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Minimizing the Risk in the Process Industry by Using a Plant Simulator: a Novel Approach

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Technological advancements have fostered the automation, the intensification, and the optimization processes, which, in turn, have profoundly transformed the process industry requiring operators to perform more cognitive than manual tasks. Aim of this work is to understand, perceive, and assess risks from a perspective that is not merely focused on technology (equipment and process) but that includes Human and Organizational Factors (HOF). Specifically, the perspective is that of the operator who is immersed in a process plant and interacts both with the machines (as well as the software and the sensors controlling them) and the colleagues in a specific way that is defined by the procedures, *i.e.* by the organizational set-up.

It is explained how the proposed solution of using a Plant Simulator (PS) allows the operators not only understanding the critical areas of the plant (where risks are higher), but also allows increasing their skills to anticipate what might go wrong and (self-)training on the identified critical scenarios. In addition, the paper highlights how a PS enables operators to acquire new skills necessary to increasing the reliability of the entire productive system. The presented work was stimulated by the fact that today productive processes are so tightly coupled that even minor (human) errors (either by a control room or a field operator) may put the whole process at risk (and, conversely, even a minor adjustment can save the situation). The paper presents a methodology for the anticipation and reduction of risks by means of a PS. A replica of an industrial plant is recreated through an Immersive Virtual Environment (IVE) featuring spatial sounds to increase the degree of immersivity of operators (*i.e.* the user). To increase the realism and transforming an IVE into a PS, *i.e.* a realistic, immersive working environment, the IVE is coupled with both a real-time process simulator and a real-time accident simulator. The PS allows implementing and testing normal and abnormal scenarios of industrial processes and finally assess the performance of operators. The operators are exposed to these scenarios through the PS in order to perceive and be trained better to face with risky situations.

1. Introduction

The prosperity and revolution in the industrial sector brought economic, social and cultural benefits that resulted in making the life of humans relatively more comfortable (Wall, 2009). However, these benefits came at the cost of a substantial increase in both complexity and risk. Productive processes are more complex to design and operate, technologies that in the past were a choice toady are a must, automation advancements cannot be avoided (on penalty of losing competitiveness), and severe operating conditions (even in harsh environments) seem to be unavoidable. Thus, if industrial development has, on the one hand, undeniably brought numerous benefits and comforts to our modern life, on the other hand, has substantially increased the risks associated with them. Actually, when accidents occur, their consequences are much harder to bear. Additionally, with the increase of complexity, the number of risks has also increased, making more difficult the identification of critical scenarios that might occur, *i.e.* the paths an initiating event might take to give rise to an accident and the consequences associated to it. Socially, the risk aversion has also substantially increased due to the various devastating accidents that took place in the last few decades (Manca *et al.*, 2013). The Bhopal disaster (Union Carbide, 1984)

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has been certainly a revelation for all stakeholders involved: operators (companies), regulatory bodies, insurances, governments, population, and engineering companies. Nevertheless, the Bhopal disaster occurred in years when safety was not perceived as important as today. This is why, in terms of perception (and consequent population reaction), the most shocking accidents were the more recent Toulouse (AZF, 2001) and Deepwater Horizon (BP, 2010) accidents. European risk aversion is so high that the Toulouse accident caused the AZF plant to close, and, with it, all chemical plants in the Toulouse area (today there is no a single process plant operating there).

The aforementioned context calls for appropriate methods and tools to enable all stakeholders to face with the increasing complexity and design, operate, maintain and dismiss complex plants in a sustainable way, *i.e.* productive processes which are less prone to loss of production (waste), chemicals (pollution), and, most of all, humans lives (Manca *et al.*, 2012a).

