development of the required VR environment.

2.1. The needs of the trainer and the learner in the chemical industry

Training today in the chemical industry is facing certain challenges. Trainers and trainees reported[3] that there is a high amount of information (in some cases too much), which makes the training session long and tedious. Such sessions typically take place in traditional classroom settings or through e-learning environments. The employees often lose motivation to complete them, demonstrating a lack of interaction in the session, silences, or distractions with external stimuli, such as mobile phones. Also, it has been reported that learning all the necessary information in a short period of time is overwhelming. Because there is a need to continue the development of skills and competences, some sessions are repeated every year, which could become uninteresting. Both trainers and trainees have reported that increasing the training in the field could be an improvement, where from the trainees' perspective they would learn the most, and the trainers would benefit from the observation of behaviour during role-play situations. The effectiveness of training, meaning the defined acquisition of the knowledge and skills, is highly important, even more than the efficiency of the training (in terms of speed and minimal cost) (Wilk et al., 2020). Field training in VR has the potential to provide these

[3] „Round table talk with Trainers & Apprentices on Education and Training“ in the Third Network Wide Event of the CHARMING project – March 2020, Darmstadt, Germany. https://charming-etn.eu/2020/03/26/charming-third-network-wide-event-and-midterm-check/

functionalities, also allowing emergency field training, such as fire or spillages, which is not possible to perform in real life.

Practical sessions, which for example are used in the German System, in the process plant learning or apprenticeships programs are based on a "godfather/tutor methodology" where a trainer or an experienced operator provides guidance and feedback during the sessions (Ho et al., 2018; Kluge et al., 2014). This method is very time consuming and presents a challenge because it is common that the trainer is outnumbered by the trainees. This means that the trainee cannot be supervised all the time, and during the practice sessions feedback might be delayed. Also, this methodology can be subjective and intrinsically biased from the perspective of the expert trainer (Manca et al., 2012a; Nazir, 2014). Trainers have reported that VR sessions could improve this aspect of training if continuous feedback to the trainees is provided while allowing them to make mistakes safely within the virtual environment. In addition, VR can provide neutral operator assessment, bypassing the human judgement of the trainer (Manca et al., 2012a).

One thing that would benefit both the trainers in teaching and the trainees in learning the required knowledge and skills to perform work-related tasks is support for decision making related to training and learning processes (Ifenthaler et al., 2018). For example, if there were easier ways for a trainer to identify the weaknesses and strengths of each learner or groups of learners, then they would be able to allocate their training efforts more efficiently and effectively. This is where the application of learning analytics can help along with accurate assessment and feedback.

To achieve analytics of learning in the VR environment, it is important to identify what information should be extracted from the trainee's interaction data. Moreover, it is important to evaluate the corresponding weighting of this information according to the given criteria. Therefore, a methodology which unobtrusively embeds and improves the validity of the assessment in the virtual environment is needed to provide automated data recording, analysis, and visualisation processes of the data generated from the VR training.

2.2. Safety and process plant training

In this multidisciplinary development, one of the key aspects is "what" is going to be the training of the immersive experience. In the framework of the CHARMING project, two beneficiary organizations are multinational chemical companies (i.e., *Merck KGaA* and *Arkema)* who provide the requirements and recommendations for content development. There are two main aspects considered when defining the "what": first the educational content, and second, the way it is presented to the trainee.

2.2.1. The content of the training

The chemical reaction selected for this training is the commercial production of n-butyllithium (n-BuLi or n-C_4H_9Li), an organolithium compound, from the reaction of metallic lithium and chlorobutane (n-BuCl) in n-hexane. The n-butyllithium has an estimated annual usage of 1-10 tonnes per year in the organic synthesis and polymer industries in the European Economic Area (ECHA, 2020a). This reaction was chosen as the training use case due to its hazardous conditions during the preparation, production, and handling of the final product: flammability, corrosivity, toxicity, and pyrophoricity (Merck KGaA, 2012). The operator must be highly trained on how to proceed to avoid circumstances where the organolithium compound is in contact with air, oxygen, moisture, water, and a source of ignition (Rathman and Schwindeman, 2014).

There is a set of documents that are crucial in chemical plant operations, and every operator should be highly familiar with them:

- Standard Operating Procedure (SOP), a document that describes a detailed set of instructions to follow during routine operations and emergency procedures;
- Safety Data Sheet (SDS), a document that "should provide comprehensive information about a substance or mixture for use in workplace chemical control regulatory frameworks. Both

employers and workers use it as a source of information about hazards, including environmental hazards, and to obtain advice on safety precautions" (ECHA, 2020b). Also listed here are the requirements on Personal Protective Equipment (PPE);

- Piping and Instrumentation Diagram (P&ID), a process engineering drawing that describes all the piping connections and equipment used in the process design of the plant (Cook, 2010).

