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The Plant Simulator as viable means to prevent and manage risk through competencies management: Experiment results

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ABSTRACT

Making decisions and managing competences in complex systems is a challenging task to accomplish. Specifically, the process industry is known for its complexity and sensitivity to critical procedures. Recent disasters like the "Deepwater Horizon" (2010, 11 fatalities), BP Texas City (2005, 15 fatalities), and AZF Toulouse (2001, 29 fatalities), clearly showed the risk to which we are all exposed. The increasing complexity of processes, due to the simultaneous escalation of automation, optimisation and intensification processes (followed to face globalisation challenges), are moving the attention to the management of abnormal situations, which are even more complex in nature and frequent. This increasing complexity, coupled with the fact that abnormal situations may lead to irreversible losses, is imposing the adoption of adequate approaches and tools that allow for better learning and properly managing abnormal situations. The paper presents a simulation-enabled, experiment-based approach that can be used to prevent and manage risk through competencies management. More specifically, the paper presents the results of the first experiment campaign performed in a Plant Simulator (PS), the first known in the process industry domain, and shows the efficacy of using Immersive Virtual Environments (IVE) both to make decisions and to train teams (not just single operators).

The experiment results presented in the paper show the effectiveness of IVE to increase the competencies and train operators and managers. In addition, they explain how conveniently the data collected by means of the PS can be used for making daily decisions to better prevent and manage risks.

1. Introduction

The optimization, intensification, and automation processes taking place in industry to face globalization are significantly increasing the complexity of productive processes. This transformation is making progressively difficult to anticipate and predict the combined effects that those transformation processes have on operations, thus practically translating into complex systems that are increasingly difficult to manage and operate.

Operations of safety–critical systems (Knight, 2002; Pimentel, 2003), such as those of the health, the nuclear, the aviation and the process sectors are certainly difficult to manage and complex to operate and, consequently, the task of managing the competencies, needed by operators and managers to cope with their complexity, is increasingly difficult. The Board that investigated the loss of the Columbia space shuttle noted that "*complex systems almost always fail in complex ways*" (NASA, 2003). Actually, when an accident takes place in such complex systems, it is always tempting to ascribe to one crucial error and point the finger at one bad operator. Failing to identify the real, complex causes is highly risky as any reductive (accident) reconstruction provides a dangerously incomplete or distorted picture of what really went on. This distortion negatively influences the subsequent decision-making process (Harms-Ringdahl, 2004; Lundberga, 2010), as decisions are grounded on misleading conclusions (as partial). Further, the simplistic or distorted picture does not have either all or the correct details to unveil the cause-consequence chain that brought to the accident. This leaves those who contributed to the accident but were "untouched" by the accident (*i.e.* were not mentioned in the investigation report) unaware of their contribution, thus risking to leaving space to (or even reinforcing) the dangerous complacency that led to the accident.

Amongst others, it is thanks to Perrow (1984), Sagan (1993), Reason (1990a, 1993, 1997), Weick and Sutcliffe (2001), Hollnagel (2004), and Hollnagel et al. (2006) that the organizational dimension of accidents became clear, enabling operations safety to start going beyond the classical, technical,

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shop-floor-related explanation of accidents and embracing an organizational and systemic dimension. These studies and theories have been very useful and enlightening as they allowed to understanding that the shop floor activity is (tightly) linked to the managerial one and, being the two (tightly) coupled, whatever happens to one activity influences the other. In addition, the higher the coupling level the higher and quicker the reciprocal influence.

What these studies did not help to clarify and solve is the very root cause of accidents: the (human) difficulty of learning and acting (*i.e.* operating) in complex systems. Before enlarging the perspective to the organization, many studies and groundbreaking theories came off the research scene. It is thanks to Rasmussen (1986), Reason (1990b), Hollnagel (1994, 1998), and Endsley (1995) that the human role and dimension in highly automated systems became clear: a system's function which is more devoted to performing supervisory rather than manual tasks, *i.e.* cognitive rather than physical tasks.

Wickens and Hollands (2000) clearly explained the complexity that operators have to face during operations. According to such authors, industrial processes are generally highly complex and involve a high number of interacting variables and many degrees of freedom (Moray, 1997). Variables can be cross-coupled, so that changes in one variable affect several other variables simultaneously. Further, the effect of the change in one process variable, *e.g.* opening a valve on a Distributed Control System (DCS) to increase a mass flow, may significantly differ in time and space, thus making it very difficult to envisage the overall effect on the plant. Modern control rooms comprise more than 5000 synoptic displays and thousands of control loops and related alarms to get the whole picture of these processes (Sheridan, 2006; Vicente et al., 2004). Such complexity can severely overburden the operator's mental model of the status of the plant, thus making extremely difficult to identify the state of the plant. The mental model of the status of the plant, however, is critical for both normal operations, *i.e.* nominal conditions, and abnormal situations. The added stress and anxiety experienced during an abnormal situation may increase the cognitive load and attention requirements of the operator (Wickens and McCarley, 2008). For this reason, it is of paramount importance to anticipate, measure, and assess what might be the effects on learners' performance caused by both an increase of plant complexity (typically due to process and/or interface changes) and abnormal situations.

Understanding and learning the complexity of the process by following the correct procedures and keeping a good level of (situation) awareness and readiness during both nominal and abnormal conditions is the important task an operator is responsible to manage. On the other hand, measuring and assessing these capabilities with the ultimate goal of identifying the necessary competencies and tools operators need to have to safely face their daily duties is the task an operations manager is responsible for. Today, due to the increasing high complexity, both these tasks are challenging already during nominal operating conditions; accomplish them during abnormal situations might turn out to be a struggle. Aim of this paper is to propose a viable way forward to both these challenges.

2. The simulation teaching method and the learning theory

The simulation is an active teaching method founded on the problem-based learning (PBL), which is a general model developed in medical education in the early 70ies; since then it has been adopted in an increasing number of other education disciplines (Business Administration, Architecture, Engineering) to replace the traditional lecture-based approach (Savery and Duffy, 2001). In the PBL perspective the learner faces an unstructured problem, which reflects a complex work situation (*i.e.* identifying and preventing specific risks), whose solution is to make an individual or group decision with colleagues (the superior or peers) according to the nature of the risk at stake.