An industrial accident can result in disruption of workflows, equipment damages, injuries, and even deaths (Pariyani and Seider, 2010). Moreover, an industrial accident may produce severe consequences on the environment and on the population surrounding the plant. In recent years, some of the causes that might bring to accidents were tackled at design level with the so-called inherently safe design; but despite this the number of accidents per year is still growing, the reason being most probably ascribable to the growing complexity of processes and operating procedures. Human errors are one of the main root causes for accidents in various, complex, and safety-critical industries such as the aviation, the nuclear, the health care, and the chemical processes. The role of industrial operators is to ensure smooth operations, *i.e.* reach production goals in an economically viable and safer way. This goal can only be achieved with an accurate and in depth knowledge of the productive system (Human, Technology and Organization), a systemic hazards identification, as well as a clear knowledge and a structured management of the nominal and, most of all, abnormal operating conditions (the so-called abnormal situations).

This paper focuses on a novel methodology aimed at improving the conventional training and assessment methods of industrial operators as a step towards the mitigation of risks in the process industry. The first section presents the human errors most commonly performed by industrial operators and introduces the concept of situation awareness, which is followed by the details on the Plant Simulator (PS). Subsequently, two use-cases are presented to clarify the features and application of the PS. The conclusions section draws the comments and discussion on the possible safety enhancements introduced by adopting the PS to train and assess industrial operators.

2. Human error and industrial risk

Human beings are inherently flexible and capable to face with complex situations at a limited level. These distinctive characteristics, in some cases, enable abnormal situations to be successfully dealt with (by overcoming the potentially inherent rigidity of automation systems). Nevertheless, human beings can make errors. This happens particularly in those systems where human, technological, and organizational functions are not well balanced (*i.e.* not well designed). Human beings tend to become prone to failures when the tasks required to them are either much complex or much simple. Repetitive, low cognitive tasks (in terms of reasoning) are certainly more suitable for machines than for humans as the level of attention (directly proportional to correctly perform the task) is kept only by the high pace of movements required (coordination). O, cognitive intense tasks (in terms of systemic reasoning) push humans to increase their proneness to failure due to the complexity of links to make. Therefore, the higher the task complexity the higher the probability of errors, and consequently the higher the likelihood of proneness to risks (Nazir *et al.*, 2012a). However, complex and highly automated systems are becoming a must to sustain competitiveness and enable social and sustainable growth. In this context, the human function can enhances the chances of “saving the situation” as it is the only function that can truly adapt to circumstances and find alternatives (something a machine can hardly do).

Well-designed systems take into account the potential of the different system functions (Human, Technological, and Organizational) by assigning the tasks more suitable for humans to the humans and those more suitable for machines to the automation system. The rapid, yet necessary, adoption of “technological improvements” (*i.e.* automation) has increased the challenges industrial operators have to face. Actually, the pace of progress in technology failed to properly account for the cognitive-related implications (on observation, interpretation, planning, and execution) that such advancement would introduce. Aim of this paper is to analyze these implications and explain how the adoption of a PS might help in overcoming the difficulties introduced by new technologies and enhance the human potential to take the best out of them. Specifically, the work is focused on understanding how to enhance human skills to cope with complex and cognitive demanding tasks (*i.e.* those requiring a systemic reasoning and the associated complex decision-making). Situation Awareness (SA) is a key concept to understand human failures. SA is the term (coined by Endsley, 1995) to describe, as a whole, the degree of understanding, consciousness and decision capacity of people involved in specific activities within specific environments (Endsley, 1995; Nazir *et al.*, 2012a; Stanton *et al.*, 2001). Should this perspective be shared, the improvement of human performance has necessarily to go through the increase of SA.

Focusing on the human function, the industrial risks associated with the process industries can be broadly divided into two categories: intrinsic, technology-related risks and extrinsic, human-related ones (Figure 1). The risks associated with the organizational function are kept, for the time being, out of the loop.