2.2.2. The training experience

The learning objective of the prototype is focused on how to operate a chemical reactor and how to respond to emergencies. Therefore, we consider it not a problem that the reaction of formation of n-butyllithium and the associated reactor operation is not exactly known to the employees. The prototype embeds sufficient information to fill in some essentials on the product and process. Moreover, operator training is mostly focussed on training operational and safety procedures. The virtual production takes place in a universal batch reactor of 1.6 m^3, which is a common equipment in the chemical industry. This makes the acquired skills of the training easier to transfer between companies.

There are three main stages of training regarding content, presented in Figure 2. First, the operator learns about the nature of the chemicals that are involved in the procedure, the hazards related and how to handle them, and about the Personal Protective Equipment that is required. The emphasis of this phase is on understanding the hazards and safety requirements of the procedure before the start of the task. Then the trainee is allowed to learn and practice the reaction procedure, following the Standard Operating Procedure. The trainee operates the reactor manually (identification of equipment) and through the control screen next to the reactor. There is a special mode of simulation in which emergency events are incorporated, the trainee is required to identify those, and follow the correct Emergency Standard Operating Procedure to solve the situation before it evolves into a serious accident. During training in the chemical industry, rehearsing potentially dangerous situations, for example, a pump failure that could trigger a leakage of n-butyllithium, is highly important. In this situation, the operator must act quickly following the correct Standard Operating Procedure. Training this situation with traditional methods means assigning, reading or showing consequences with pictures or video in a classroom PowerPoint-presentation. In our prototype, the possibility of simulating events that can evolve into accidents is included to provide a degree of immersion during the training that cannot be achieved during the traditional training. These events are selected as a result of a simplified hazard and operability (HAZOP) analysis.

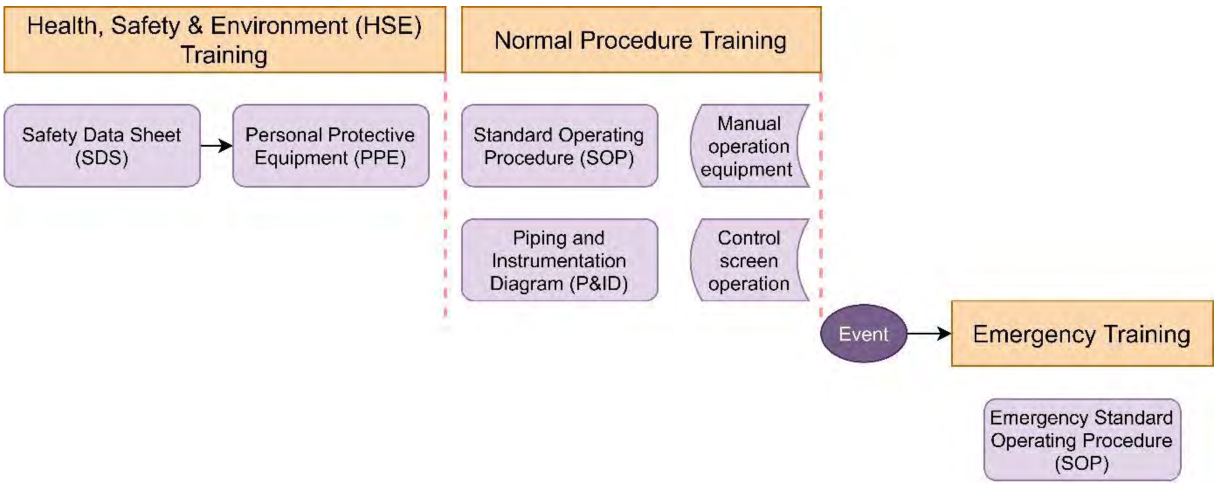

Figure 2. Content and main training stages in the VR prototype.

2.3. Virtual reality prototype design for training

For the purposes of this training requirement, VR technology is used. In Figure 3, the environment and interactions of a chemical plant training are mapped into the VR design for our prototype (as illustrated in Figure 4). The VR design consists of two main components. One is the VR environment which a user sees when wearing a VR headset and the second component is the VR interface for interacting inside the environment.