The application of the simulation teaching method is particularly suitable in safety education: learners live vivid, realistic experience in a virtual environment (which replicates the concrete work situation) of how to make decisions to manage dangerous and unexpected events. The learning situation is completely safe as learners' wrong decisions and behaviours do not have real, dangerous effects and consequences can be traced and measured for further investigation (*e.g.* root cause analyses).

The PBL (or simulation-enabled approach) is founded on the constructivism theory, which is based on the following four assumptions, namely: (1) learning depends on the previous knowledge of the trainee; (2) the design of the education or training process must be learner's centred; (3) the teacher/trainer is responsible to design a learning situation where the trainee is enabled to explore problems, make decisions and find solutions autonomously; and (4) the correct behaviour is rationalized with the application of the theory at the end of the learning process (and not on the contrary) (Del Fiore and Martinotti, 2006). In the constructivism research program, the situated and social learning sub theory (Lave, 1988) defines the knowledge as expertise, that is practice knowledge in action, embedded in an wider organisational action system. Consequently, the learning process is necessarily situated in a specific environment, which is formed of technological artefacts (and even of other persons like trainees and/or trainer/teacher) with which the learner interacts. The learning process is then twofold: individual and social (Bandura, 1986).

The simulation-based approach (which based on an IT infrastructure or artefact) is known as a virtual reality simulation, *i.e.* a technology-based learning (Tarique, 2014). It is composed by three elements: ICT created environments, agency and isomorphic representation (Cerande, 1993). Virtual environments offer the possibility to recreate the real world as it is or new ones (particularly useful during the design phase of a project). Agency (or interactivity) enables the learner to be active by interacting with the virtually risky situations (and make decisions). The isomorphic representation (or placement) of the body's learner (or its body's parts) or its total immersion is where the learner experiences the virtual environment as immediate and through multiple senses. The application of virtual reality simulation/simulators has several advantages in developing safety skills to prevent and manage risks in industry. It improves the recipient's absorptive capacity (both at individual and group level), providing expertise that help learners understanding work situations and problems and in improving their decisions process (Pasqualotti and Dal Sasso Freitas, 2002). Trainees acquire more information if more senses are involved in the learning process; they are more receptive when they see, listen, hear, communicate and act at the same time (Barraclough and Guymer, 1998). The virtual reality simulation is a valuable substitute for dangerous real experiences as it allows for learners to acquire tacit knowledge that otherwise will not be transferred trough traditional educational methods (book, manual, lessons). This is relevant in the case of organisations that require nearly error free operations, because otherwise they are likely to incur in catastrophes (Roberts, 1990). Virtual reality simulators are very useful to help workers and managers in learning how to perform specific activities (both at individual and group level) that must be repeated as often as required to in a safe environment (Chittaro and Ranon, 2007). They could represent an effective tool to enhance coordination and synchronization skills in groups operating in high reliability organisations (HROs). Through repeated simulations, team members can experience group activities coming to a shared understanding of why and when certain decisions and behaviours are appropriate, thus increasing their skills in mutual coordination and adaptation (Golzio et al., 2006). As it happens in the HROs, virtual simulators could be used to train groups to adapt quickly and accurately to non-routine events (Waller, 1999). This use of virtual simulators is relevant in improving safety management systems: it helps groups in abandoning quickly and timely routines in favour of more flexible and contingent behaviours when unexpected and non-routine events occur; it enables workers to acquire collectively an adequate mindfulness (Weick and Sutcliffe, 2001). The evaluation of educational efficiency of virtual reality simulation has privileged usability issues rather than its learning efficiency. A general evaluation framework that consider the multidimensionality of learning has been proposed (Roussos et al., 1999):

- The technical dimension concerns usability issues (interface, physical problems, hardware and software systems).
- The agency or interactivity dimension examines the interaction between the learner and the virtual environment (navigation, spatial orientation, presence and immersion, feedback issues).
- The affective attitude evaluate the engagement of the learner (appreciation, confidence in the virtual environment).
- The cognitive dimension concerns the learning improvement of the virtual experience.
- The pedagogical dimension examines how to design a virtual reality simulation, the role of trainer/teacher, to gain knowledge effectively by the learner.

A recent pilot study focused on the development of a 3D virtual safety training program dealing with specific hazards and safety measures related to grinder operation and simulating a live hands-on environment. Results indicate that in the 3D virtual environment participants learned more than did their peers in the lecture-only group: on average (quiz assessment) the lecture-only section scored 47.72%; the lecture-physical lab section scored 68.06%; the lecture-virtual exercise section scored 86.11% (Nakayama and Jin, 2015).

3. Competences management and performance assessment – the Plant Simulator (PS)

Managing competencies (and the associated learning processes) in modern complex systems requires innovative approaches like virtual reality as accidents caused by human-related tasks (*i.e.* the so-called human errors), are estimated to be in the range of 50–75% (Endsley, 1995; OECD, 2003; Salmon, 2009).

The simulation-enabled approach gives much more flexibility to both the trainer and the trainee to experience the out-of-specs conditions and experience how the system (*i.e.* the plant) behaves in those situations.

3.1. The Plant Simulator (PS)

The Plant Simulator (PS) is the expression coined in Colombo et al. (2011), for chemical production sites, to address something that is in analogy with the flight simulator paradigm. The PS is an IT infrastructure created to replicate the exact plant conditions and to enable both the CROP(s) and the Field Operator(s) (shortly referred to as FOP) to cooperate as they would do in reality, *i.e.* as a team. The PS allows for CROPs and FOPs to experience both rationally and emotionally the same situations they would live in reality in terms of process behaviour and consequences originated by either nominal or abnormal operating conditions.

The PS comprises at least two rooms, namely the CROP room and a FOP room, to be separated and isolated from one another, as the CROP and the FOP(s) have not to see and hear each other as in reality. Similarly, the CROPs and FOPs can communicate by means of the so-called "*walky-talkies*". This setting is necessary to replicate realistic working conditions.

The three features that make an IT infrastructure a PS are as follows:

1. The capability to allow the CROP and FOP(s) to operate in the PS as they would do in reality with the field of operations, *i.e.* perform realistic actions as close as they are performed in reality (in terms of gestures) and get realistic information and response from the system.
2. The capability to emotionally involve people in the simulated environment so that they behave the same way they would do in reality (*i.e.* reach a "psychological fidelity").
3. The capability to assess the CROP and the FOP(s) performances, as well as those of both as a team, in real-time.