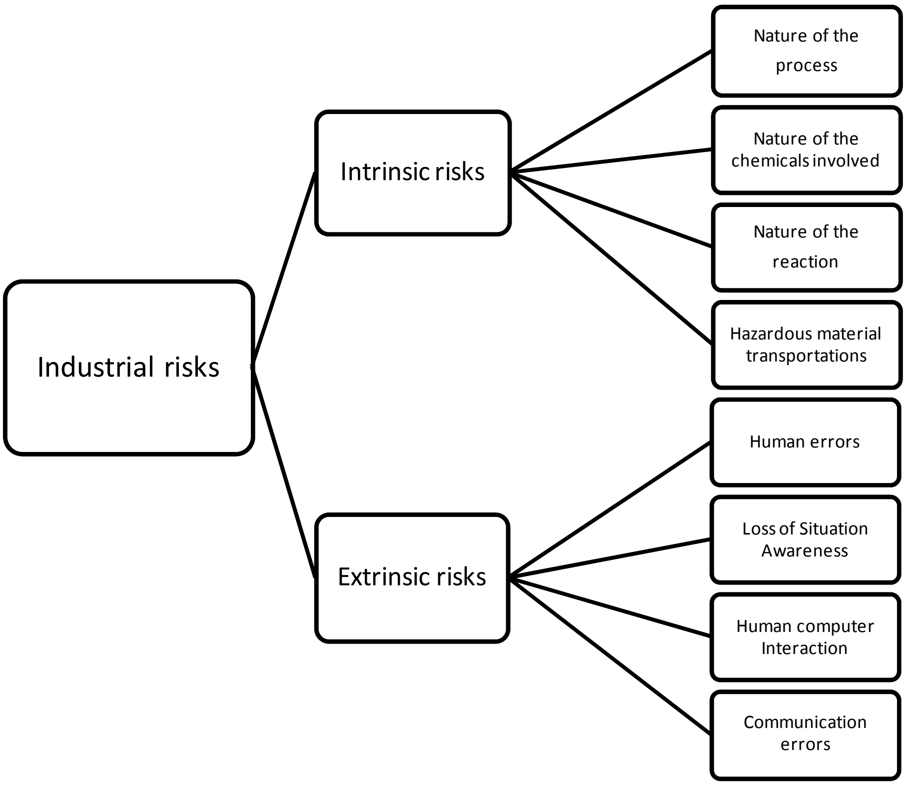

Figure 1- Categorization of risks for process industry.

Figure 1 depicts a limited number of categories, which can be extended and widened according to the required depth of the analysis. Our primary goal is to propose means for minimizing the accidents and the abnormal situations through the enhancement of human capabilities by means of the PS paradigm. The authors are encouraged to render the numbers specifying the dot as a decimal separator and the comma as a thousands separator.

2.1 Plant Simulator

The Plant Simulator is the expression first coined in Colombo *et al.*, 2011 to refer to an engineering solution consisting of an integrated simulation environment where people can experience realistic situations, with the same degree of realism they would experience in reality. The PS couples a conventional Operator Training Simulator (OTS) with an Immersive Virtual Environment (IVE) (Nazir *et al.*, 2012b). The PS is created to replicate the exact plant conditions and enables the Control Room Operator(s) (shortly referred to as CROP) and the Field Operator(s) (shortly referred to as FOP) to cooperate as they would do in reality, *i.e.* as a team.

The OTS is an Information Technology (IT) solution that replicates the control room both physically and behaviorally. Figure 2 shows a screenshot of a CROP's interface. Physically, the OTS is realistic because it replicates the physical environment a CROP is immersed into, furniture included. Behaviorally, the OTS is realistic too as the values of the variables displayed in the CROP's interface realistically reflect the behavior of the plant as they are calculated in real-time by a high-fidelity dynamic process simulator. The inherent limitation of the OTS is that it only enables to train the CROP as the field part, necessary to involve the FOPs, is usually not implemented.

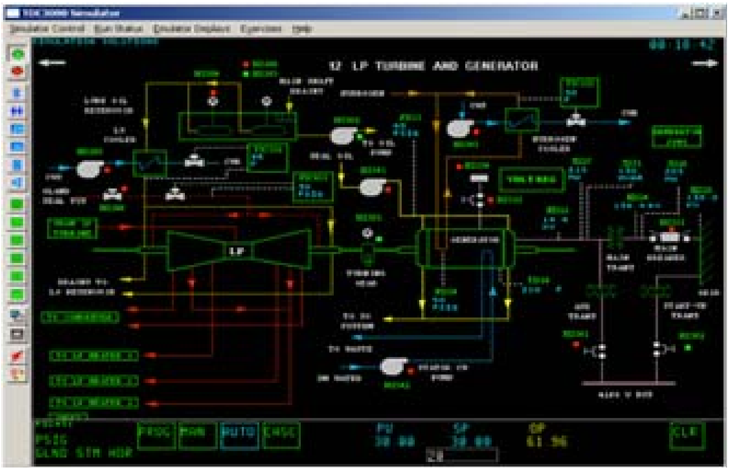

Figure 2 – Screenshot of an OTS interface.

