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Procedure for Automated Assessment of Industrial Operators

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The paper discusses the specifications and features of an automated assessment procedure for training of industrial operators. A case study applied to a real catalyst-injector-switch procedure in a polymer plant is presented and commented. The automated assessment procedure is made possible by the Plant Simulator tool that is conceived to log the actions of the operators, who are trained in its 3D immersive virtual environment, and the values of the process variables, which are simulated by a dynamic process simulator that runs in the background. The automated assessment procedure helps the trainer focusing on more human-oriented issues and leaves the quantitative marks/scores to the computer algorithm that analyzes and processes the trainee’s actions. The performance assessment is then characterized by an aseptic judgment that can be invoked as many times as one pleases. The automated performance assessment is unbiased and does not make distinctions of age, sex, race, experience. During the training session (that is propaedeutic to the assessment one), the performance assessment can be run also by the trainee alone without the psychological pressure exerted by the presence of the trainer/examiner.
In addition, being systematic and automated, the performance assessment can be of real help for both trainers and decision makers. Trainers and managers can use the quantitative evaluation of performance assessment for decision-making purposes. The automated procedure also allows scheduling operators’ shifts in case of complex or periodic procedures, planning training courses, recruiting, and taking insurance related decisions.

1. Introduction

Skilled operators are an inevitable precondition for ensuring and enhancing safety in organizations, especially in the chemical industries. Current training developments and their empirical validations show the potential of innovative and effective training solutions, *e.g.*, which build on 3D technology. In that respect, the papers from Manca *et al.*, 2013a,b; Nazir *et al.*, 2012 discussed extensively the features of the Plant Simulator (PS), which is a software tool that couples a 3D immersive environment to train field operators (FOPs) of industrial plants and a conventional operator training simulator to train control room operators (CROPs). Looking from a safety management perspective, the PS can simulate both nominal operating conditions and abnormal situations that may lead to near misses or even accident events. From a technological and fidelity perspective, it allows CROPs and FOPs interacting in a realistic simulated environment that on one hand reproduces the control room features in terms of DCS synoptic panels and on the other hand simulates the real plant through an immersive 3D stereoscopic environment with spatial sounds (Manca *et al.*, 2013b). Additional features such as augmented virtual reality, gesture interaction with virtual valves and devices, contextual help, and guided tour supplement the PS (see also Nazir *et al.*, 2012).
Looking from an instructional design perspective, the PS addresses different training levels. Starting from a very basic introduction of the plant layout with the naming, position, and functions of single pieces of equipment, the trainee is led through a progressively more complex and challenging interactivity with the

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process operations that may comprise uncommon procedures, unexpected events, abnormal situations, and accidents. Essentially, the PS can make the trainee(s) facing with tightly interwoven human, technological, and organizational issues. Finally, from a training outcome and evaluation perspective, once the trainee has been trained and is prepared to deal with plant dynamics, s/he undergoes the so-called assessment procedure where s/he proves his/her process understanding and capability to tackle and solve specific operating conditions. The availability of an automated assessment procedure to measure the achieved degree of vocational training allows disposing of a tool that produces unbiased, neutral, and reproducible results. This assessment procedure can be used as a powerful feedback instrument either by the trainee, to measure his/her training progression and proficiency level, or by the trainer to get an standardized and validated measurement of the trainee preparation and process understanding. Besides supporting the trainer, the results produced by the assessment procedure may help the company managers to schedule operators' shifts for complex or periodic procedures, planning training courses, recruiting, and possibly taking insurance-related decisions.

2. Performance assessment

The previous section introduced the opportunity of disposing of a tool capable of automatically assessing the performance of industrial operators during their training activities. The most important characteristic of an automated assessment procedure is the unbiased ranking and marking of actions performed by the trainee. Human judgments are intrinsically subjective (Colombo *et al.*, 2011, 2012). Consequently, the assessment of operators by trainers is a complex function of trainer-trainee affinity/relationship and is subject to dynamic aspects that depend again on the human and subjective characteristics of such a binomial (Manca *et al.*, 2012b).

In addition, the previous work experience of the trainer and his/her sensibility to specific issues play a significant role in giving more significance to particular features and behaviors. There is also a further aspect to be taken into account, which relies on the information processing capabilities of the trainer to perceive, select, value, recall, and analyze the process evolution subject to the actions and decisions of the trainee "online" because of the fact that the human information processing capacity is limited (*e.g.*, Wickens and Hollands, 2000). This is quite antithetic to the multidimensional nature of chemical processes. Consequently, the automated assessment procedure can be of real help for the trainer to extract, organize, and quantify the actual contribution of the trainee's decisions and actions with respect to the operating conditions of the investigated process/plant.