In order for a PS to reach the aforementioned features, it has to be equipped with the following software:

- A real-time dynamic process simulator (to simulate the behaviour of what is occurring inside the pipework and the process units).
- A real-time dynamic accident simulator (to simulate possible incident/accident phenomena, *e.g.* leakages, pool fires, jet fires, gas dispersions).
- A real-time tracking system (to track every action performed by both the CROP and the FOP).
- A real-time performance assessment (to measure and assess in real-time the performance of the CROP, the FOP and that of both as a team).
- A suitable IT infrastructure to seamlessly link all the aforementioned components to work in real-time and allow both the CROP and the FOP to interact with the simulated environment and get realistic responses in terms of process behaviour and environmental effects (*i.e.* noise, light, process parameters).

The PS links together, synchronously and in a multidirectional way, all the aforementioned components to work in real-time and allow both the CROP and the FOP to interact with the simulated environment and get realistic responses in terms of process behaviour and environmental effects (*i.e.* noise, light, process parameters). In practice, this means that if a FOP opens a manual valve in the field, the CROP has to see it (if the valve is represented) on his/her control screen and vice versa.

3.2. How a Plant Simulator looks like

The PS has to replicate the working environment in a way that, overall, is perceived as realistic. For the FOP room, the realistic visual perception is reached by means of an Immersive Virtual Environment (IVE), neither a simple desktop nor a non-immersive Virtual Reality screen, while the auditory perception is achieved by spatial sound (the so-called 3D sound).

As (the left of) Fig. 1 shows, the realism in the CROP room is reached by creating the exact replica of the control room, furniture included. Typically, the CROP, once immersed in the simulation, does not feel any differences with respect to the real control room of the plant.

On the other hand, the FOP room is far more complicated to replicate due to the inherent (potentially huge) dimension of the operations field. (The right of) Fig. 1 shows a typical IVE displayed in the FOP room. The FOP operates the equipment (*i.e.* interact with them) by staying in front of the immersive screen (typically with natural gestures). The screen size, in order to reach a good degree

Fig. 1. A typical replica of a Control Room (left) and a replica of an Immersive Virtual Environment of the Plant Simulator (right – courtesy of the Virthualis project).

of immersivity, must be in the order of 3 m wide and 2 m height (for each FOP).

The CROP and FOP(s) rooms are connected through the PS infrastructure.

The strength of using a PS consists of giving the possibility to train the CROPs and the FOPs, as well as managers, as a team, thus replicating the exact conditions of the real plant. By means of a "what if" approach, scenarios are experimentally experienced and data are collected and automatically manipulated to generate and display, in real-time, the Key Performance Indicators (KPI) of each operator and those of the team.

In the PS the CROP and the FOP can perform the actions they "wish" to and those they have doubts for, as well as experience the system response and test their capability to cope with the scenario, be it a conventional (*i.e.* programmed), an abnormal, and even an accident situation. The manager(s) can always be involved in the simulation by staying in a remote room, as it would happen in reality when staying in the crisis room, and by interacting with the CROPs and FOPs via walkie-talkies.

3.3. Limitations overcome by the PS with respect to the OTS

Commercially, the simulation-enabled approach is covered nowadays by the mature technology of the Operator Training Simulator (OTS). The OTS replicates the control room both physically and behaviourally (the left side of Fig. 1 shows a typical replica of a control room). Conceptually, OTSs are applied successfully in different domains such as the nuclear, the avionic, the naval, the military, the health and the process one.

The inherent limitation of the OTS is that it enables to train the control room operator (CROP) only as the part simulating the field, necessary to train field operators, is not technologically implemented.

In an OTS, the scenarios CROPs are faced with are "rigidly" implemented into the system and are always the same. The operators then stay in the simulator for days (in some companies CROPs "work" in the simulator for an entire week every year or every semester) and go through the same scenarios repeatedly. CROPs have not the flexibility of behaving the way they would like to, *i.e.* trying the things they do not dare to try in the real plant and whose consequences make them feeling unsecure.

There are two further limitations traditional OTSs hold, namely: they are not designed to train FOPs and they cannot simulate incident/accident events.

In a conventional OTS the FOP part, *i.e.* the field operation, is not technologically implemented because it is assumed that, given the high level of automation, the human part that counts for managing the plant is only the CROP. The five-year research performed within the European project VIRTHUALIS (the largest European project on industrial safety financed by the European Commission under the VI Framework Programme), allowed to understand that, even in the most automated plants, the interaction between CROPs and FOPs is fundamental to reach the correct understanding of what is going on, and then to make the right decisions. The reason lies in the different perspectives brought in the decision making process by CROP and the FOP(s). Actually, the CROP sees a global (but artificial), schematic, and plant-sensor-driven reality displayed in the synoptics of the control room, while the FOP sees a partial (but real), "touchable" and human-sensor-driven reality. The two views are complementary and, above all, incomplete. This is why it is important that the two types of operators team up to decide what to do next.

4. The paradigm shift

4.1. From a speculative to an experimental approach in decision making

Today, operations safety decision-making is widely grounded on risk assessment outcomes, *i.e.* safety reports, whose creation is typically outsourced to consultancy companies. In these analyses, when the Human and Organizational Factors (HOF) are to be accounted for, even for conventional systems, risk assessment methods available today are all but robust (Skogdalen and Vinnem, 2011). When it comes to more modern and innovative production systems, like in the Integrated Operations (IO) scheme, the situation gets even worse as both risk assessment and risk management methods become weaker (Andersen and Mostue, 2012), thus imposing the adoption of new and more effective paradigms.

For these reasons, the proposed approach is to:

1. Ground the well-known KPIs used by managers to make their decisions on the real capabilities of operators and managers operating in the plant.
2. Gather data on operators' and managers' performance (*i.e.* on the real capability to operate the plant during normal and possible abnormal conditions) by means of an experimental approach, *i.e.* by means of realistic experiments performed within a PS.

