How a Plant Simulator can Improve Industrial Safety

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INTRODUCTION

Progress in the industrial sector brought economic, social, and cultural benefits that resulted in making the life of human beings relatively more comfortable. However, these benefits came at the cost of processes that are more complex, in terms of technological integration and automation, with more severe operating conditions and reactive chemicals. This complexity calls for implementing enhanced methods and tools to make the systems and operations less prone to hazards and accidents and avoid possible loss of production, chemicals, resources, and even operators [1, 2]. An industrial accident can result in the disruption of workflow, and in equipment damage, operator injuries, and even deaths [3]. In addition, it may produce severe consequences on both the environment and population that surround the plant. Finally, an accident usually interrupts the operations with major consequences on the economic balance of the company due to penalties, refunds for damage, and court and attorney expenses [3]. In recent years, some of the causes, which may trigger an accident, were considered and, where feasible, also mitigated. Nonetheless, the number of industrial accidents has been growing [4]. Human error is one of the main reasons for the accidents in the aviation and military sectors. Process industries are not exempted from this evidence [5]. Various literature studies were conducted on industrial accidents. The incorrect manipulation of process units by the operator(s) was found to be the main source of abnormal situations and potential accidents [6]. Table 1 summarizes some of the major industrial accidents of last decades with their consequences. The role of industrial operators is that of assuring the smooth operation of the plant. This goal can be better achieved with an accurate and in-depth knowledge of the process, relevant hazards, chemistry, and impact of both nominal and abnormal operating conditions on the process [7].

Unfortunately, the focus on process safety aspects is by far lower if compared with other fields like aviation and medical sector. Contribution of human error to industrial accidents is reported to be in the range of 60–80% [8]. A timely response to the accident can reduce the escalation of the event and limit the possible damage. Even an abnormal shutdown can result in significant financial losses to the industry. In addition, the restart procedures are often hazardous and time consuming. Therefore, approaching industrial safety in terms of improvement in the performance of operators is one of the possible and viable solutions to overcome or at least reduce the number of accidents and their impact. With these targets and issues in mind, the article proposes a Plant Simulator (PS) as a training and a performance assessment tool working in an Immersive Virtual Environment (IVE).

Antonovsky *et al.* [9] found that operator (i.e., human) error is the reason behind 79% of accidents in the Oil & Gas industry. In most cases, the accident is preceded by an abnormal situation, where usually the process can be returned to its normal operation. However, once the accident is triggered it is much less likely to have the process returning to the normal conditions and an emergency shutdown is the only option. According to the authors, the operator is not the only actor that should be blamed for the error. Conversely, the problem should be solved at a system and organizational level.

The roles and jobs of industrial operators have been significantly transformed with the increase in the complexity of modern process-control systems which begun with the inclusion of automation-related tools and technologies. Vicente [10] in his famous work on cognitive task analysis

Table 1. Notable industrial accidents and their impact in the last decades.

Industrial Accidents	Impact
Flixborough, United Kingdom (1974);vapor cloud explosion.	28 fatalities; USD 232 million damage; damage to houses off site.
Seveso, Italy (1976); toxic material release.	Widespread contamination on-site and off-site.
Bhopal, India (1984); toxic material release.	Thousands of fatalities; USD 20 million damage; mostly off-site.
San Juanico, Mexico City LPG (1984); LPG explosion.	2500 fatalities; several casualties off-site.
Chernobyl, Ukraine (1986); fire and radiation release.	31 fatalities; 300 square miles evacuated; widespread contamination.
Sandoz Warehouse, Switzerland (1986); toxic material release.	Major impact on ecology of Rhine river
Louisiana, USA, Shell Norco Refinery (1988); vapor cloud explosion.	Seven fatalities on-site; neighboring town evacuated; damage exceeded USD 50 million. Widespread damage to houses off-site.
AZF, France (2001); chemical explosion.	29 fatalities and 2500 casualties; structural damage in surrounding; economic loss: USD 1.1 billion.
Texas, USA, BP Refinery (2005); fire and explosion on the isomerization plant.	15 fatalities and 180 casualties; economic loss: USD 1.5 billion.
Gulf of Mexico, BP Deepwater Horizon Oil Spill (2010); marine oil spill.	Serious risks to marine life with several fatalities of dolphins economic loss: USD 42.2 billion.
Ajka Aluminum Plant, Hungary (2010); reservoir breaking resulting in red mud spill.	9 fatalities and 122 casualties; demolished life in 100-km Marcal river.
Neptune Technologies and Bioresources. Sherbrooke, Quebec, Canada (2012); a huge blast followed by smaller ones.	2 fatalities and 17 casualties.