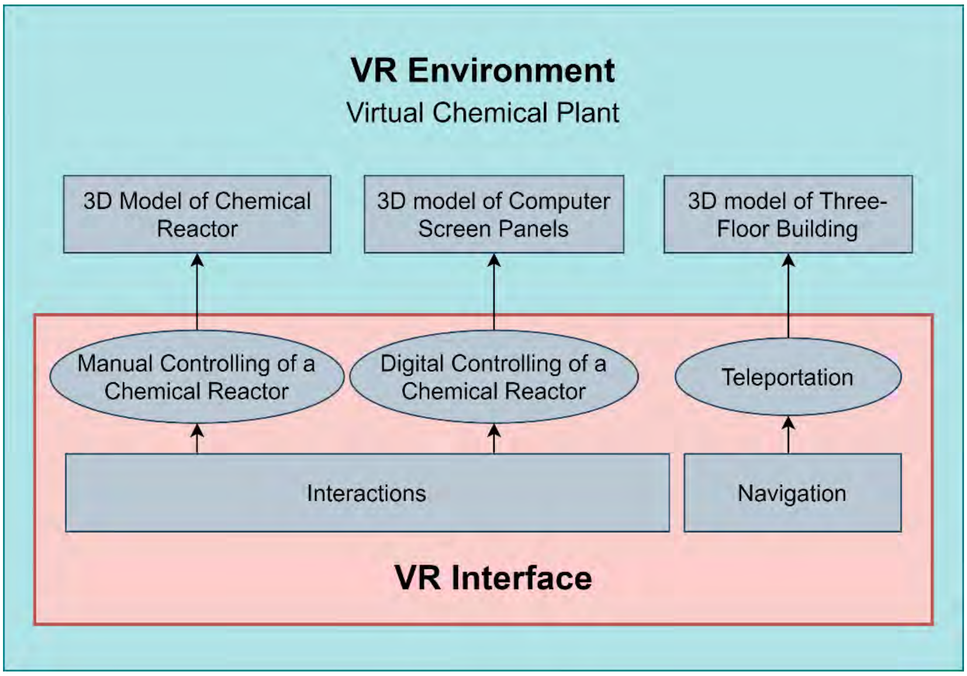

Figure 3. Primary VR design for the prototype of chemical operator training.

1. VR environment

A chemical reactor setup inside a three-floor building is designed in a VR environment to represent a 3D virtual chemical plant (as shown in Figure 4). The information is taken from industrial partners to represent the same situation that a trainee would experience in a real plant. The factors which make a virtual environment to feel real are as follows:

- 3D model of a chemical reactor which is an exact model of a reactor that is used for multiple chemical procedures in the real plants.
- Real size, colours, and textures of a chemical reactor.
- A 3D environment of a chemical plant with three floors connected with stairs.
- A 3D model of computer screens used to control the reactor digitally.

2. VR interface

A VR interface is needed to carry out interactions and navigation inside the VR environment to perform training activities with a virtual chemical reactor. These training activities include manual actions (e.g., opening valves by hand) as well as interactions with the process control systems displays (e.g., opening valves by computer screen). It is necessary for VR training to include these hybrid interactions for simulating an exact procedure. The proposed VR design, therefore, allows the user to control the virtual chemical reactor both manually and through 3D computer screens inside the VR environment. The computer screens are present next to a chemical reactor and both manual and digital controls are implemented. For example, a user in VR presses a button on the virtual screen to start liquid feed addition to the reactor, but first, they need to open a block valve that prevents accidental addition of feed into the reactor. When the user forgets to open this valve in the VR design, the virtual screen will give an error indicating “no-flow” to the reactor as would be the case in a real process. There are several common scenarios in which valves are opened digitally but here, we are incorporating manual actions so that a user should be aware of the manual skills to be acquired. It is either to open the valve by hand or just validating that a valve is opened by a computer digitally. Thus, it depends on the VR training requirements on how much it can balance between manual and digital actions. Regarding navigation in a virtual plant, teleportation is being used to allow the user to move freely between the floors and navigate easily to the desired target. While undertaking training activities, there should be few destination points in which a user can easily snap to the correct position so that they can see the output and read the text clearly in the VR world.

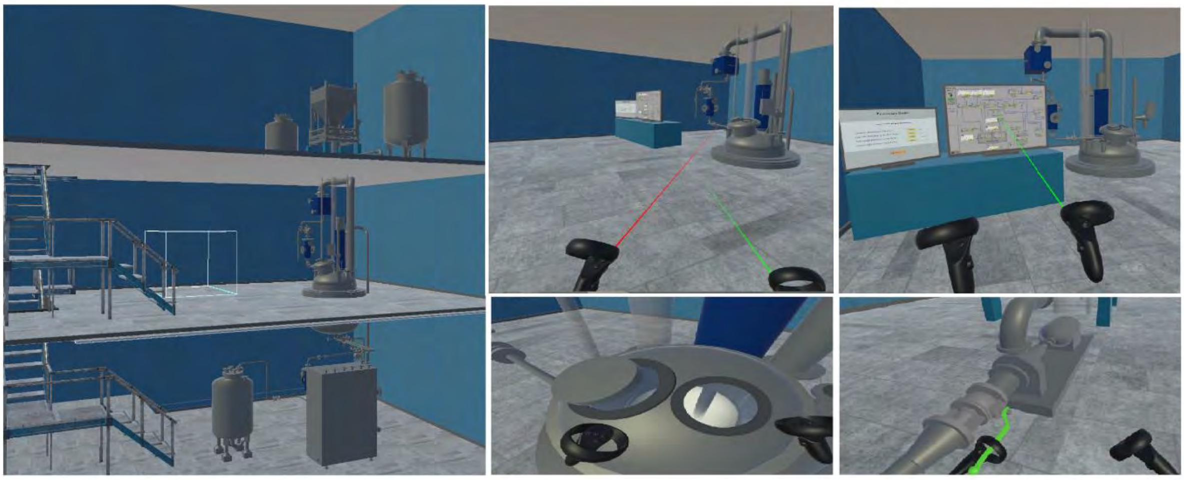

Figure 4. Illustration of a Preliminary Version of the VR Training Prototype.