In order to create a PS the FOP space is to be replicated too, and this is done by means of an IVE (which is neither a simple desktop nor a non-immersive Virtual Reality screen). The degree of realism perceived by the FOP is primarily given by five factors: the size of the screen, realism of plant reaction (in terms of dynamic display of variables: pressure, flow, temperature, concentration…), the realism of graphics, and the realism of noises. Figure 3 shows an IVE of a process plant and gives an idea of what the PS physical features should be about.

Figure 3 – Picture of an IVE interface.

In addition to nominal and abnormal conditions, the PS can be enabled to simulate and virtually experience accidents. However, to do this, in addition to the real-time dynamic process simulator, the PS has to be equipped with a real-time dynamic accident simulator (Brambilla and Manca, 2011) and the two have to work synchronously together (Manca *et al.*, 2013). Figure 4 shows the visual representation of the PS.

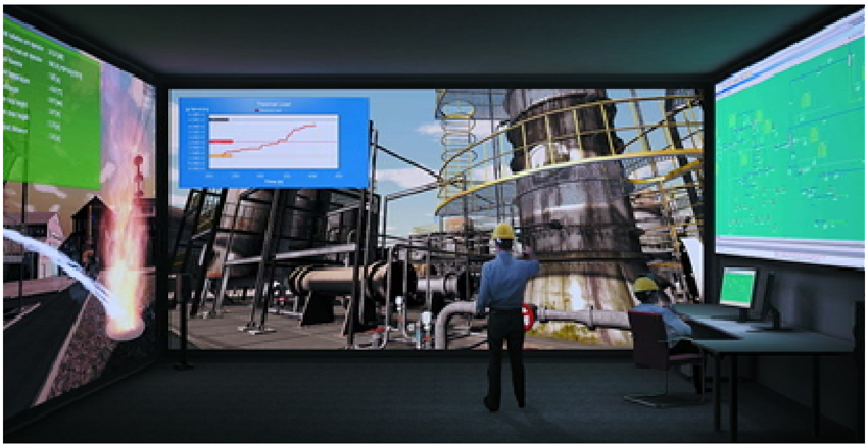

Figure 4 – Representation of the concept of PS (image courtesy of Virthualis company).

Actually, the PS simulates the dynamic evolution inside the process units and the pipework but it is not able to describe what happens outside of the equipment. Conversely, the accident simulator simulates the dynamic evolution outside of the process units and of the pipework by receiving information from the dynamic process simulator to evaluate the possible release, outflow, emission, and leakage that on their turn represent the initial and dynamic conditions to calculate 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, as well as on the involved operator(s). 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 the effect on the process variables accordingly. In short, the communication between the two simulators is two-way as they get influenced mutually.

The benefit of this solution is that the data exchanged between the process simulator and the accident simulator allow for:

a. tracking the dynamic evolution of the process when an accident occurs;
b. quantifying the possible effects and damages on the structures and the equipment;
c. quantifying the potential injuries that might be suffered by field operators in real life.

The technological innovation brought about by the PS is a breakthrough in terms of training too: it enables to train teams, *i.e.* CROPs and FOPs together. This approach provides a very new perspective to system design, retrofitting, maintenance, and decommissioning as it enables to test experimentally how the (productive) system would work as a whole, *i.e.* including the Human and Organizational functions, which are typically outside of the design loop.

3. Methodology

3.1 Training

Cognitive and manual skills (*e.g.*, identification, understanding, planning, attention, modeling, projection, association, memorization, responsiveness, coordination, precision) can be significantly improved by different training methods. Training is an essential component of industrial safety as it enhances the skill level, and, consequently, increases productivity, motivation, reliability, and commitment amongst the trainees.