demonstrated that new technologies demand new skills. A few years ago, the demands by the operators were more physical than mental and manual intervention of physical devices was sufficient for continuous and safe production. A number of recent studies highlighted the benefits of operator training and its correlation with decrease in accidents and abnormal situations [11–14]. The work of Kluge *et al.* [15] discussed the gap between demands to the operators and current training practices. That paper emphasized the need for developing training simulators that can result in improved performance of operators for both normal and abnormal operating conditions. Similar questions were raised in other recent papers [15–17].

Training simulators capable of satisfying the needs of operators working in the control room and in-the-field have been rarely conceptualized and developed. Control Room Operators, CROPs and Field Operators, FOPs, tackle on a daily basis. CROPs interact generally with Distributed Control Systems (DCSs) featuring synoptic charts, process flow diagrams, and huge amounts of data often represented by a large number of dynamic graphs. FOPs interact with physical devices located at the plant site and communicate frequently with CROPs.

This article focuses on a novel tool, whose name is "Plant Simulator," capable of improving the conventional training and assessment methods for industrial operators with the perspective of facilitating the operator to perform better, specifically in terms of safety. The features of the proposed PS are presented in the following sections. Two case studies allow discussing its features, applications, and benefits. The Conclusions section draws the comments on the possible safety enhancements introduced by adopting the PS to train and assess industrial operators.

PLANT SIMULATOR

The Plant Simulator (PS) comprises the following items and features:

a. Dynamic process simulator
b. Dynamic accident simulator
c. Virtual and augmented virtual environments
d. Dynamic performance assessment

The dynamic process simulator simulates the evolution of the process conditions inside the process units and the pipe network, but is not able to describe what happens outside of the equipment in case of accident. The dynamic accident simulator receives the details on possible releases, outflows, emissions, and leakages from the process simulator and calculates in real-time the accident evolution (e.g., how a pool fire or a gas dispersion spatially evolve over time). The dynamic accident simulator quantifies also the effects of the accident on the surrounding equipment and on the involved operators. To close the interaction loop, the process simulator receives as input data the quantities determined by the accident simulator (e.g., thermal fluxes) and determines accordingly the effects on the process variables. In short, the communication between the simulators is bidirectional as they get influenced mutually. Figure 1 shows a visual representation of the PS.

The PS can be a suitable solution to educate, train, and assess the performance of operators carrying out both cognitive-related and manual-related tasks [18, 19]. The following section discusses the features of the PS in more detail. The technical details about the dynamic process and accident simulators are available in Brambilla and Manca [20] and Manca *et al.* [21].

Immersive Virtual Environment

The benefits of using IVEs in operators' training started to emerge during the 1990s of last century. More recently, the ease in availability, reduction in cost, and addition of several new features (including augmented virtual reality [AVR]) have made IVE a viable tool for training purposes. In terms of learning benefits, a detailed review by Dalgarno and Lee [22] demonstrates the "learning-affordances" of IVEs in various contexts. The added value of this methodology, specifically for process safety, is the possibility of simulating different abnormal situations and accident scenarios within a virtual environment. These features are nearly and in many cases completely impossible to simulate in a real environment. The PS allows the operator not only to understand the details of the process but also to absorb and virtually live the sensations and emotions associated with it. The virtual environment features both a three-dimensional (3D) stereoscopic representation of the spatial domain of the plant with background sounds, typically reproduced in high fidelity (by multipoint speakers) to increase the immersivity of the training experience.

IVEs are 3D immersive environments, which allow operators performing tasks and collaborate within a virtual representation of their normal working environment. The ability of a PS to create dynamic, immersive, three-dimensional, fully immersive settings, where the behavioral response can be recorded, offers a number of assessment and rehabilitation options that are not available with conventional assessment methods [23]. An IVE is a synthetic environment that allows the operator(s) understanding the schematics of both the process and the plant (e.g., Figures 2a and 2b). In addition, an IVE allows experiencing the corresponding feelings and emotions, that is, those felt in reality. The operator, during the training session, experiences his/her physical presence within the rendered environment where she/he is free to move around the virtual equipment without the risk of getting injured, being exposed to heat radiation, or being affected by real accident events. In fact, there is also the opportunity of experiencing the same emotions and feelings she/he would experience in reality, for example, the similar anxiety, fears, and concerns [24].