Starting from specifications as repeatability and automation, the assessment procedure of industrial operators should meet the following requisites: consistency, quantitative marking, and fairness. These features call for reducing the role played by questionnaires that would require the consequent review and judgment by trainers who act as examiners. In addition, the automatic specification of the assessment tool requires the implementation of a software capable not only of evaluating the performance marks of trainees but also of registering, storing, and analyzing the actions and decisions taken by the trainee during the training/assessment session. It follows that the assessment procedure should be an Automated Computer Algorithm, ACA. Such an algorithm assures that the assessment is based on uniform methods and principles that are independent of the sex, age, and race of the trainee. Also, the assessment does not depend on the time when it is performed and can be run as many times as one requests. This last feature allows tracking the trainee's performance and observing possible improvements. Moreover, the automated feedback may enhance the trainee's motivation to use more frequently and extensively the PS as an effective training tool to either overtake some prescribed thresholds or even improve rankings, which are already satisfactory. Another advantage of the ACA is that during the training phase, which comes before the assessment phase, the trainee can test personally his/her degree of training progress and can prepare for the final assessment without having to rely on the trainer to get a preliminary feedback concerning his/her own qualification. As a function of national unions, the ACA may allow performing extensive selection campaigns to either certify the preparation degree of existing personnel or recruit new workforces.

With reference to the valuable personal relationship between trainer and trainee and the sensitive balance between human and machine, the ACA does not exclude the trainer. In fact, the trainer's contribution is welcome and it is enhanced by the automated assessment, which provides the trainer with valuable bits of information to finalize a well-thought assessment based on quantitative measures and on marks that retain the neutrality and reliability attributes. The trainer can add to the final assessment his/her experience and impressions that can record and judge shadings that a computer algorithm can neither register nor appraise.

2.1 An applied case study

Taking the raised proposition together, Manca *et al.*, 2012a,b, introduced the recommended specifications that a performance assessment tool should feature. They proposed a hierarchical structure of levels, which the ACA should rely on. Those levels are the reproduction of a general operating procedure and try to organize it by dissecting the sequence of actions into separate sections. When a definite operating procedure is either not available or cannot be run then the ACA must be able to record the actions taken by the trainee(s) together with the effects produced on the process and measure the consistency of outcomes respect to a fan of possible nominal, or optimal, or acceptable, or safe conditions.

To illustrate this, the present manuscript focuses on a specific procedure for catalyst injector switch, CIS. This procedure is run periodically in polymerization plants where the reactions call for the presence of a liquid catalyst (Urdampilleta *et al.*, 2006). The catalyst is injected together with monomers, initiators, and solvents into the inlet stream of the polymerization reactor by means of an injector. Periodically, the injector is maintained to remove the fouling and scaling that accumulates during normal operation. The maintenance requires switching between the active and spare injectors to keep the process running while the off-line injector is serviced. The periodicity of this procedure may go from few weeks to some months according to the specific polymerization process.

Figure 1: View of the congested and densely populated area of the CIS procedure within the virtual environment of the PS where both the training and assessment sessions are run.

The CIS-case study analyzed here refers to a real polymerization process that produces one of the most important and diffused polymers and refers to a very detailed procedure where the steps to be performed are organized in a rational list of actions. The procedure is run monthly in a North European plant of a multinational company. Specifically, the whole CIS procedure comprises 32 actions (organized in 5 distinct groups) that are performed by a single field operator who works in a rather limited area of the plant (*i.e.* few square meters) where the injectors are installed. As Figure 1 shows, this area is rather dense and populated with pipes, flanges, fittings, branches, valves, instruments, and switches. The operator has to perform the actions consecutively according to a strict sequence of actions that comprise:

- switching on and off some manually-operated switches;
- opening and closing manually-operated valves;
- observing some process instruments, (*e.g.*, flowmeters and pressure gauges) and proceeding with or waiting for the next action as a function of the measured values;
- waiting for predefined time intervals before proceeding with the following action.

On average, the operator takes few minutes to finalize the whole sequence of actions. Due to the structure of the congested area of the plant and to the pipes, valves, and levers that are very similar if not identical, the operator may easily make unintended errors with severe consequences. Common faults are:

- operating the wrong valve, as the proximity of neighboring valves can be as small as 20-30 cm;
- skipping an action, as there are sequences of up to 13 actions in a row devoted to the operation of the same typology of devices, *i.e.* valves, applied to different items;
- waiting for a time that is shorter than the prescribed one, as the operator is alone, s/he is not provided with a chronometer and does not receive any support from the control room.