2.3.1 Modes of training in VR:

It should be noted that VR training can be the first VR experience for many trainees and employees. They may have never used VR headsets or never encountered ‘virtual reality’. So instead of confronting them with all the information on VR and operations of chemical process at once, a step-by-step approach is recommended. In this approach (as shown in Figure 5), training modes are structured to enable progressive knowledge acquisition of VR and training features.

The first mode of training is to allow the user to familiarise themselves with the VR environment by making them explore the VR controls and the virtual chemical reactor. It is a kind of a virtual tour of the virtual chemical plant and the virtual controls. After the user becomes familiar with the environment, the training mode can be initiated. In this mode, a detailed step by step guidance is provided, and continuous feedback is given to the user to learn the training content. Here, the user can practice this mode multiple times to achieve perfection. After this, the user enters the evaluation mode. It is the same as the training mode but this time without any guidance. The overall feedback and report are shown to the user only at the end of the training. In addition, this report is also sent to the trainer for further evaluation. Thus, this design enables the ability to provide an environment of exploration, guidance, practice, feedback, and evaluation minimizing the restrictions of cost, time, and safety.

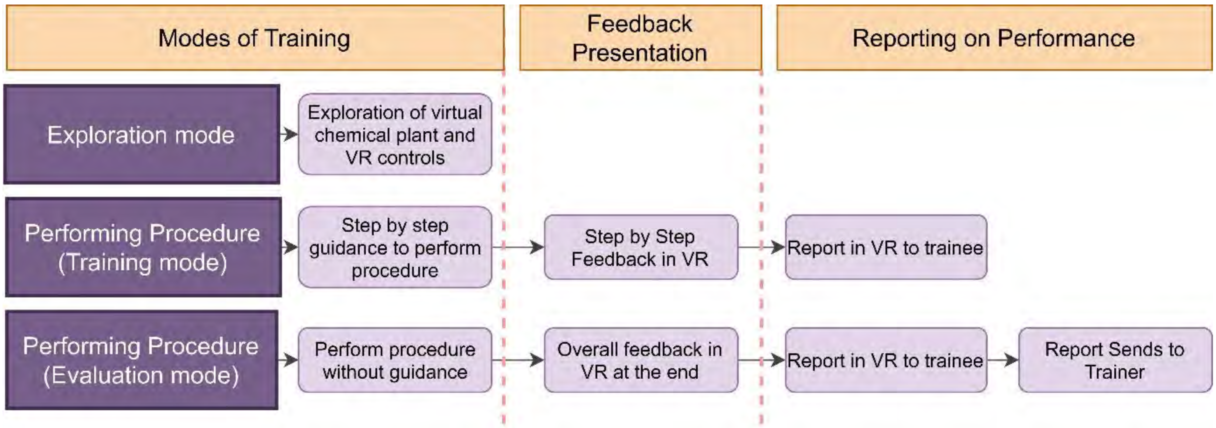

Figure 5. Modes of training to be adopted in VR prototype.

2.4. Immersive learning environment design principles

The development of a VR training environment for the operations of a chemical reactor requires more than just the learning content and technological design. Other design elements should be implemented in the training that supports both the trainee's needs and the needs of the organisation. For instance, adding game-based learning elements could improve the motivation and sustain the engagement of the trainees during the training. Furthermore, by implementing learning analytics into the design, and by presenting them in a meaningful way to the different training environment stakeholders, more informed decisions can be made related to the performance of the users. These learning analytics require accurate and reliable data generated by in-game assessment - another design element to be considered. The technological affordance to generate and store data during the intervention provides an optimal method of assessment which can be useful for all learning environment stakeholders. In the following section, design guidelines and examples are discussed for how to improve VR training environments with game-based learning elements, learning analytics and assessment methods.

2.4.1. Game-based learning elements

An important aspect of the design of a VR training of chemical employees is the engagement and active involvement of the trainee with the training program. While VR might result in engaging the trainee through an increased sense of presence in the virtual environment, the interactivity of the learner within this environment is another key component for effective engagement (Checa and Bustillo, 2019). Here, the emphasis is on the design of the learning experience rather than the technology. Games are widely known for effectively sustaining the engagement and entertainment of the player within the virtual environment. Researchers have suggested that playing games meant for educational purposes leads to greater involvement with the learning experience and motivation to train longer than with traditional teaching methods (Girard et al., 2013). However, other researchers have mentioned that implementing VR does not always result in increased learning, nor that implementing game-elements automatically makes the training motivating (Makransky et al., 2019b; Wouters and van Oostendorp, 2013). It is a more complex interplay between cognitive capabilities and psychological factors of the learner. In general, implementation of game-based learning elements in the training of chemical employees can enforce engagement, only if the game is carefully designed to support their competence to learn and their motivational needs.

To foster optimal engagement of the learner through game-based learning elements, one must understand how to create a state of flow within the learner (Plass et al., 2015). The concept of flow was coined by Csikszentmihalyi (1990) who stated that it is a “state in which people are so involved in an activity that nothing else seems to matter”. In this state, the player is so engaged with the game or task that they lose the sense of time and self-awareness (Garris et al., 2002). Thus, when training makes use of game-based elements, controlling the flow of the learners, enhanced engagement and attention on the learning material can be accomplished.