The addition of the AVR feature to IVEs can significantly enhance the training level of operators as they can visualize several hidden aspects of the process. The AVR feature (see also Figures 3a and 3b) enables the operator to understand and quantify the background information. Some examples of AVR applied to normal process operations can be the interior structure and operation of the equipment, the nature of reactions and of the process variables, the flow rates and holdups in both pipes and vessels. AVR can also be used to train operators under abnormal and accident conditions so to provide information about the heat radiated by overheated equipment and accident fires, the thermal load absorbed by the FOP as a function of his/her personal protective devices and exposure times, the concentration of toxic components in a dense/buoyant gas cloud emitted by a damaged unit, the incident overpressure in case of deflagration/detonation with the probability of eardrum and lung ruptures. As a consequence, the details and dynamics of the process can be better understood with the support of AVR.

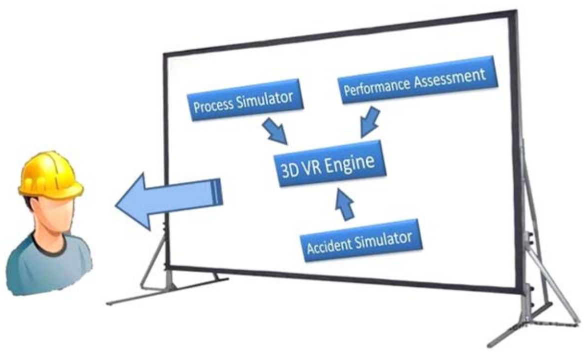

Figure 1. Representation of the PS showing the main components.

Training with Use of PS

The ability of human beings to enhance their skills, understanding, comprehension, responsiveness, attention allocation, mental modeling, and mental associations can be improved by different training methods [25]. Training and development activities allow organizations to improve adaptability, competence, profits, production, and safety [15]. In the United States, the amount of money spent in training individuals is about USD 135 billion per year [25]. Kluge and Frank [13] and Nazir *et al.* [26] have discussed the positive correlation between training and performance in case of process industry.

Unfortunately, there are evident shortcomings in the training methods used by most of the organizations [15, 25]. Besides the lack of thorough training methods, there is also a lack of training assessment based on exhaustive task, person, and organization analyses [27, 28]. A well-designed, effective, and efficient training method is necessary for the process industry to mitigate the number of accidents and their impact. Another field, where both operator training and assessment are of paramount importance, is workers' replacement, due to the ageing workforce, in most industrial sites. A viable means to train new and unskilled crews is a common request from process industries. This is also a means to keep process knowledge inside the plant by minimizing the losses due to the retirement of expert workers. These issues call for new features and new perspectives in operators' training, based on reproducible and effective tools. The repeatability of training allows achieving a standardized approach to operator formation and the administering of well-accepted and validated procedures.

For the sake of clarity, Figure 4 presents and categorizes the training stages that can be carried out with the PS.

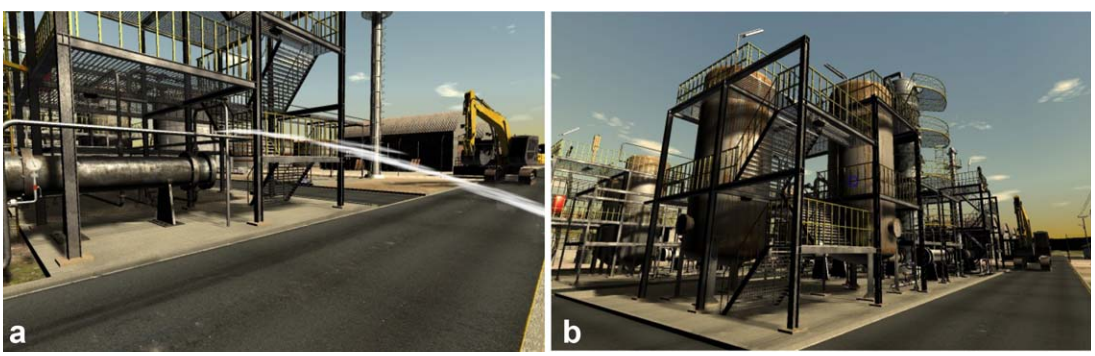

Figure 2. (a) Example of IVE showing a leakage from a pipe. (b) Example of IVE showing a refinery subsection.