This experimental approach, in contrast to the more classical and "speculative" one (based on experts' analysis capabilities and experience), guarantees that decisions embed the effective capability of the productive system to respond to both abnormal and emergency situations, as well as to cope with daily upsets to avoid production discontinuity.

4.2. Why a PS is needed

In the proposed approach the assessors, who are typically experienced CROPs and FOPs, contribute with their operational experience to the definition of the assessment software (structure, hierarchy, logic, and weighting). Their experience is then used to develop the algorithm that assesses, in real-time during the simulation, the performance of the operators and that of the team. By doing so, a twofold benefit is achieved, namely: (a) the assessment variability given by the subjectivity of the trainer is avoided by design; (b) operators' benchmarking is made reliable, consistent, and reproducible. Furthermore, the time spent conventionally by the trainer to assess the trainee(s) can be conveniently and more efficiently devoted to design new scenarios to better challenge operators and managers, *i.e.* teams, with the ultimate goal of increasing their resilience.

In the proposed technology-enabled performance assessment approach, the technology captures the actions made by the operators (*e.g.* opening and closing valves – either in the field or in the control room, communicating with colleagues, searching for equipment), measures the parameters associated with these actions and, in real-time, assesses the performance of each operator and that of the team. Consequently, the shared, validated, and agreed subjectivity is "built-in" in the algorithm once for all. In addition, its logic applies to everybody in the same way, *i.e.* performance is assessed independently on the assessor's lucidity and feeling (as well as tiredness and boredom).

The PS allows operators performing any needed actions (as actions are only bounded by the laws of physics representing the phenomenon). This is the reason why operators in a PS become profoundly involved in the simulation and the behaviour they show during the simulation can be assumed to be the one they would take in reality. Thanks to this, what the PS measures about performance can be assumed to be realistic, *i.e.* reflecting what would happen in the real plant, and thus used as a viable ground for decision-making.

The first immediate benefit is that, if the operators' behaviour within the simulator can be assumed to be the one they would take in reality then the PS can be used for selecting and certifying operators. Actually, this is exactly what happens in the aviation domain since years. Nowadays, there are no pilots worldwide that before piloting a real aircraft have not passed the flight simulator barrier, *i.e.* they must be certified through the simulator first. In addition, even when a pilot is certified for real flights, in case s/he has to stop piloting for a certain period, before being allowed to go back and pilot an aircraft again s/he has to perform a certain number of hours in the simulator and pass the test again. Therefore, the question is: why should it not be the same for operators in the process industry, where there are operations that are as much critical (in terms of production continuity and safety implications) as those required to piloting an aircraft?

The second immediate benefit is that the time spent in the PS has a double value: for operators training and for decision-making. Actually, if operators perform well in the PS and they are confident about the realism of the PS, then they will feel safer as they will feel to have good chances to cope with that situation even in reality. In addition, the PS will give them the possibility to experience the complexity and the difficulty of coping with both abnormal and emergency situations, thus contributing to fade away the dangerous complacency that might lead to an accident.

The same positive effect applies to decision-makers. Let us take as example the shift supervisor that has to define the shifts for a plant operation that is critical both in terms of business continuity and safety, *e.g.* the switch of catalyst injectors in a polymerization plant (Wang, 2007). Let us now suppose the shift supervisor has a PS to train and assess the operators on that process/procedure. Then, s/he would be able to browse the simulation results obtained in the weeks before the catalyst injectors switch, look at the operators' performances and put on shift the one(s) who best performed in the PS. By doing so, the time spent by operators in the simulator would not only serve to train, motivate, and make them more resilient, but would also to be used for decision making purposes to daily manage the plant in a safer and more efficient way.

5. The experiment campaign

5.1. The goal of the experiment campaign

The goal of the experiments performed in the PS was to understand and, above all, measure the impact of Immersive Virtual Reality (IVR) on the performance of industrial operators when facing abnormal situations.

In order to reach this goal, the last two years of research were focused on two main streams, namely:

1. Designing and implementing an accident scenario in the PS involving both the CROP and the FOP.
2. Designing and developing an algorithm (within the PS framework) capable to automatically measuring, objectively and in real-time, the performance of operators.

Questions like "Does IVR truly increase performance?" and, given it does, "What is the extent to which performance is increased?" are the main questions our experiment campaign focused on and whose results are described hereafter.

5.2. The experiment scenario implemented in the PS

The context implemented in the PS is a C3/C4 separation section of a crude-oil refinery. Fig. 2 shows a snapshot of the IVR used for the experiment.

Typically, in a C3/C4 separation section, there are flammable and hazardous hydrocarbons involved. The accident scenario implemented in the PS is that of a "hot work" being performed in the field in which something goes wrong. Specifically, an excavator working close to the C3/C4 distillation unit accidentally hits a pipe in which is flowing a stream of pressurized liquid butane (C4). The collision breaks the integrity of a flange of the C4 pipe resulting in a liquid jet and in the spreading of a pool on the ground. Fig. 3 shows the accident event (*i.e.* the leak and the fire).

After a given time (the same for all participants), an ignition source ignites the pool and generates a fire. As soon as the collision occurs, the FOP is supposed to report the event to the CROP. Once the FOP identifies and acknowledges the leakage, the CROP and the

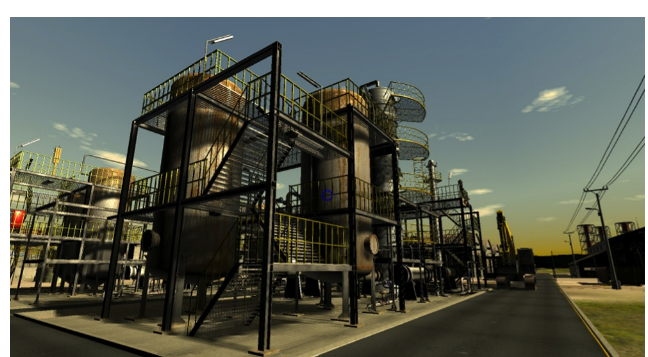

Fig. 2. Immersive Virtual Environment of the C3/C4 separation section of a refinery used for experiments.