Traditional training methods (classroom and on-the-job training) are both ineffective and risky when complex systems are at stake. In addition, the training contents are not shaped based on exhaustive task, person, and organization analyses. A well-designed, effective and efficient training and assessment method is a powerful tool to reduce the number of accidents and mitigate the consequences in case of accident. Workers replacement (workforce turnover and shift management) is another area where training and assessment of operators are of paramount importance. A reliable and effective means of knowledge transfer and assessment for preparing new and unskilled workers, as well as old ones in facing new technologies, is one of the top priorities today. The reason is associated to three main processes that are taking place in the industry: ageing workforce, creation of new and more complex plants, and retrofitting of old plants. In all cases, the problem is associated with the knowledge management: retaining the knowledge of retiring people to transfer to new and inexperienced people, on the one hand, and "upgrading" the skills of experienced people to handle new technologies (and to cope with both the retrofitting and building processes), on the other hand.

These issues call for a new perspective in terms of both methodologies and tools to train. Actually, the strongest limitation of classical classroom and on-the-job trainings (apart from the already mentioned risk and inefficiency brought about) is the subjectivity. This "flaw" becomes evident during the assessment process, when a decision is to be taken on whether the person is adequate for the task assigned to him/her. The first, mandatory requirement for new approaches ought to be then repeatability as it allows achieving an objective, "standardized" approach to management of operators' competence. In line with these concepts, the present work proposes the adoption of a PS both to eliminate the subjectivity from operators' training and assessment and to create a harmonized, replicable approach (at company level) to competence management.

Figure 5 schematizes the two-stage approach that the PS allows achieving through a training and assessment method.

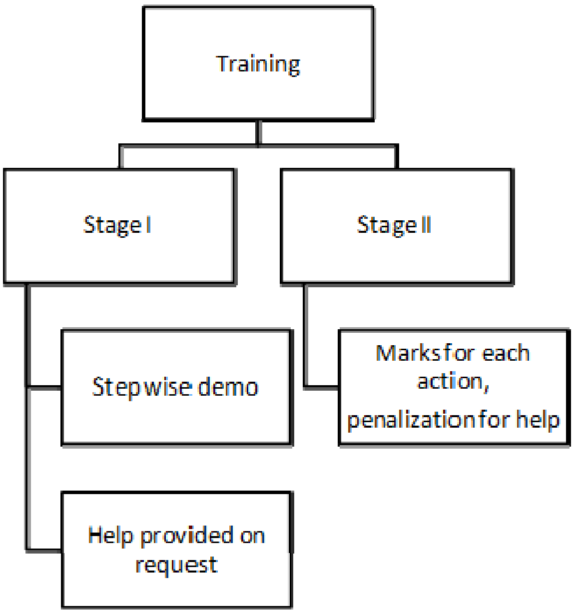

Figure 5 – Stages of training with the plant simulator.

At stage I, the operator can be faced with two hierarchical levels of training. At level 1, the operator is guided step-by-step to perform the task on any given section/unit; the guidance is given by the software, through digital, fictional hints, *e.g.*, highlighting the next valve to open. This way the support is the same, *i.e.* homogenous, for all operators since they are spectators of a predefined instructional procedure. The training procedure is performed at nominal conditions, *i.e.* the conventional and most clear operating conditions, to improve and maximize the process understanding and the plant situation awareness of the operator. The use and support of colors, sounds, alarms, and visual aids/helps/hints are appropriately chosen to stimulate and enhance the understanding of the operator(s). Once the trainee has learnt to interact and operate within the PS, s/he can perform, at any time, a number of predefined scenarios and put his/herself to the test in a self-training mode, thus improving (even autonomously) his/her skills. Level 1 of the training hierarchy is characterized by the automatic help and support by the PS infrastructure that, when necessary, can drive the operator in performing the correct actions and taking the proper decisions. At level 1, the PS provides also a support when the operator makes any wrong action by