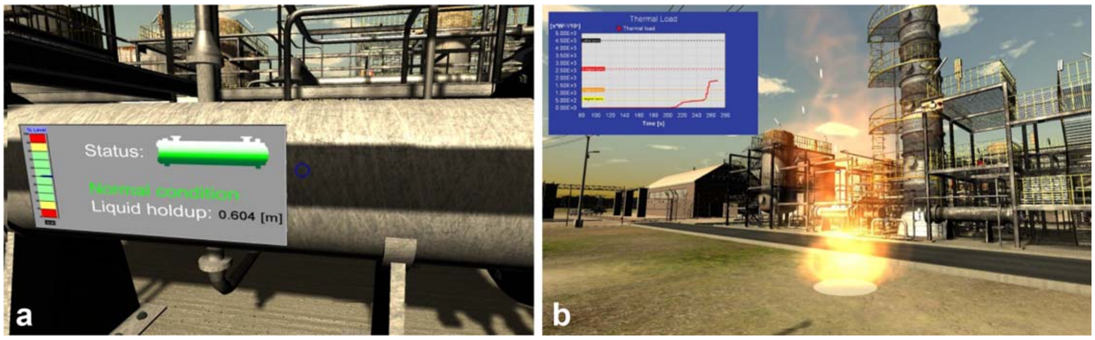

Figure 3. (a) Example of AVR showing the internal operating conditions of a reboiler in a refinery. (b) Example of AVR showing the thermal load on the FOP exposed to a pool fire originated by the ignition of the liquid emitted by the ruptured pipe of Figure 3a.

The operator undergoes two stages of training that are organized according to a suitable hierarchy. At Stage 1, after the lectures given by the trainer in the IVE (see Figure 5a), the operator is guided/supported step-by-step to perform the task (on any given section/unit, see Figure 5b).

The training procedure is performed at the best and most crisp operating conditions to improve his/her process understanding. The use and support of colors, sounds, alarms, beeps, and visual helps, is appropriately chosen to stimulate and enhance the understanding of the trainee. Once the trainee has learnt to interact and operate with the PS, she/he can undergo, at any time, a number of personal exercises and tests to improve his/her skills. Stage 1 of the training hierarchy is characterized by the automated help and support of the PS infrastructure that, when necessary, can drive the operator to perform the correct actions and take the proper decisions. At Stage 1, the PS provides also a support when the operator makes a wrong action by highlighting either the device or the process unit where the error occurred and by providing suitable and interactive explanations to reproduce, but also recover from, the wrong action/decision and eventually take the correct one(s).

Stage 2 of the PS training session takes the trainee toward a more demanding environment that is closer to the real one and is devoted to his/her assessment. Stage 2 differs from Stage 1 for three main points:

1. Every action undertaken by the operator has a relative marking according to its significance with respect to the process. The relative marking is based on a deep and extensive knowledge of the process and operating procedures. To determine the relative weights among different actions that contribute to assess the final mark, the assessors can rely on well-known and widely accepted methodologies such as the Analytic Hierarchy Process technique [29]. For the sake of clarity, the assessors are expert people who are involved, at different levels, in the process management and in the plant operation, and have a good knowledge of both its dynamics and evaluation methodologies. The identification of relative weights is therefore done once for all before performing the assessment procedure (i.e., Stage 2) and is based on an interdisciplinary exchange of visions by a group of experts.
2. The information on mistakes/errors is not provided at all (i.e., in line with what happen in real operating conditions) and no special hints are provided to the trainee unless she/he specifically asks for them (see also the forthcoming point 3).

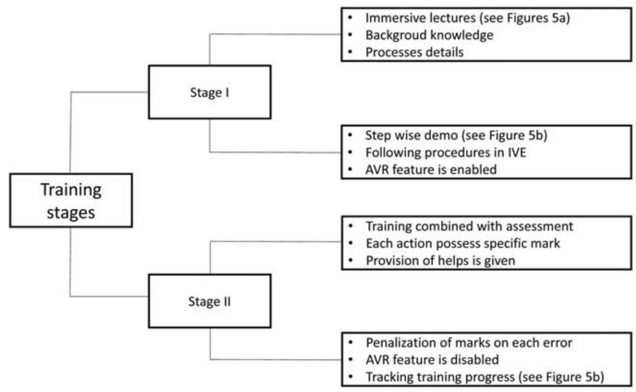

Figure 4. Stages of training phase in the PS.