Achieving this state of flow is closely linked to the motivational needs of the trainee, more specifically their intrinsic motivation. Intrinsic motivation arises when the trainee is engaged in the activity because they perceive this as inherently enjoyable and interesting, driven by internal rewards set up by the trainee themselves (Nicholson, 2015). Extrinsic motivation, on the other hand, is the motivation driven by external rewards that are provided by the system, such as points and scores (Nicholson, 2015). However, training activities should be developed with a focus on the trainee's intrinsic motivation, because a system that mainly contains external rewards might not be sustainable long term and could diminish intrinsic motivation (Deci and Ryan, 2002; Nicholson, 2015).

Researchers believe that applying game elements based on the Self-Determination Theory of Ryan and Deci (2002) greatly enhances the motivational engagement during gameplay and as such also the motivation to learn (Nicholson, 2015; Plass et al., 2020; Wouters et al., 2009). The theory explains that intrinsic motivation is supported by the satisfaction of inherent psychological needs of competence, autonomy and relatedness.

Competence satisfaction refers to the feeling of mastery or effectiveness at challenging tasks. Achieving the task brings a sense of confidence within the player and strengthens the desire for more challenges. This is closely related to the state of flow when players face clear, reachable goals that are not too challenging in a way that causes anxiety, nor too easy in a way that increases boredom (Plass et al., 2015). Game levels with increasing difficulty and variability sustain this challenge while the player's skills evolve progressively. In this case, external rewards (e.g., points, badges, achievements, etc.) can be used meaningfully as feedback to address the player's progress and performance (Petersen et al., 2019; Plass et al., 2020). This is where accurate game assessment and informative learning analytics can be used to track the player's mastery.

Autonomy satisfaction refers to personalisation and control of oneself. Allowing the player to pursue choices that are meaningful to themselves sparks personal interest and enjoyment. (Makransky et al., 2019a; Nicholson, 2015). A game can satisfy the autonomy needs by letting the player explore the environment and make critical choices in decision-making events that could alter the outcome of the game progress (Plass et al., 2020). In the context of plant operator training, decision-based scenarios can be implemented that presents different dangerous outcomes based on the actions of the trainee (Nakai et al., 2014).

Relatedness satisfaction refers to the feeling of connection and social relationship with significant others. Engaging with other players in the same virtual setting, promotes the sense of presence and supports the social needs of the player. This satisfaction is even more intensified if collaboration is possible between the players, communicating and working together towards a common goal (C.-H. Chen et al., 2015). Relatedness satisfaction can also be stimulated when multiplayer is absent in a game by the interaction with non-player characters (Rigby and Ryan, 2011). These virtual characters, controlled by the software system, can interact with the player to form a social connection. In the context of the operation of a process plant, highly collaborative work environments are certainly not uncommon. A team of plant operators often require high communicative and coordinating skills to control the process safely (Kaber and Endsley, 1998). A training enhancing their collaborative skills in a chemical plant environment can indeed be worthwhile (Ouyang et al., 2018).

In conclusion, to sustain the motivation and engagement of the trainee in the VR training of a chemical pilot plant beyond procedural skills, one should take account of incorporating game-based learning elements that support the motivational needs of competence, autonomy and relatedness. Some examples that could be implemented in the training of chemical plant operators include:

- Game levels with increasing challenges (e.g., difficult hazardous scenarios, more complex operating actions) that triggers the need for accomplishment with high performance;
- Multiple choices that the trainee can perform that makes their actions more meaningful (e.g., risky decisions with hazardous consequences);
- Social interaction either with non-player characters or through collaborative training.

2.4.2. Learning analytics

When trainees interact with the VR training environment, it often registers the trainee's activities (e.g., type of assignments, mistakes, success, time to complete certain tasks). Due to recent technological developments, VR training environments have the potential to utilise the activity data for fostering the trainee's expertise. The VR training environment could, for example, be enhanced with learning analytics features. Learning analytics is "the measurement, collection, analysis and reporting of data about learners and their contexts, for the purposes of understanding and optimising learning and the environments in which it occurs" (George et al., 2011). Though designing such training environments may sound promising, clear guidelines for doing so are often still lacking. This hinders both developers and trainers in aggregating the training data into understandable and meaningful suggestions for fostering the trainees' development. The CHARMING Project is taking the first steps in this direction by developing a framework for guiding the learning analytics related design decisions. Based on prior research three main focus areas should be taken into account: *the what*, *the when*, and *the who*.