highlighting the device/process unit where the error occurred and by providing suitable and interactive explanations to reproduce but also recover from the wrong action/decision and take the correct one(s).
Level 2 of the training session in the PS takes the trainee towards a more demanding environment that is closer to the pure assessment stage. Level 2 (of stage I) differs from level 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 assessing the final mark, one can rely on a well-known and widely accepted methodology such as the AHP technique (Saaty, 1980).
2. The information on mistakes/errors is reduced from the overall marking and no special hints are provided to the trainee unless s/he specifically asks for them (see also the forthcoming point 3).
3. Contrary to level 1 (of stage I), where the software guides the operator through the procedure (allowing him/her to correctly perform and understand the procedure), level 2 is to be designed so that helps are provided only upon request. The trainee is provided with suitable helps and hints that are aimed at explaining how the process works and how the plant is structured. This allows improving the situation awareness of the operator. Moreover, there is a well-defined penalization of the overall marking devised according to the number and level of help requests.

Stage II is what we call the “free mode”. The trainee can freely move around. No guidance, hints, and marking are provided. In the free mode, the trainee is given a synthesis of his/her performance only at the end of the session. It is like being in the real plant with no fictional disturbances and helps. This is done on purpose to avoid influencing the operator during the assessment procedure: s/he has to feel as if s/he were on shift.

3.2 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 skill 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, however, performance assessment of industrial operators is a topic yet to be dug into and extensively discussed by the scientific community.
The most common procedure adopted by several organizations is the conventional approach to assessment through the direct contribution of the trainer. According to the Authors, a human judgment can be rather weak since it is based on subjective impressions (that can even vary significantly within the same day). Such a biased judgment may vary as a function of both trainer(s) and trainee(s) (Colombo *et al.*, 2012). It would be then highly desirable to ground operators’ assessment on a reliable, repeatable and automatic tool that is completely neutral and avoids any subjectivity. This means that the operators’ assessment should not be based on the trainer judgment, which is intrinsically and variably biased. An assessment procedure focused on industrial operators (both FOPs and CROPs) should therefore meet the following prerequisites: consistency, quantitative assessment, repeatability, and neutrality. To reach and satisfy the neutrality feature, the assessment procedure should be “automatic”, in a sense, and avoid questionnaires and the consequent analysis and correction from examiners. Accordingly, advanced tools for operator training call for an automatic procedure to assess the training degree of operators. This assessment should be implemented in a computer program capable not only of evaluating the marks about the performance of operators but also capable of registering, storing, and analyzing the actions and decisions taken by the operator(s) during the training session. Under this perspective, the assessment procedure should become an algorithm to be implemented in a computer program by means of an automated procedure. From a (conceptual) design standpoint, Stage II has exactly this aim and, from a practical standpoint, has a twofold goal: neutrally assessing the performance of trainee (*i.e.* guaranteeing consistency) and allowing operators to self-train and self-assess themselves even outside the planned training and assessment campaign. What increases the motivation, the credibility, and the acceptance is the fact that the algorithm used to assess the different people is exactly the same for all. This guarantees consistency across trainees independently of the day and the hour of the day the assessment is performed. This is something that is rather difficult to achieve when only a (human) trainer who assesses directly the trainee, without any objective support, does the assessment. Certainly, the trainer can capture nuances a machine cannot do. It was bearing this in mind that the PS approach proposed in this work does not exclude the trainer from the training and assessment loops. On the contrary, the

PS empowers his/her decision-making process by feeding him/her with objective parameters that can be contextualized by the trainer. This approach has a twofold beneficial effect: it gives more value to what a machine can offer (a dry, decontextualized assessment) and valorizes the best part of what a human being can offer for this task (the contextualization of an analytic, impersonal assessment). The performances can be measured consistently across trainees and throughout the entire training and assessment campaign (typically performed for the personnel working at each unit or section of the plant). Adopting a PS ensures and motivates trainees because it guarantees the overall judgment given to them by the trainer is grounded on the same, objective, and repeatable process. Trainees are then motivated to compare their respective marking with those of colleagues, as they are confident that the mark is not the result of a biased, personal judgment of the trainer. Another advantage of this approach is a greater precision. The tasks that operators are required to accomplish are divided into subtasks, which are analytically assessed by the software with a specific marking that is eventually provided to the trainer. Altogether, the trainer is given an overall marking that reflects the overall performance of the operator respect to the process specifications (in terms of both production and safety), and receives also specific markings that assess the goodness in performing specific subtasks. The trainee can understand precisely what are the part, section, procedure, task, and action that weigh the most in his/her final performance judgment.