3. Help is provided only if requested, contrary to Stage 1, where the program guides the operator to follow and understand the procedures. Moreover, there is a well-defined penalization of the overall mark as a function of the number and level of help requests.

Performance Assessment

Training procedure and performance assessment are two distinct but at the same time interconnected features of the PS. If the operator assessment is not meant to test the real understanding and skills improvement achieved by the training session, the benefits of training can be refrained from achieving its potential. In recent years some work, as reported before, has been focused on training improvements [2, 17, 30]. However, it is opinion of the authors that performance assessment of industrial operators is a topic yet to be dug into, and extensively discussed by the scientific community.

The common procedure to assessment adopted by several organizations is centered on a conventional approach based on the direct judgment of the trainer by the trainer. A human judgment can be rather subjective since it is based on the personal impressions [31]. Such a judgment may vary as a function of both the trainer(s) and the trainee(s). Thus, it is highly desirable that the operators' assessment is carried out by implementing and then running a reliable, repeatable, systematic, consistent, and automatic tool that is completely neutral and avoids any subjectivity [28]. In addition, advanced tools for operator training call for an automatic

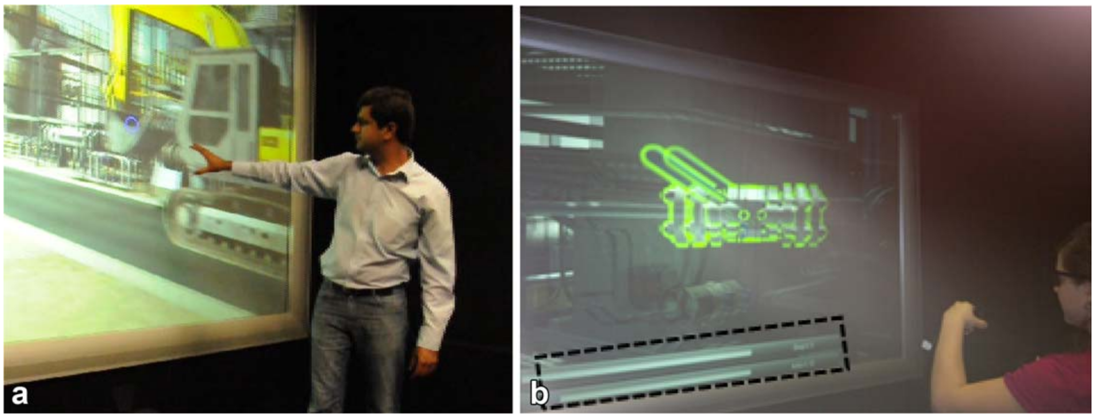

Figure 5. (a) Trainer providing process details in an immersive lecture. (b) Trainee following the automatic training session in PS where the progress can be seen (see dashed bottom rectangle).

procedure to assess the training degree of operators. Such an assessment should be implemented in a computer program capable not only of evaluating the marks about the performance of operators but also of registering, storing, and analyzing the actions and decisions taken by the operator(s) during the training session (within PS/Virtual Environment). This tool would not only add precision to the assessment but also the possibility to define each parameter with its relative marking and store all the data. The capability of the developed tool to store all the actions and errors conducted during the training sessions can generate a large amount of data that can be capitalized for further Human Factors studies (see Manca *et al.* [28] for further details). Eventually, safety critical actions can be identified, leading to amendments in the existing training methods and design modifications [15].

Human beings tend to give equal marks to all (apparent) parameters without considering the relative significance and statistical comparison of single parameters [29]. Therefore, a trainer may make judgments and evaluations according to his/her understanding and experience at the plant site and thus introduce the possibility of misinterpretation of the trainee's performance. By doing so, the job assessment of the operator would be influenced by the final evaluation of the trainer. The personal/individual evaluation, especially in presence of some shortcomings, can result in the inconsistent job allocation to an operator who might be either incapable or inadequately trained to perform efficiently that allocated task.

In order to overcome the challenges and reduce the gap between the current methods of performance assessment and the one discussed above, the Authors designed and implemented a software tool for the assessment of industrial operators. This tool gauges and records in real time a set of process and accident variables, actions, decisions, and time intervals that come from both the process-accident simulators and from the human machine interface of the IVE and determines/evaluates (again in real time) the performance indicators required to quantify the training level of the operator.