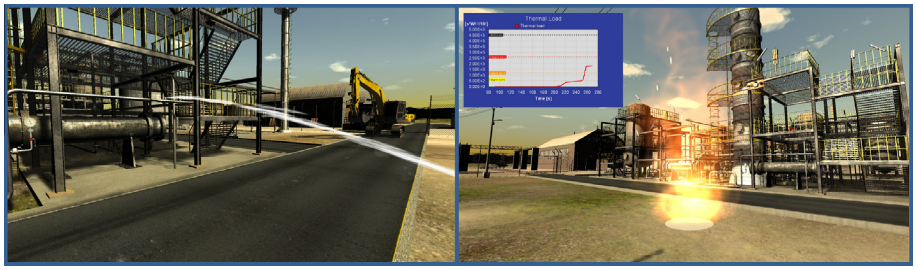

Fig. 3. Liquid jet of butane as a consequence of flange integrity rupture (left) and pool fire of butane as a consequence of the leakage from the flange (right – both courtesy of the Virthualis company).

FOP cooperate to figure out which is the best action to take and, once agreed, the CROP closes the automatic remotely-operated valve necessary to cut off the flow of butane in the pipe, thereby stopping also the outflow from the ruptured flange.

To avoid any inconsistency, the CROP's role is played always by the same expert person who perfectly knows how to operate and interact aseptically and unbiased with the FOP who undergoes the experiment.

The FOP is also required to acknowledge the shutoff of the liquid jet and report it to the CROP. The next event to occur is the ignition of the spreading pool. In this situation, the FOP is expected to become aware of the situation and immediately report the fire to the CROP. The CROP then performs the necessary actions (*e.g.* s/he alerts the internal fire fighters team). However, the situation is not over as, because of the closing of the automatic valve in the DCS (to block the C4 outflow), the reboiler level starts increasing. The two operators (*i.e.* CROP and FOP) have to cooperate/interact in order to flush off the liquid in excess in the reboiler and control its pressure. Consequently, the FOP has to identify and open the correct manually operated valve (*i.e.* the one shown during the training session). Table 1 summarizes the sequence of the simulated events. All participants of Group A and B performed the same exact sequence reported in Table 1.

5.3. The key performance indicators for operators

The performance measurement and the associated assessment for every FOP/trainee/participant is based on specific KPIs and the comparison is made with respect to the aforementioned two distinct training methods, namely:

- A slide-supported presentation (typically used in industry after a critical accident or near miss has occurred).
- An immersive 3D training environment.

Table 1
Description of relevant assessment steps.

Steps	Description of the events
1	The FOP is at the C3/C4 separation section of the refinery (see Fig. 2)
2	The excavator hits a pipe and breaks a flange
3	The liquid leaks from the ruptured flange (see Fig. 3) and spreads on the ground creating a pool
4	The pool gets ignited and a pool fire starts burning (see Fig. 3)
5	The FOP alerts the CROP (who interacts with the FOP)
6	The CROP closes a remotely controlled valve (from DCS)
7	The outflow stops but the liquid level in the reboiler starts increasing and reaches the high level alarm
8	The CROP asks the FOP to open a manually operated valve (FOV) to decrease the reboiler level and then to close it back again (to recover the original operating conditions)
9	The reboiler level decreases back to the correct value

Both methods were used during the briefing phase of the experiment.

In case of an industrial operator, the measurement and the associated assessment of the KPIs do not make any difference. The KPIs for a human being should reflect the decisions made and the actions performed *vis-à-vis* the plant, which are the driving force for the assessment. An action then is not good or bad in itself but it is so in relation to the timing, magnitude, effects, and the associated consequences it causes to the plant. The same applies for the assessment of the difficulty in performing cognitive tasks. The task is complex not just in itself but in relation to the context where it is to be performed (*i.e.* the complexity of the context).

Before computing a KPI of an operator/trainee, it is necessary to define its nature and analyse its corresponding consistency and feasibility. The consistency feature reflects the human factors and those intangible attributes that are rather distant from both extensive and intensive variables of industrial processes.

To enable the minimization of the consequences (*i.e.* the C4 leak from the flange), nine key parameters were selected, namely: (1) hints provided, (2) message repetition, (3) leakage identification, (4) valve I identification, (5) fire reporting, (6) valve II identification, (7) pool diameter, (8) flame height, and (9) total time taken.

These parameters were used to build the proposed KPIs used to assess the FOP. Amongst the many KPIs it was possible to design (see also Henderson and Feiner (2009) for further details), those proposed refer to the specific scenario implemented in the PS (and described above).

According to the experience gained within the 5-year research of the Virthualis European project, the performance of (industrial) operators is so much bounded and dependent on the specificity of both the procedures adopted and the operating conditions of the plant at stake that its measurement must be tailored accordingly.[1] In practice, the deployment of the performance assessment module (of the PS) depends on the procedure, conditions, and situation that are to be addressed and evaluated on a case-by-case basis (*i.e.* for each plant).

5.4. The experiment participants – the guinea pigs selection and the grouping

Participants that took part to the experiment were 24 (Male = 20) and they were split into two groups, comprising 12 participants each. They aged in the range between 19 and 22 years (average 20.8 years and SD 1.03 year) and were students attending the third year of the bachelor degree in Chemical Engineering at the Politecnico di Milano, Milan, Italy. To ensure a homogenous

[1] For the sake of clarity, it is worth noting that the KPIs built (on the nine parameters measured) to assess the overall performance of operators and managers are not described in this paper as the ultimate goal of the paper was that of presenting the viability of using IVE both to assess and increase operators' and managers' performance.

sample in terms of technical background (and potentially similar understanding), students of the same course and year were selected.[2]

According to the scientific literature, groups used to perform experiments of similar typology in other domains, such as the aviation and the nuclear domains, are in the range of 8–10 participants for each group (Dehais et al., 2012; Silva et al., 2012; Paige Bacon and Strybel, 2012; Cai and Lin, 2011). Thus the number of participants used for the experiment campaign can be assumed to be in line with the number needed and used since years in the scientific community for this type of experiments.[3]

5.5. The experiment environment

The experiment of the 24 participants was performed in the neutrality of the environmental variables that were kept constant. This means that the environmental conditions, such as light or noise, were not used as performance shaping factors (PSF) (*i.e.* they were not used to make the task harder to face). Fig. 4 ought to visually clarify the neutrality concept with the respect of the environmental variables.

