

Exploiting Operator Training Systems in chemical plants: learnings from industrial practice at BASF

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ABSTRACT

Demographic shifts and increased automation in chemical plants are reducing the experience and skill levels of plant operators. Therefore, BASF has implemented Operator Training Simulators (OTS) to allow operators to practice and improve their skills in this safe and controlled environment. The OTS consists of a dynamic model of the process, a control system and safety logics. This paper describes the learnings from using OTS at BASF, where they are used to train operators in process understanding, optimization, procedural training, and disturbance handling. Benefits include reduced training costs, minimized risks and improved efficiency. Also organizational guidelines are provided to ensure that the mentioned benefits are realized in industrial practice. Additionally, high-accuracy OTS models support HAZOP, debottlenecking, and optimization studies.

Keywords: Simulation, Optimization, Modelling and Simulations, Training Systems, Digital Twin, Dynamic Modelling

INTRODUCTION

The chemical industry is characterized by complex processes and stringent safety requirements, making the training of operators a critical component for ensuring operational efficiency and safety. Traditional training methods, while effective to some extent, often fall short in providing hands-on experience and real-time decision-making skills necessary for modern plant operations.

Furthermore, a significant demographic shift and a surge in automation, has led to a decline in the experience and skill levels. This trend is further exacerbated by the fact that new operators are accustomed to different learning methods compared to their predecessors. Consequently, there is an urgent need for innovative training solutions to bridge the skills gap and ensure operational safety and efficiency.

Operator Training Simulators (OTS) (see, e.g., [1-3]) have become indispensable tools within BASF to address these challenges. OTS provide a realistic and immersive training environment where operators can practice and enhance their skills in a safe and controlled setting. Furthermore, the OTS system serves as a *digital twin* of the plant, allowing to test changes in control structure and perform optimisation process studies [4]. These OTS's

simulate the dynamic behavior of the chemical plant with a *dynamic first principles model*, replicate the behavior of the *Distributed Control System* (DCS) system including the *Human Machine Interface* (HMI) and process controls and the safety logics, offering a comprehensive training experience.

In this paper, first the different types of OTS systems are discussed, followed by the technical details of how an OTS is set up. Third, insight is given in the way OTS's are embedded in the organization from a management perspective followed by some case studies. Operators trained with OTS exhibit improved problem-solving skills, faster response times, and a better understanding of process safety. Furthermore, the use of OTS has been linked to a reduction in operational errors and incidents, contributing to overall plant safety and efficiency. Finally, a summary is presented including lessons learned.

TYPES OF OTS SYSTEMS

Industrial OTS systems consist of 3 distinct main parts as depicted in Figure 1:

- a detailed *dynamic model* which accurately describes the plant behavior.

- an emulation of (i) the *Distributed Control System* (DCS), comprising the process controls and logics, and (ii) the *Safety Interlock System* (SIS), comprising the separate safety system.
- a *Human Machine Interface* (HMI), displaying all sensor values on a process diagram and allowing the operator to interact with the process.

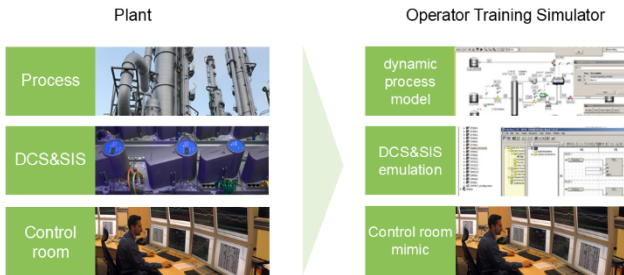


Figure 1. Components of an OTS system.

A distinction between 3 classes of OTS's can be made based how accurately the real plant is represented by the OTS and the way the above-mentioned components are implemented: (i) *High Fidelity* (HiFi) OTS, (ii) *Mid Fidelity* (MiFi) OTS and (iii) *Low Fidelity* (LoFi) OTS. Here is HiFi-OTS the most expensive and complex to implement while the other two are a less accurate representation of the plant, but at a significant lower implementation cost and complexity. Below, we will briefly discuss every type. Figures 2 and 3 summarize their features.