Figure 6 shows a simplified structure of the performance assessment algorithm. During either the training or the assessment phases all the actions, errors, and events are logged. This information is analyzed in real time with the help of a Process Assessment Module (PAM). The PAM includes the reference procedures, the marks for each set of procedures and the weighing criteria for the actions, events, and possible errors.

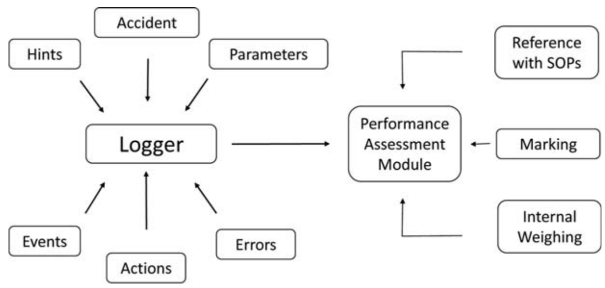

Figure 6. Schematic representation of the performance assessment algorithm.

CASE STUDIES OF THE PLANT SIMULATOR

As discussed in the previous sections, the coupling of a dynamic process simulator with a dynamic accident simulator allows describing in real time the evolution of a large number of processes/plants. The availability of an IVE (see also Figures 3 and 5) and some human-machine devices to interact with the PS, allows experimenting immersive and realistic training sessions. The following subsections present two distinct case studies the allow grasping more in detail the applied advantages conveyed by the PS.

Case Study I

The first case study, partially shown in Figures 2 and 3, is based on a C3/C4 splitting section of an oil refinery. The experiment consists in simulating the sudden and unexpected flange rupture in a butane pipe. An excavator working in proximity of the C3/C4 splitter hits accidentally a pipe rack causing the flange rupture. The consequent butane (flammable) outflow produces a liquid jet that forms a spreading pool on the ground. The coupling of the process and accident simulators allows describing in real time what is happening. The IVE, which is projected onto a large screen, shows in 3D the accident event and calls for the prompt intervention of the FOP. This case study requires the interaction between a CROP and a FOP. The CROP participates to the experiment in front of a conventional operator training simulator (OTS) that reproduces the DCS of the real control room and exchanges information with the FOP by means of a two-way push-to-talk device (e.g., walkie-talkie). The experiment consists in both operators (i.e., CROP and FOP) playing their respective roles and dealing with the accident event. In practice, this calls for either closing or opening some remotely operated, as well as in-the-field, valves to first intercept the liquid outflow and then control the level of the upward reboiler that gets flooded by the abnormal situation. An event scheduler, which can be configured once for all by an expert trainer, allows triggering the events (e.g., excavator hit, pool ignition, and fire extinguishment) according to either assigned times or the occurrence of specific events (e.g., ignition of the pool when it reaches a specific dimension; extinguishment of the fire after a given time). The experiment can be run either unattended (i.e., without the presence of the trainer) or with the trainer observing the reactions of the trainees and even triggering the aforementioned events or modifying the time of the day/night and the weather conditions (which not only modify the process/accident outcomes but also play a role on the fruition of the experiment by the FOP). Throughout the duration of the experiment, the information-technology infrastructure of the PS records and stores the process variables, valves position, accident parameters, and reaction times of both the CROP and FOP to finally assess their performance (see Figure 6). This feature allows to track dynamically the preparation, skills attained, knowledge retained, and actions performed by the industrial operators. It also allows selecting the trainees who are ready to operate in the real environment. The performance assessment procedure produces two detailed personal reports that are usually sent to the trainees (i.e., CROP and FOP) and the trainer (depending on the organization's policy). This feature rises the level of the PS from an advanced OTS to a decision-making solution that allows also identifying the optimal composition of the team of operators which best suits the efficiency and safety requirements of the company.

Since the process and the accident simulators are tightly interlinked, they allow calculating the two-way effect and consequences of possible accidents on both the equipment and the FOPs. In addition, the effects of the accident on the equipment (such as the radiative flux emitted from a pool/jet fire) can produce a counteraction on the accident event due to the modified process conditions (such as the temperature, pressure of the process streams, and of the process units). Some experiments were performed using the case study discussed here and it was found that trainees trained with the PS were able to mitigate the consequences of the simulated accident [19, 26].