In principle, given that the PS allows for changing the environmental conditions in real-time (*i.e.* light, noise, wind speed and direction, clouds, fog, snow, visibility), we could have performed the experiment during the sunset of a foggy day, thus making it more difficult for participants both to find themselves in the environment (orientation) and to identify the right equipment. Then we would have not been able to assess the weight of light and fog on performance because the benchmark (*i.e.* the performance in neutral conditions) was not available.

Actually, reading the same pressure gauge either at optimal daylight condition (no reflections) or at the sunset (reduced visibility) makes the task substantially different (the former being easier than the latter).

Overall, the design, organization, and arrangement of the experiment campaign took about one year to develop. This time includes the experiment design, people profiling and selection, scenario and KPIs implementation in the PS, as well as coding the performance algorithm for the specific experiment.

5.6. The training context

Before performing the assessment, the two groups needed to be trained properly on the accident scenario that hypothetically happened in the plant. Group A, wearing 3D passive glasses, was trained within the PS with the stereoscopic feature activated (the stereoscopic feature is necessary to provide the sense of depth, which is fundamental to increase immersivity).

(The left of) Fig. 5 shows the experimental environment used even as a training room for Group A during the briefing phase.

Group B was trained using a "conventional" slide-supported presentation comprising twelve slides. Images from the 3D virtual environment (used for Group A) were used to prepare the slides for the presentation (images consistency). (The right of) Fig. 5 shows the classroom environment. Both training sessions lasted about 1 h.

To keep the two training methods comparable, *i.e.* not activating further cognitive channels in one group only, the spatial sound and the Augmented Virtual Reality (AVR) features of the PS were both disabled. This choice was necessary for the two training methods to activate in the trainee just the visual and the listening senses (*i.e.* two cognitive channels), and neither the auditory nor the extra visual channel provided by AVR[4] (Nazir et al., 2012).

5.7. The experiment setting and execution

Thanks to the tracking features implemented in the PS, it was possible to measure, record and process in real-time (*i.e.* during the experiment) several interaction parameters aimed at evaluating the performance of operators (in this case, the students).

Each participant was tested individually without anybody else attending. This choice was made intentionally to increase the similarity of the simulation environment with the real plant. In addition, it was opted to keep constant the time between the training and the assessment sessions in order to avoid any discrepancies between short-term and long-term memories. To equalize the assessment and get consistent results, the same highly trained and expert person, who used the same phrases, hints, and times to interact with participants, played the role of the CROP. In addition, the same expert person was in charge of the training sessions of both groups and made them lasting the same amount of time. The CROP operated in a separate room from that of the FOP and, to replicate realistic conditions, the two could neither see nor directly hear each other. The communication between the CROP and the FOP was done via walkie-talkies only (as it happens in reality). Finally, to ensure "clean" results, all participants played only the FOP's role.

6. Results and discussion

Participants who were trained in the 3D environment (Group A) performed undoubtedly better than those trained with the slide-supported training containing 3D images of the C3/C4 separation section (Group B).

During the experiment, the aforementioned nine parameters were measured. Specifically, the first parameter measured was the number of hints provided to participants. Actually, hints were provided according to the actions performed and requests made by participants (*i.e.* their acting in the (virtual) field). To preserve the experiment consistency, such hints were the same (in terms of contents and tone) for all participants. Just to give an example, if the participant found him/herself lost in the (virtual) plant (*e.g.* s/he was getting far from the accident scenario), s/he was advised to move towards the accident scene. This hint was given after a specific and constant time interval, chosen to be 90 s.

As (the left of) Fig. 6 clearly shows, the number of hints given to participants of Group A were significantly lower than those given to Group B, and, for some participants, were even absent ($t(20) = 3.05$, $p < 0.006$).

Specifically, in 41% of the cases, participants of Group A did not even ask for hints (*i.e.* absent bars in left of Fig. 6). In the remaining 59% of the cases when Group A participants asked for hints, they needed much less hints to orient themselves in the context and figure out what to do next. Numerically, the participants of Group A requested 11 hints whilst participants of Group B requested 29 hints. This translates into 164% more hints needed by Group B with respect to Group A.

Normalizing the overall number of hints, one discovers that Group A requested an average of 0.92 hints per participant, while

[2] The participants were volunteers who responded to an open call and were deliberately not paid for their participation. This choice was done with the purpose of ensuring homogeneity and harmonization even in terms of motivation (i.e. participants to be driven by the interest of taking part to a scientific experiment).

[3] One of the reasons it was decided not to splitting the 24 participants into 3 groups of 8 participants each was that of increasing the reliability of the experiment (given that, to our knowledge, this type of experiment, with the support of a PS, has been performed for the first time).

[4] For the sake of clarity, the AVR feature superimposes to the screen some additional bits of information, which are not available in the real environment. Thanks to the augmented information provided, the user can better understand what s/he is experiencing. As an example, the blue window at top left of (the right of) Fig. 3 reports the thermal load dynamics on the FOP in case of pool fire.

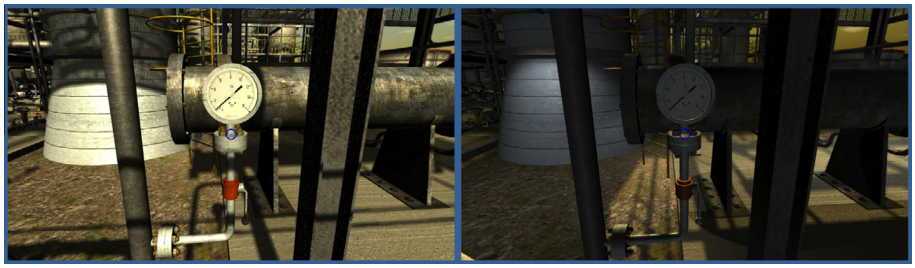

Fig. 4. Pressure gauge at neutral daylight conditions (no refraction, optimal readability – left) and at the sunset (diminished reading capability – right).

Fig. 5. The two training methods: 3D immersive training (left) and classroom (slide-supported) training (right).