The **HiFi OTS** is distinguished by its highly detailed and realistic modeling, designed to closely replicate actual plant operations. This system facilitates comprehensive training, encompassing both the start-up and shut-down processes of the plant, as well as the management of random scenarios. The HiFi OTS employs components for the DCS that are virtually identical to those used in the actual DCS, ensuring that the training environment accurately mirrors the real control system. Furthermore, it features the same HMI as the real DCS, providing operators with a familiar and intuitive interface. The SIS within the HiFi OTS is also an exact replica of the real SIS, enhancing the realism and effectiveness of the training experience. Because this type of OTS matches closely the real plant, the OTS also serves as a digital twin allowing to, e.g., test DCS changes and perform plant optimization and safety studies. A HiFi-OTS is particularly advantageous for plants that experience infrequent shut-downs and where unplanned trips are exceedingly costly. In general, this OTS is considered for larger plants with typically more than 5000 IO's (Input/Output points). By providing a realistic and immersive training environment, the HiFi OTS enables operators to develop and refine their skills, thereby improving operational efficiency and safety.

The **MiFi OTS** is most suited for smaller plants which have more frequent shutdowns, are less complex and

have less costly plant trips. For such plants, MiFi OTS offers a better balance between cost and functionality, making it a practical choice for enhancing operator training and plant performance. The development of MiFi OTS was primarily driven by the need to reduce the investment costs associated with a traditional HiFi OTS, thereby allowing a broader adoption across various plants and processes. By simplifying the OTS architecture, MiFi OTS achieves a significant cost reduction. It employs a simpler first principles model, which focuses on fundamental process dynamics rather than the precise replication of real plant behavior. As a result, MiFi OTS typically does not support plant start-up simulations, which are often complex and require much more modelling effort. One of the key cost-saving features of MiFi OTS is the elimination of the substantial expenses linked to the representation of the DCS system and the SIS system. Instead of relying on these complex and licensed systems, MiFi OTS integrates process controls, DCS logic, and SIS logic directly within the first principles model. This integration not only reduces costs but also simplifies the overall system architecture. The graphical interface of the DCS HMI is emulated using a multifunctional graphical software package, ensuring a user-friendly interaction that generally mimics the actual plant HMI environment. MiFi-OTS is generally envisioned for plants with 1000-2000 Input/Output (I/O) points, seeking a cost-effective and less complex OTS, while still enabling training of normal operations, standard scenarios and standard procedures.

LoFi OTS (or generic OTS) are designed around standard unit operations to train new operators during their initial weeks. They provide a foundational understanding of basic processes and procedures, aiming to enhance the competence and confidence of new hires.

At BASF Antwerpen, the focus is on MiFi OTS and HiFi OTS. These systems allow for plant specific training with higher effectiveness on different training levels. LoFi OTS is not used often within BASF Antwerpen due to the limited learning experience which is only relevant during the first weeks of onboarding. In this paper we will therefore further focus on HiFi OTS and MiFi OTS.

BUILDING AN OTS

Different elements are needed to build an OTS. Depending on the type of OTS envisioned and the plant condition, the requirements can change slightly. As mentioned, we focus in this paper on the cases of MiFi and HiFi OTS.