Even a single error in the sequence of 32 actions may result in severe process consequences. This is the case where no significant (at least expected) risks on the safety of operators can be envisaged. Conversely, the possible consequences on the equipment can be dramatic in terms of production losses, and unforeseen further maintenance. Specifically, a rather likely event in case of wrong sequence of actions is the obstruction of the catalyst injector. This event triggers an emergency shutdown of the plant, as the polymerization process cannot be run in absence of catalyst. Once the shutdown is completed, the injector/pipes, which have been affected by the polymer obstruction, must be removed and cleaned with pressurized steam. Eventually, the maintained devices are reinstalled and the startup procedure is invoked. This production loss can result in large amounts of money in terms of production losses. This illustration demonstrates the importance of effective and efficient operator training and shows the advantage of a PS and the benefit that an ACA for performance assessment can deliver to ensure skilled and proficient performance of industrial operators.

3. Method

The ACA evaluates the performance of the trainee by means of two modules that work in series. The former registers the events that occur in the PS; the latter receives as input data those events and assesses the performance of the trainee.

3.1 The recording module

The architecture of PS (Manca *et al.*, 2013b) comprises a dedicated module that logs the events that occur within the 3D interactive environment. The human-machine devices, which allow the trainee moving and operating in the virtual plant (Nazir *et al.*, 2012), facilitate the actions performed by the trainee. Whenever the human-machine devices issue a software event, the corresponding action is recorded chronologically. In addition, the logger module can be connected to both the dynamic process simulator and accident simulator (when and if necessary) and can store through a sampling procedure the process and accident variables that are periodically updated. Eventually, a data repository contains the operator and process/accident data that can be saved in dedicated files whose records are arranged according to the requirements of the programs that will use them as input data. As far as the performance assessment of the operator working at the CIS procedure is concerned, the logger has to store the data about the actions done on any piece of equipment and device with the corresponding timings. Equally, the logger has to register the number and quality of requests for help made by the trainee (if any). During the training procedure the PS allows the trainee to make help requests organized in different levels of complexity and hierarchy. Conversely, during the assessment procedure, the PS reproduces the real operating conditions and environment. Therefore, the trainee has no access to any support features such as help, guidance, and augmented virtual reality (Nazir *et al.*, 2012).

Whenever the trainee performs a new action, the logger prepares an input file for the assessment algorithm. This allows dynamic tracking of the performance of the operator and giving him/her a prompt update with marks and ancillary bits of information at every action taken during the training session. Conversely, during the assessment session the performance appraisal is presented only at the end of the session in order to strictly respect the real operating conditions of industrial plants. By doing so, the trainee is neither distracted nor informed dynamically about the correct/wrong actions and s/he has no idea of how s/he is performing until the end of the test.

3.2 The performance assessment module

The Performance Assessment Module, PAM, is the core of the ACA that receives as input data the file prepared by the logger described in previous section. The PAM starts reading the nominal procedure that, according to the case study presented above, comprises the sequence of 32 actions (organized in 5 groups) in accordance with the company policy. Then the PAM reads the input file produced by the logger which reports the list of actions performed by the trainee in the PS. Every single action done by the trainee is compared with the reference one to check for consistency in terms of sequence, duration, device typology, equipment name, and operation. The PAM assigns a positive mark to the correct actions whilst gives a negative score to the wrong actions. The quantitative values of the positive/negative marks are assigned by process experts who may comprise trainers, process engineers, safety responsible, and plant managers. In previous papers (Manca *et al.*, 2012a,b), the authors discussed extensively the most appropriate methodologies to achieve a shared opinion and extract weighing factors for the marks of the performed actions.

A viable methodology to reconcile the different opinions from expert people and produce a final shared advice on both the absolute and relative weights of the marks/scores for every action is the AHP technique (Saaty, 2007). This methodology, based on qualitative binary comparisons about the relative importance of factors such as the procedure actions, was adopted to determine the relative ranking of prescribed actions in the CIS procedure.