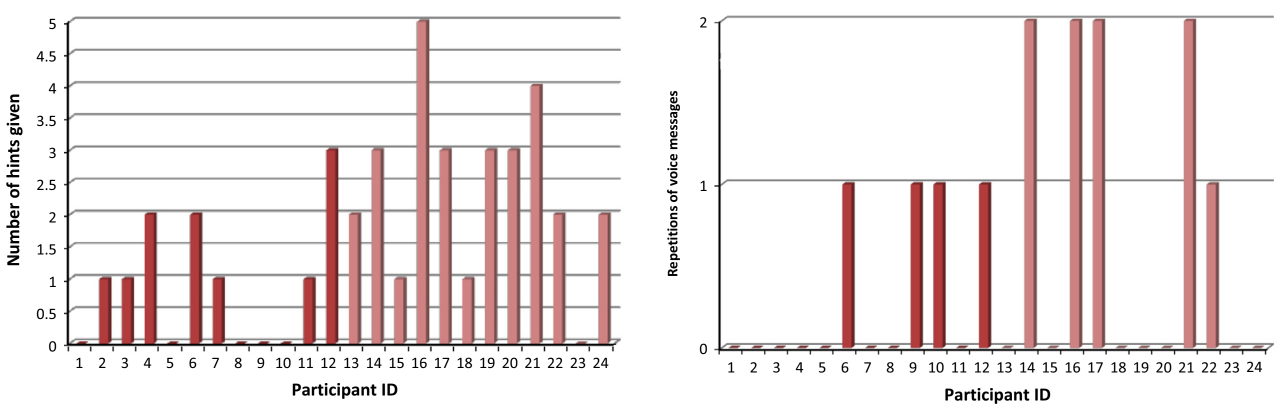

Fig. 6. Number of hints provided to each participant of Group A (ID 1–12) and Group B (ID 13–24) – lower is better (left) and number of voice message repetitions to each participant of Group A (ID 1–12) and Group B (ID 13–24) – lower is better (right).

group B requested an average of 2.42 hints per participant. Given that the number of hint requests by participant of Group B were fairly equally distributed, we can assume that not just Group B (*i.e.* the overall sample) needed more hints to cope with the situation but on average each individual of Group B needed more hints. This means that there were not any outliers moving the team average and that almost all participants behaved in a similar way.

Actually, with reference to Group B, there was just one participant over 12 who did not need any hints. This result was widely compensated by the rest of participants asking for an average of 2.63 hints each.

The second measured parameter, which is tightly coupled to the number of hints, is the number of voice message repetitions required by participants to the (person playing the role of the) CROP. This value is particularly important because it is a strong indicator of the level of confidence the operator has with the situation (*i.e.* it reflects the operator's situation awareness). Actually, the more one knows about something, the lower the difficulty in understanding the message when it is not communicated clearly in terms of both volume and speaking clarity (walkie-talkies are naturally affected by noise disturbances due to electromagnetic interferences).

As (the right of) Fig. 6 clearly shows, the number of repetitions requested by participants of Group A is significantly lower than those requested by participants of Group B. This demonstrates much less capacity from participants of Group B to understand the hints requested by and provided to them to cope with the situation. Overall, in 67% of the cases participants of Group A did not ask for any repetitions while this percentage for Group B drops to 58%. In addition, among those who asked for repetition, 80% of Group B asked for two repetitions, against none of Group A. Thus, even for this KPI, Group A outperformed Group B by a 125% difference in message repetitions.

The subsequent four parameters measured and used for assessing the training level of participants refer to the equipment identification (fault diagnosis) and localization (orientation). These parameters are particularly important as they influence the final impact of an abnormal situation. If the operator successfully and

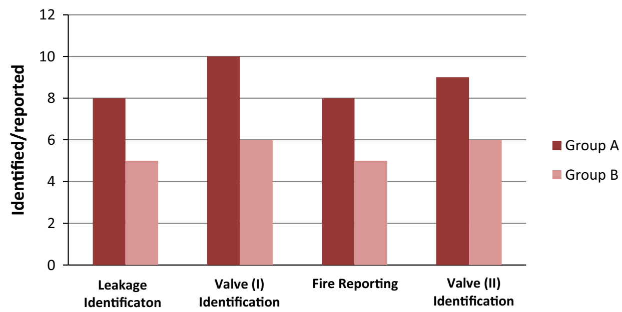

Fig. 7. Number of identifications of devices and reporting in the experiment for Group A and Group B.

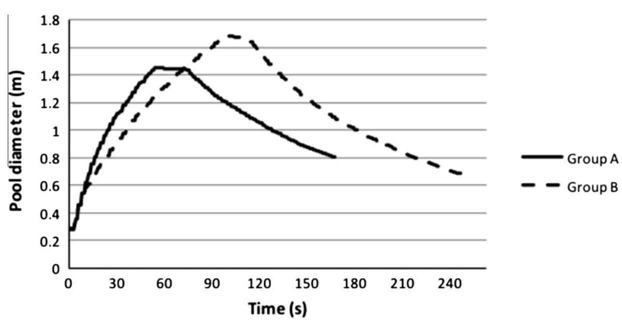

Fig. 8. Averaged pool diameter during the experiments for Group A and Group B.

timely identifies the equipment and its orientation during an abnormal situation, the possible damage can be reduced significantly.

In the given scenario, the simulated accident requires the operator to prove at four stages of the experiment his/her fault identification and diagnosis skills gained during the training session. In the accident timeline, these four stages are as follows: leakage identification, DCS valve identification (*i.e.* valve I), (timely) fire reporting, and, lastly, the manual valve identification (*i.e.* valve II). The identification-related parameters were separately grouped from the reporting-related one.

Fig. 7 shows both the identification capabilities (*i.e.* identification of valve I, valve II and the leak), and the reporting capabilities (*i.e.* reporting the fire).

Looking at the results it is evident that Group A outperformed Group B both in the identification and in reporting capabilities, thus showing a higher level of situation awareness, concentration and reactivity.

The seventh parameter measured to assess the performance of operators was the maximum pool diameter reached during the accident (*i.e.* a consequence-related parameter). Clearly, the smaller the pool generated by the leak, the better the FOP performance. This is because it is assumed that a smaller pool diameter means a quicker reaction of the FOP (response time) in identifying (fault diagnosis) and reporting (communication & coordination) the leakage to the CROP (who is in charge to closing the valve to cut off the leakage).