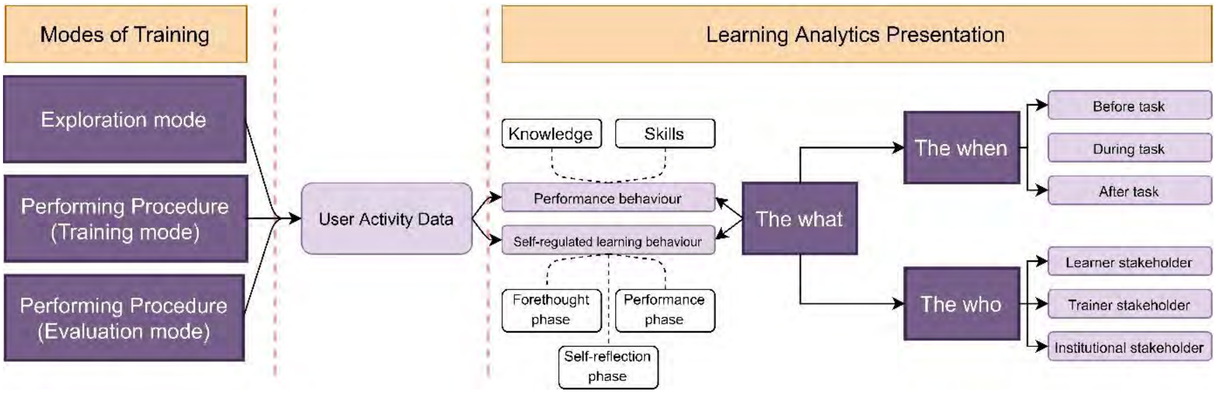

Figure 6. Learning analytics presentation: *the what, the when and the who.*

The what refers to what types of learning analytics should be presented and can be divided into two parts. Firstly, research suggests that learning analytics which targets performance behaviour, which integrates both knowledge and skills is important. This is supported by the Van Merriënboer and Kirschner (2018) strategies. An example of targeting performance behaviours is providing instant feedback on mistakes by blocking trainee progress until the mistakes have been corrected

(Sankaranarayanan et al., 2018). By being made aware of their mistakes when they happen, trainees can potentially avoid making the same mistake in the future. The second part of '*The what'* concerns the targeting of self-regulated learning behaviours, which are essential to the learning process and are related to how people manage their thoughts, behaviours and emotions while learning new things (Panadero, 2017; Zimmerman, 2000). An example of targeting self-regulated learning behaviours with learning analytics can be found in the training environment presented by Lyons et al. (2014), which asked trainees to self-evaluate their performance once they completed a training task. By promoting self-reflection after a training task, the trainee has the potential to better prepare themselves for what they need to do next to succeed.

The when refers to the timing of learning analytics presentation and can be divided into three stages: before the task, during the task and after the task. There appear to be benefits when presenting learning analytics at each of these stages and in different combinations of each of these stages. For example, Li et al. (2017) investigated the learning effectiveness of a serious game designed for training complex manufacturing tasks and found its design had positive impacts on both self-regulated learning behaviours and performance behaviours. When learning analytics are presented before a task, trainees can set goals and plan their performance. When presented during a task, learning analytics can assist with performance monitoring and after a task, trainees can be encouraged to reflect upon their performance. *The who* refers to which learning environment stakeholders are presented with learning analytics: the learner, the trainer and/or the training institution. There is evidence to support the value in presenting learning analytics to both the learner and the trainer(Lee & Lee (2018)). Institutional stakeholders can also benefit from being presented with learning analytics as they can help inform broader policy decisions related to human resources and recruitment, planning and funding (Chan et al., 2018). For example, if we can identify in advance, shortages in skilled employees needed for a specific chemical process, we can adapt our training schedule in advance to ensure this skill shortage is met.

The next step for the project is to determine the best design of learning analytics presentation for the context of the VR training environment being built – a chemical reactor training for employees. To successfully integrate learning analytics into the VR training environment it is vital that the assessment procedures and methods are in line with expected performance behaviours.

Figure 7. Illustration of learning analytics presentation design.

2.4.3. Implementation of assessment into VR elements

In general, assessment is considered an important and vital part of the learning process since it is a process of collecting, analysing, and interpreting data about learners (e.g. knowledge, skills, and attitudes) to provide feedback and make improvements of their current performance (Daoudi et al., 2017; Eseryel et al., 2011). Assessment is both an instrument and a process of obtaining and presenting relevant information to a known objective with the different target audience (e.g., trainees, trainers, institutions).

Several reports around the world confirm that it is important to develop an efficient and authentic way of conducting an evaluation on 21st-century skills (e.g. problem-solving, teamwork, etc.), as these skills are vital to the success in a constantly evolving society (Trilling and Fadel, 2010). However, most of the assessments still use a traditional paper-and-pencil format (e.g., multiple-choice and short answer), which are efficient for measuring declarative knowledge but not effective for measuring the above-mentioned skills. Since the success of an assessment method is based on the level of reliability (i.e. consistency of assessment results across conditions) and validity (i.e. accuracy and defensibility of the predicted outcomes made) of the whole course and process of analysis, it is important for the researchers to go beyond the standards and begin exploring ways in which to develop new assessment methods (Shute and Wang, 2016).