The ACA evaluates the scores of performed actions and shows as results not only the overall mark, with a qualitative explanation attached, but also additional statistics that highlight the shortcomings and the room for improvements as well as the good performance of the trainee. Figure 2 shows the final report generated by the ACA. That report simulates the assessment of a trainee that finalized only a fraction of the whole procedure (this is the reason for the very low final mark and the qualitative description of his/her performance). Specifically, s/he performed 12 actions applied to the first two groups of actions (for the sake of space in Figure 2). The trainee did not make any errors in group 1 that comprises 7 actions, whilst s/he made 3 errors out of 5 actions in group 2 which requires carrying out a total of 6 actions.

```
TRAINING_SESSION: CATALYST INJECTOR SWITCH
-------------------------------------------
Friday 21 November 2025 11:08:24
The FOP mark is: 10.12 over 100
The operator needs MORE TRAINING.
The sequence of actions to be performed by the FOP comprises 32 actions
Total number of actions performed by the FOP: 12
- Number of correct actions performed: 9
- Number of wrong actions performed: 3
--> Percentage of procedure completion: 28.13%
--> Percentage of correct actions respect to the total ones performed: 75.00%
The whole training session lasted: 6 min and 4 s
-------------------------------------------
Group #1 consists of 7 actions
Number of correct actions: 7 over 7
--> Percentage of completion of this group of actions: 100.00%
Number of wrong actions: 0
--> Percentage of correct actions respect to the ones performed in this group:
100.00%
Time taken in this group: 4 min and 38.06 s
-------------------------------------------
Group #2 consists of 6 actions
Number of correct actions: 2 over 6
--> Percentage of completion of this group of actions: 33.33%
Number of wrong actions: 3
--> Percentage of correct actions respect to the ones performed in this group:
40.00%
Time taken in this group: 1 min and 26.39 s
-------------------------------------------
Group of Actions #3 not performed
Group of Actions #4 not performed
Group of Actions #5 not performed
-------------------------------------------
Time taken by action # 1 on DEV-101: 37.17 s
Time taken by action # 2 on VLV-11: 34.35 s
Time taken by action # 3 on VLV-02: 7.57 s
Time taken by action # 4 on VLV-08: 8.01 s
Time taken by action # 5 on VLV-21: 2 min and 23.48 s
Time taken by action # 6 on VLV-14: 13.89 s
Time taken by action # 7 on VLV-19: 33.59 s
Time taken by action # 8 on VLV-09: 48.98 s
Time taken by action # 9 on VLV-12: 37.41 s
-------------------------------------------
```

Figure 2: Output results of the performance assessment produced by the ACA. The training session is cut to a fraction of the first 2 out of 5 groups of actions for space reasons. This is the reason for the negative mark obtained by the FOP.

As a general remark, the partial results targeted to the single groups of the procedure allow discerning the groups of actions where the trainee is less efficient and expert. This allows focusing on the weaker points of the training procedure thus replicating with greater care the most delicate and sensible actions and preparing for the final assessment session. In addition, the actions timing reported in Figure 2 can be compared with a reference procedure (*i.e.* the one performed by an ideal operator) so to understand if the completion time is consistent with the expected results or some adjustments should be implemented.
The overall mark also takes into account the possible contribution produced by the requests for help raised by the trainee during the training session. Evidently, the support of help in finalizing the actions sequence, being facilitating, reduces the trainee skill. This reduction depends on the number of help requests and on the help level asked by the trainee (Manca *et al.*, 2013b). The negative contribution provided by the possible help requests is displayed only at the end of the whole training session instead of updating the partial score whenever an help is asked. The reason is that the operator should not be worried to see that any single request for help is detrimental in terms of achieved mark. Instead, the help should be invoked whenever there is need for support and explanation, so to strengthen the process understanding and to avoid *parrot-fashion* learning.

4. Conclusions

The ACA saves each result of the PAM into a separate file that allows tracking dynamically the evolution of the operator's preparation and highlighting the achievement of a suitable learning level. The trainee can understand precisely what are the parts, sections, procedures, tasks, and actions that weigh more/less in the final performance judgment. The results produced allow the trainer focusing on a more human-oriented assessment since the quantitative details shown in Figure 2 are delegated to the ACA. These results are not only restricted to the trainer but can support further decision oriented activities peculiar of the company management, such as: workforce recruiting, selection of most suitable operators for critical operating procedures, definition of minimum requirements to be admitted to real field operations, and enhanced assessment tools to be spent in negotiating insurance policies. As the PS simulates in background the process evolution affected by the trainee's actions, it is also possible to provide the performance assessment with further details about the economic impact of the procedure. The economic appraisal would use as input data the process variables that are evaluated by the dynamic process simulator.

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