Case Study II

The second case study is based on the polymerization process for the production of propylene with a Ziegler–Natta catalyst [32]. An inlet stream of catalyst that enters the pipe network by means of an injector characterizes this process. At periodic time intervals (in the order of a month), the injector gets fouled and it is necessary to run an injector-switch procedure for maintenance purposes. This procedure is performed by a FOP and lasts few minutes. It comprises 31 precise and sequential operations mainly based on opening and closing field-operated-valves (FOVs). In addition, the operator has to watch, understand, and verify the value of some flow meters and wait for a specific time interval before proceeding with some further actions. The difficulty of the whole procedure consists in working in a quite congested area of few square meters where there are tens of pipes and more than 50 FOVs (see Figure 7). Among these valves, the FOP has to identify and operate about 20 valves for a total of more than 30 actions (i.e., open/close, watch, wait). The correct sequence of actions is well defined and cannot be subverted.

Any deviation from the prescribed sequence may have fatal consequences on the process. A quite high probability of process failure consists in the polymerization of the monomer

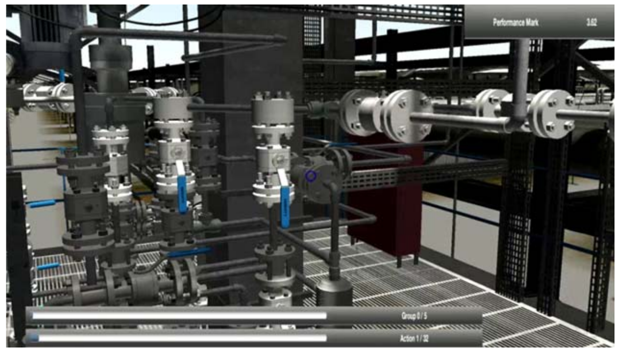

Figure 7. Three-dimensional representation of the catalyst-injector-switch procedure.

inside the catalyst injector. If this happens, the whole polypropylene plant must be shut down, and the injector removed and cleaned off-line with high-pressure steam jets. Moreover, an error in following precisely the sequence of actions may lead to hazardous situations. It is straightforward understanding the economic impact on the plant operation played by a wrong action. In this case, the PS plays the primary role of loss-prevention tool. Consequently, the PS is focused on the process simulation and on showing the correct sequence of actions to achieve the proper injector switch. The performance assessment is based on the reference sequence of actions and the corresponding time-intervals between consecutive actions. The FOP receives a detailed report at the end of the experiment that analyzes the relevance of the deviations from the correct sequence of actions. The PS can be used repeatedly up to when an acceptable threshold is reached and held. The final overall mark with an accompanying qualitative description of the training level reached, allows understanding when the FOP is ready to perform the real injector-switch procedure. The trainer can use the PS to select the best candidates for the monthly procedure while forcing those, who are still not ready, to undergo some further training sessions. In addition, thanks to the modularity of the PS, the trainee can focus the exercise on the specific group(s) of actions where she/he performed worse. On the other side, by collecting the performance results of a large number of trainees, the company can infer some important statistics than can outline the weak points of the official procedure, thus focusing on improving/modifying the actions/features/devices in order to debottleneck the procedure and reduce the risk of failures. This case study shows how the PS can be used not only for OTS purposes but also for decision-making and process/procedure improvement.

The PS is able to couple process details, evolution of accident, and record the actions and errors done by the operator. These features combined together in an IVE make the PS an advanced tool for training and assessment. Aim of this work was to demonstrate the benefits that can be obtained by combining various disciplines (e.g., cognitive sciences, information technology, organization psychology, Human Factors, and engineering) to raise the standards of operator training and performance assessment, which can eventually make the process industry safer.

CONCLUSIONS

The article introduced the concept of PS, which consists of a dynamic process simulator and a dynamic accident simulator interlinked in a 3D IVE supported by AVR. The necessity of realizing and overcoming the current shortcomings of training and assessment methods for process industry and proposing appropriate solution were the main features of this work. The proposed solution, that is, the PS, showed its efficiency in improving the overall process safety by empowering the understanding, performance, responsiveness, and precision of industrial operators. The assessment of the operators was presented and discussed through the introduction of an *ad hoc* software tool capable of producing automatic, reproducible, and unbiased evaluations of the performance of the trainee(s) based on a multidimensional set of parameters. A range of rather promising future research activities can be envisioned. By focusing on possible improvements in areas such as training, spatial learning, knowledge improvement, and performance assessment (as this topic has been overlooked in the process industry) several abnormal situations and incidents/accidents might be prevented and avoided. The article introduced a few areas to be further investigated and raised a number of issues that need to be addressed in the future.

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