OTS – different types

Operator Training Simulator

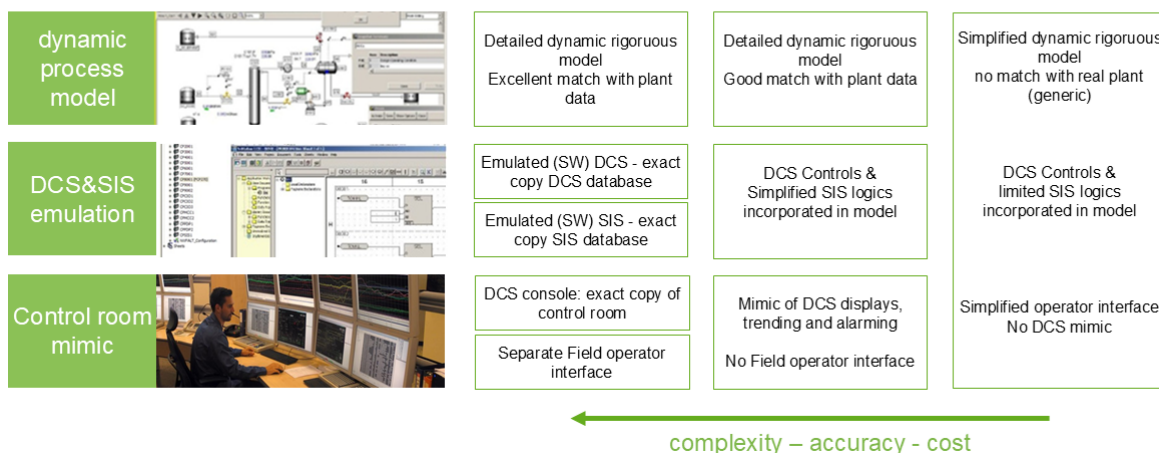


Figure 2. Different components of the various types of OTS systems.

Type	Scope	Training					Testing		Cost	
		Training level	Understand process	Defined scenarios	Startup/S shutdown	Random scenarios	DCS/SIS changes	Process changes	Invest	Maintain
Hi-Fi	Whole plant (>5000 IO's)	Monitor Operate Master	✓ ✓ ✓	✓ ✓	✓	✓	✓	✓	1000k€ - 2000k€	5-10%
Mi-Fi	Section/small plant (250 – 5000 IO's)	Monitor Operate Master	✓ ✓ ✓	✓ ✓	✗ ✗	✗	limited	limited	150k€ - 500k€	5-10%
Lo-Fi (generic)	Unit operation (<250 IO's)	Monitor Operate Master	✓ ✓ ✓	✗ ✗	✗ ✗	✗			50k€ - 150€	5%

Figure 3. Comparison between different types of OTS systems.

REQUIRED INFORMATION

Different information is needed for the dynamic model of a plant. In view of the general plant set-up this includes (i) process flow diagrams (PFD) for the general plant lay-out (including the material and heat balances), (ii) Piping and Instrumentation Diagrams (P&IDs) for the over-all pipe connections and control design, (iii) equipment design sheets of all equipment (e.g., reactors, columns, tanks, heat exchangers, pumps, valves, compressors, sensors, ...) for the mechanical and thermal behavior, (iv) a scheme describing the relative heights of the different equipment. In view of the chemical and thermodynamical modeling this includes among others reaction kinetics, vapor-liquid equilibrium data. For HiFi OTS detailed information for all items is needed. For MiFi OTS, several aspects of can be simplified (e.g., linear valve curves, lumped kinetics and thermodynamics, and

approximated thermal and kinetic equipment inertia). In view of process control functional descriptions of the different control structures are needed. When constructing an OTS, the dynamic simulations must be validated against plant data. Typically, this is performed section by section. For the brownfield OTS projects (where the plant already exists) this can be done against actual plant data. For greenfield OTS projects (where the plant is being constructed) it must be done against the (steady-state) simulation data that was gathered during plant design phase, more specifically the heat and material balance of each unit and stream.

In view of the HMI interface, there is a large difference between MiFi and HiFi OTS. For HiFi OTS the actual DCS configurations and faceplates are needed and have to be available. Typically, the actual DCS system will be emulated. For MiFi OTS a selection of the actual DCS features has to be programmed using DCS screenshots.