Recently, the advances in VR assessment technologies have made it possible to trace and capture learner-generated data, especially their in-game actions and behaviours (Loh, 2012; Loh and Sheng, 2013a; Moraes et al., 2009). Since the emerging pattern of learners' behaviour within the virtual environment is expressed as a function of the learners' understanding of the learning problems, this collected information then can be used to reveal their corresponding knowledge and skills (Loh, 2011). These learner-generated action data is analysed and transformed into real-time usable reports by using information visualisation techniques.

One way of increasing the quality and utility of assessment in VR is to use an evidence-centred design (ECD) framework According to (Mislevy et al., 2003) this framework requires assessors to: (a) state the collection of claims on users' competencies, (b) establish a logical link between the task and the claim, and (c) determine what tasks or situations that will generate that evidence (Mislevy et al., 2003).

Though there can be thousands of information points available in a given data, the key is to identify the most important information which can be used to rank learners according to their mastery of the given subject (Loh and Sheng, 2013b). However, it may be hard for the decision-makers to identify the priority of the behaviours that conform to safety rules, regulations, and operating procedures in the chemical plant due to the lack of systematic methods to deal with multi-criteria problems. Therefore, a scientific process is needed to rationally rank behaviour priority according to the level of expertise criteria.

Multi-criteria decision-making is the approach that deals with designing mathematical procedures for supporting the subjective scoring of performance criteria by experts (Zavadskas et al., 2014). Proposed by Saaty in the 1970s, analytic hierarchy process, a type of multi-criteria decision-making, is a structured method to organise and analyse decision-making problems that involve complex hierarchies and multiple factors, which is based on mathematics and psychology (Saaty, 2008; Saaty and Katz, 1990). In this process, experts will be asked to rate the relative importance of different factor using pairwise comparison, thus, this method can provide a strong conceptual framework that allows precise quantitative calculations to determine the relative importance of each criterion involved in a given qualitative and/or quantitative decision-making problem (Saaty, 2008).

Since decision-makers usually feel more confident to give their judgement in the form of words and sentences rather than in the form of numeric values, it is difficult to express these linguistic variables into traditional dual logic of either yes or no (J. F. Chen et al., 2015). Hence, the fuzzy comprehensive evaluation method is useful to deal with these imprecise and uncertain data. Developed by Zadeh, the fuzzy comprehensive evaluation method is an assessment method that applies fuzzy set theory/mathematical principles in showing a quantifiable degree of uncertainty in human judgement through evaluating things and phenomenon affected by a variety of factors in a system (Zadeh, 1965).

As the key to online evaluation process is to design the evaluation index system with reasonable and objective factors weights, this VR training prototype uses analytic hierarchy process method coupled with a fuzzy approach to enhance the ability to capture the uncertainties and vagueness of the learner’s competency perceptions expressed by the experts. Moreover, evidence-centred design framework is also used to provide an evidence-based argument that connects what learners perform in a chemical plant with appropriate skills and knowledge.

The presented multidisciplinary collaborative approach is summarized in Figure 8, showing all the design elements and their interaction within the VR prototype.