3.3 Case-studies

The PS not only adds precision to the assessment but also allows defining the parameters of interest with their relative marking. Usually, human beings tend to give equal marks to all (apparent) parameters without considering the relative significance and statistical comparison of single parameters. Therefore, a trainer may make judgments and evaluations according to his/her understanding and experience of the plant site thus introducing 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 of an operator who might not be either capable or adequately trained to perform efficiently the allocated task.

Human beings might be particularly good at assessing the overall situation and make a rapid decision on whether to keep going in a certain direction or change path according to the dynamic evolution of the system. This distinctive, human capability to quickly connecting things and give a reliable response on what to do next is particularly worthy in complex systems as in most of the cases it saves the situation. Actually, this is witnessed by our everyday life in which are clearly more the cases (nearly all of them) where abnormal situations of modern, highly automated, complex systems are stopped thanks to a human contribution than those reaching an undesired event (accident). But when it comes to (analytically) keep track of the different steps in complex systems, a human being cannot face the task due to memory capability and reduced proficiency in moving/understanding/recording the multidimensional domain where the process variables dynamically evolve. Actually, it is nearly impossible for a human being recalling every single step made by an operator and justifying why s/he has given a specific marking even in relation to the performance of other subtasks (or other operators). In other words, it is nearly impossible that a human being watches another human being performing a complex task and s/he applies the same assessment algorithm for each step and to all the operators.

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 developed a software tool for the assessment of industrial operators. This tool measures and records in real time a set of process and accident variables, actions, decisions, time intervals coming from both the dynamic process and accident simulators as well as from the human machine interface of the IVE. Then it determines/evaluates the performance indicators and the key performance indexes required to quantify the training level and situation awareness of the operator(s).

The additional benefit of this tool is its inherent flexibility that allows taking the necessary modifications and adjustments according to the needs of the involved plant (sub)sections. To understand better this point, let us take the example/scenario of an accidental butane leakage from a C3/C4 separation section of an oil refinery (for details see Nazir *et al.,* 2013). The operator is required to perform certain tasks, which can result in mitigating the impact of the accident. The performance assessment algorithm is capable of storing each action performed by the operator during the given scenario, evaluate the correctness of actions (both in relation to the specific subtask being performed and their effects on the overall task), weigh each action based on a well-defined hierarchy and relative weighing technique (Manca *et al.*, 2012a,b). Figure 6 shows the schematic representation of Performance Assessment (PA) for the example briefly explained above and for that of the catalyst injection procedure of a polymerization process. The right portion of Figure 6 shows how PA takes into account: (1) Operator Performance Indicators (OPIs) based on relevant human factors; (2) Key Performance Indicators (KPIs) based on process understanding and given situation; (3) the quantity/quality of helps requested by the operator. The details on methodology, concept, weighing methods can be found in Manca *et al.*, 2012a,b.