Modeling and simulation tools

Different dynamic flowsheet simulators exist. At BASF Antwerpen the following ones are used: Aspen HYSYS (AspenTech) for MiFi OTS and DynSim (Aveva) and UniSim (Honeywell) for HiFi OTS. Apart from typical simulation aspects (mass and energy balances), the tools also have to include typical aspects for process control and process safety. This includes PID and possibly MPC controllers as well as alarming features and cause and effect schemes that guarantee the interlock and trip behavior of different equipment.

Graphical tools

For MiFi OTS specific software is needed to create the HMI layer as the actual DCS screens and faceplates are not being emulated. Instead a mimic of the DCS displays is built covering most the most important functionality and information to be presented to the operator. At BASF Antwerpen the InProcess Infrastructure Suite IIS (InProcess) is used for this purpose.

Software and hardware set-up

From an ICT point of view, a typical set-up of an OTS will be different for a MiFi and a HiFi OTS.

In Figure 4 a typical example of for the set-up of a HiFi OTS is given. This set-up comprises two virtualized servers hosting the different components of the process control and simulation network. These components are connected via ethernet to a switch. To this switch are also a NAS, the different operator stations as well as the instructor station connected.

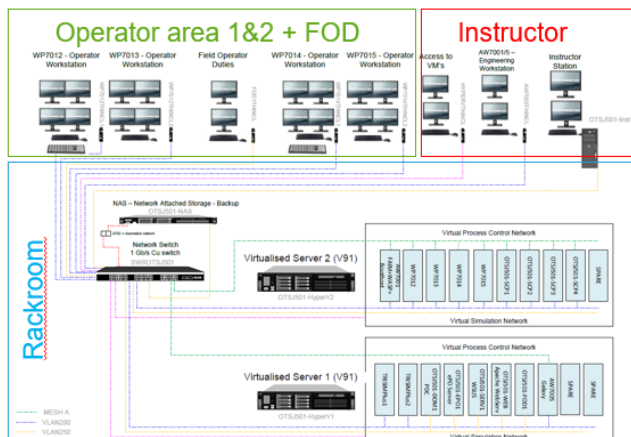


Figure 4. ICT components of a HiFi OTS system.

For MiFi OTS the ICT framework is simpler (see Figure 5). It comprises of a single server, where both the simulation and the HMI runs. This server is connected via the local network to an operator and an instructor station. The number of components for a MiFi OTS is low compared to the set-up of HiFi OTS .

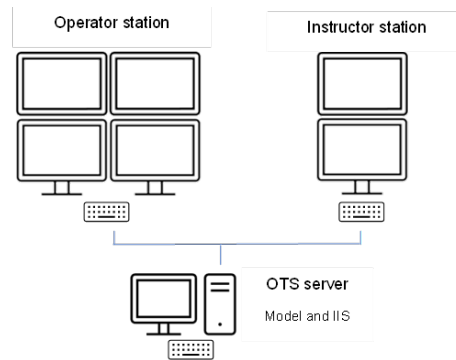


Figure 5. ICT components of a MiFi OTS system.

The operator working console should be mimicked as closely as possible in the training room. This means, for instance, that the operator should have sufficient screens to displays trends alongside the DCS screens. The typical quad-head setup is mimicked from the control room. Typically, in the training room there is a console for the trainer, who can interact with the simulation, e.g., by initiating different scenarios and disturbances. A picture of an OTS training room is presented in Figure 6.



Figure 6. View of an HiFi OTS training room.

OTS TRAINING APPROACH

Continuous training of the operators is required to improve and maintain their skill level to assure correct operator actions in case of specific situations. OTS training has become an essential part of this continuous operator training journey within BASF.

Within BASF the skill level of operators is typically increased in three steps:

- *Monitor* level: the operator needs to be able to understand and interpret how the process is working. At this level the operator is not yet allowed to operate the plant/process from the DCS panel.
- *Operate* level: the operator is able to operate the plant from the DCS panel in normal conditions and he is able to act properly to reject smaller disturbances.
- *Master* level: the operator is able to handle the

process properly in all situations including bigger disturbances and full start-up/shut-down.