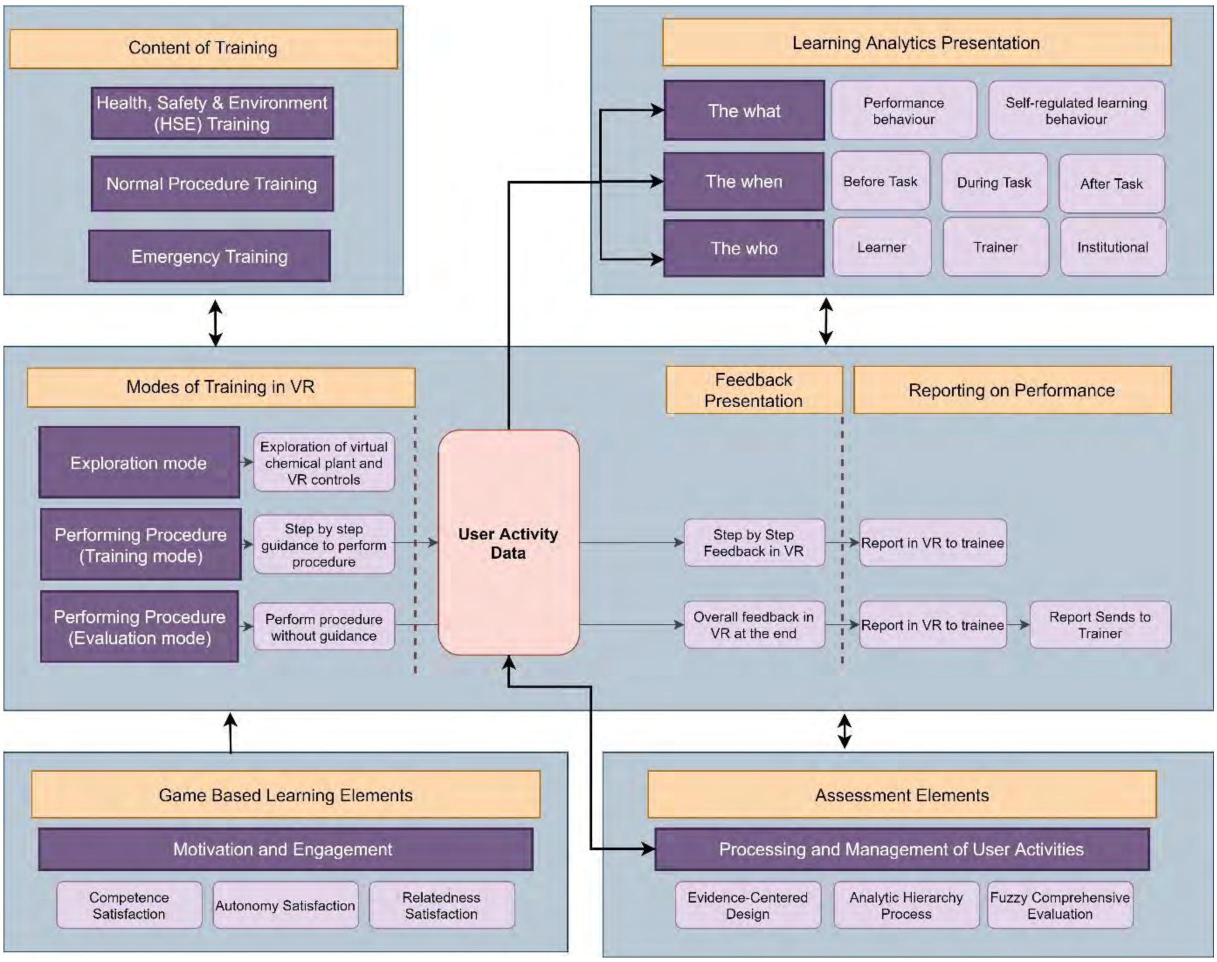

Figure 8. An integrated overview of essential building blocks and features of a VR based chemical operator training.

3. Conclusions

Training in the chemical process industry is vital because mistakes can lead to grave consequences. However, current training methods seem to have limitations regarding the format in which the information is transmitted to the trainee, motivational design and hazardous situation training. Furthermore, the high cost of the training centres and the time-consuming methodologies, are characteristics that need improvement.

VR technologies are rapidly increasing in popularity and have been shown to be effective for workforce training, especially for high-risk professions, such as military, medical, aviation and mining industry. However, there is currently a shortage of evidence that VR training in the chemical industry is effective. Using VR technology for the training of employees in the chemical process industry could be a solution to the weaknesses of traditional training methods.

We set out to design a VR training environment for the chemical process industry which incorporates elements of design from a multidisciplinary perspective that requires a close collaboration of chemical engineers, a chemist, a computer science specialist, and an educationalist. This collaboration is necessary because designing and developing a VR training requires design elements that optimally support the needs of the trainee and the needs of the training environment stakeholders. When these needs are not met, the VR training could be rendered ineffective or not optimised for its purpose.

To design effective training environments, the learning content and virtual environment are carefully selected. The training will educate chemical operators on how to operate a universal chemical batch reactor with high attention to safe operation and will include emergency cases. Accurate development of the VR environment, interfaces and interaction, that resembles the real chemical plant, ensures high immersion for the trainee during the training.

Additionally, the design of the VR training environment makes use of design elements based on key principles of game-based learning, learning analytics and assessment methods. Game-based learning elements can be implemented to sustain engagement and to promote intrinsic motivation of the trainee by complementing their needs of competence, autonomy and relatedness. Furthermore, we can utilise learning analytics to support all stakeholders in making decisions related to the performance of the trainee, by taking into account the focus domains of *the what*, *the when*, and *the who*. Finally, assessment methods, such as evidence-centred design, analytic hierarchy process, and fuzzy comprehensive evaluation can be used to capture and process generated data during the training with a high level of reliability and validity.

In the end, we have provided a theoretical framework that set a baseline for the development of virtual training experiences in the future.

4. Future work

The Work Package 3 team of the CHARMING project is working collectively towards a functional VR training for operators in the chemical industry. Future work will involve implementing key design principles of game-based learning, learning analytics and assessment. We are expecting to have a working VR prototype, that will be evaluated and tested with operators and apprentices from the chemical industry. The CHARMING project involves several European institutions, industrial participants are particularly important to design and our ability to test the prototype, as they provide an industrial perspective, expertise on chemical technology, and requirements on content training. The beneficiary companies Merck KGaA[4] and Arkema[5], and the partner company ACTA[6], located in Germany, France and Belgium respectively, are planned to be included in the testing phase of the project planned for the year 2021. The evaluation and testing phase will provide data that will be used for the validation of the first design guidelines based on empirical research related to learning analytics, assessment and game-based learning. The project will provide conclusions regarding the effectiveness and efficiency of the VR training experience compared to traditional classroom training as well as digital-based platforms training in the chemical industry. An iterative approach will take

[4] https://www.merckgroup.com/en
[5] https://www.arkema.com/en/
[6] https://www.acta-vzw.be/nl/home.arcx

place during the year 2021, targeting a validated VR experience by the end of the CHARMING project in the year 2022.

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