Further, smaller pool diameters reduce the potential consequences that might be generated by a possible ignition. This is simply because the possible damages both to the surrounding equipment (including domino effects) and to the operators standing nearby the fire depend on the flame height and the associated heat radiated. Therefore, it is assumed that the final pool diameter, which is calculated in real-time by the dynamic accident simulator (Manca et al., 2013) working synergistically with the dynamic process simulator in the PS, is directly correlated to the response capabilities of the participants (*i.e.* the FOPs) of each group. Fig. 8 shows the pool diameters (vs. time) for Group A and B.

It is evident, even for this parameter, that the average pool diameter "generated" by participants of Group A is smaller than that of Group B. The trends of the pool diameter shown in Fig. 8 can be explained as follows: the pool keeps increasing up to when the upstream valve (with respect to the ruptured flange) is closed (*i.e.* around 60 s for Group A and around 100 s for Group B). Then the pool diameter starts decreasing slowly, due to the evaporation process, up to when the pool is ignited. After ignition, the decrease is much faster due to the burning rate.

Numerically, the averaged maximum pool diameter generated by Group A is 1.42 m, while that generated by Group B is 1.65 m. This translates into a 26% larger area of the butane pool. Simultaneously, the dimension of the pool is related directly to the time taken by the operators to figure out what is going on, take the necessary decisions, and perform the necessary actions to stop the leak.

The time taken by Group A to stop the leak is around 61 s, while that taken by Group B is around 106 s. This translates into a 42% shorter time needed by participants of Group A, with respect to those of Group B, to cope with the situation (which might be seen as a 74% longer reaction time of Group B in coping with the

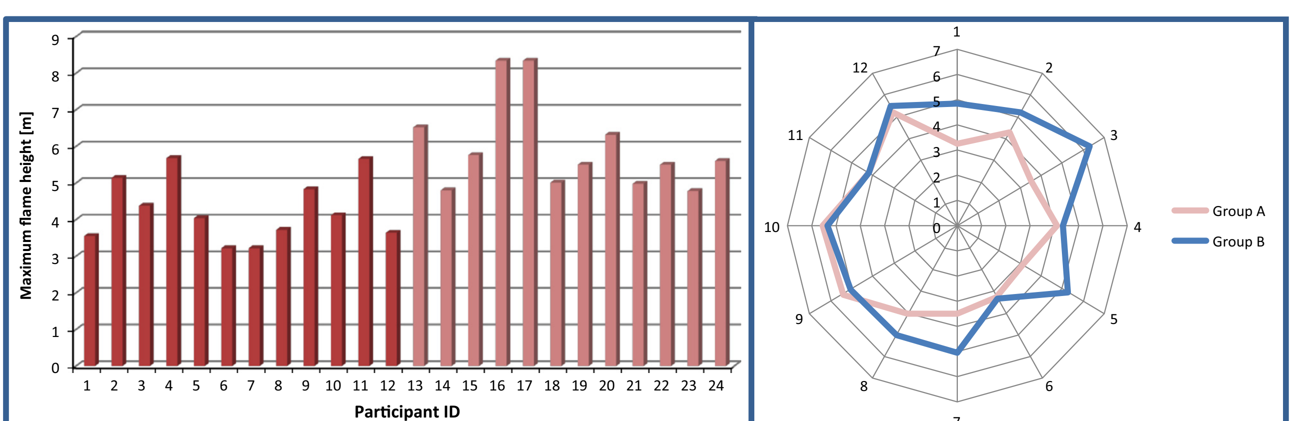

Fig. 9. Comparison of maximum flame height for each participant of Group A (ID 1–12) and Group B (ID 13–24) (left) and total time taken in minutes by each participant to finalize the experiment (right).

Table 2
Summary of KPIs measured for Group A and Group B.

KPI	Group A (mean)	Group B (mean)	Relative difference w.r.t. Group A $100 \cdot \left[\frac{Value\,B - Value\,A}{Value\,A}\right]$ (%)
Hints given	0.917	2.417	+163.64
Voice message repetitions	0.333	0.750	+125.00
Leakage identification	0.667	0.417	−37.50
Valve Identification (I)	0.833	0.500	−40.00
Fire Reporting	0.667	0.417	−37.50
Valve Identification (II)	0.750	0.500	−33.33
Maximum pool diameter [m]	1.562	1.966	+25.87
Maximum flame height [m]	4.266	5.955	+39.57
Total time of experiment	4 min 8 s	4 min 58 s	+20.17

accident scenario). Both these results are far more marked if one considers that participants of Group B requested/received much more messages/hints than those of Group A.

The eighth KPI is the maximum flame height for each participant. (The left of) Fig. 9 shows the different between the two groups in this respect.

The maximum flame height reached by Group A is 4.26 m, while that of Group B is 5.95 m. This translates into a nearly 40% higher flame height reached by Group B with respect to Group A.

Finally, the ninth parameter measured is the total time taken by participants to complete the experiment. It represents the responsiveness and attention allocation abilities. (The right of) Fig. 9 shows the time taken by Group A and Group B. The shorter the time, the better the performance, and eventually the lower the impact of the accident.

According to our understanding and observations during the experiment, the participants trained in the 3D environment got a better picture and understanding of the process, equipment locations, as well as valve positions and functioning. The enhanced capabilities enabled them to achieve better results in shorter times. Table 2 summarizes the different KPIs measured for both groups.

It is evident that Group A outperformed Group B in all KPIs measured during the experiment. Specifically, the last column of the table summarises the relative difference of Group B with respect to Group A.

7. Conclusions

The results of the experiment campaign conducted in the PS take to the conclusion that IVR allows to improving operators' performance through a deeper, contextual understanding (*i.e.* emotionally grounded). This holds for all KPIs tested. Further, given that the PS allows for reaching the so-called psychological fidelity, it can be reasonably assumed that the behaviours shown in the PS are those that will be recorded in reality, thus making both feasible and reliable the use of simulation results for decision-making purposes. In practice, this translates into the possibility of paving the way towards a more reliable, simulation-enabled, experimental-based decision-making process in operations safety.

The experiment campaign conducted do not certainly allow to unveiling all the pros and cons of using IVEs for training and decision-making purposes. Nevertheless, the results achieved are encouraging and can be seen as an important milestone towards the certification and selection of operators and managers for managing and operating complex process systems.

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