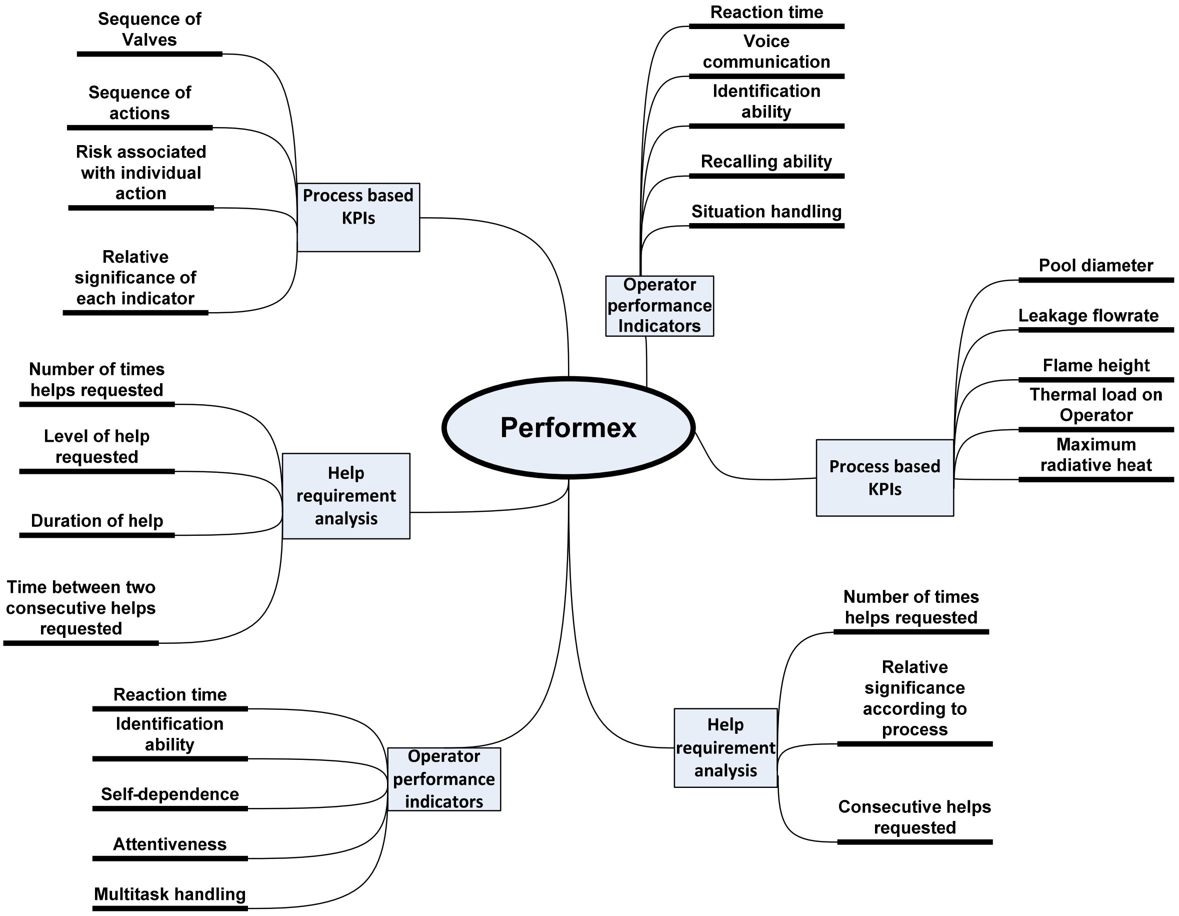

Figure 6 – Process and operator performance indicators for catalytic injector process (left side) and C3/C4 splitter (right side).

4. Conclusions

The paper introduced the concept of the PS, which consists of a dynamic process simulator and a dynamic accident simulator interlinked in an IVE. It explained how the adoption of a PS can increase the efficiency of the overall process safety through the enhancement of the process understanding, the situation awareness, the responsiveness, and the decision making processes of industrial operators, thereby decreasing the risk of operators' error and loss of SA. The "automated" assessment of operators is 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 KPIs and OPIs.
The Authors run a set of experiments to determine the practical efficiency and impact of the PS on SA and training level of industrial operators (Colombo *et al.*, 2013). Preliminary results showed how the immersivity feature of the PS allows increasing and enhancing the level of understanding and involvement of field operators. When compared to conventional training tools, the PS showed a higher efficiency in forming and achieving a good level of SA.

The paper introduced a number of areas to be investigated further and raised a number of issues that need still to be addressed and finalized. Work is currently ongoing on the implementation of the PS for different use-cases, experiments with real plant operators, impact of training on SA and on possible improvement of the PS with the help of experimental studies and users' feedback.

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