OTS is an effective training tool to reach the different skill levels mentioned above and/or to sustain the knowledge at the desired level as is depicted in Figure 3:

- **Monitor** level: basic process behavior, dynamic interactions in the plant/section can be explained and illustrated to the trainee on the OTS. The OTS is an ideal environment to explore the information displayed on and demonstrate the functionality of DCS (displays, PID faceplates, trends, alarm lists, control concepts, ...).
- **Operate** level: operators can train on the OTS how to handle the plant during, e.g., load changes or specific disturbances (e.g., smaller equipment failures) can be introduced on the OTS on which the trainee needs to respond in a correct and timely manner.
- **Master** level: the trainee can train full start-up and shut-down. Random disturbances can be introduced on OTS (equipment failures/trips) causing significant disturbances to be handled by the operator.

HiFi OTS systems can cover training to reach (or sustain knowledge at) all three levels mentioned above. In large, complex plants where an HiFi OTS is available, it is important to bring operators efficiently to a basic operating skill level but it is equally important to maintain and even deepen the skills of the more experienced operators (operate and master level). An evolution of the registered training of a HiFi OTS at BASF Antwerpen is depicted in Figure 7.

MiFi OTS systems are typically more limited in functionality (e.g. limited number of available scenario's). Consequently, they mainly focus on training towards the *monitor* and *operate* level. Typically, the plants/sections for which a MiFi OTS is available, have a smaller scope and lower complexity compared to plants where the choice is made for a HiFi OTS. In such a case (smaller scope, lower complexity plants) intensive training of operators on the *master* level is less crucial as well.

In most plants with an OTS a dedicated training instructor manages and coordinates all the training activities within the plant. The *training instructor* is key for the success and effectiveness of the OTS as training tool. In most BASF plants where an OTS is introduced we have a combination of training sessions on OTS performed by the instructor (typically during day time or depending on availability of the instructor) and training sessions without instructor (e.g., during night/weekend). *Instructor-led* training sessions are required to transfer knowledge in a consistent way to the trainees and to give them correct feedback on the actions taken on the OTS. *Instructor-*

less training sessions allow the trainee to train on his own (e.g. repeat training sessions/scenarios performed with the instructor). *Instructor-less* training is in some cases supported by definition of kpi's (key performance indicators) to track the operator performance during the execution of a certain task on the OTS: kpi's can be defined as time or process criteria: achieve goals within time limit, while assuring not to exceed certain process parameters.

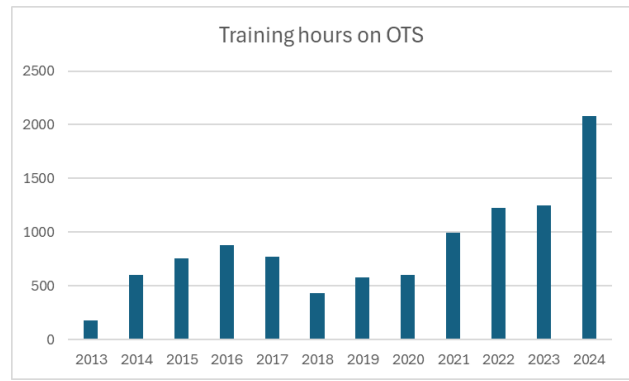


Figure 7. Registered training hours for a HiFi OTS at BASF Till 2022 only instructor-led trainings were registered.

OTS AS A DIGITAL TWIN

The focus for an OTS application is training as described above. However, the rigorous dynamic plant model and the link with the control system (DCS/SIS) allows the OTS to be used for a broader range of applications ranging from process (control) optimization and design to safety studies. Below two examples are given of how OTS can be used as a digital twin to bring substantial benefits by supporting other activities besides training.

“Parking lot” sequence for the steam cracker plant

For the steam cracker, i.e., the biggest and most complex plant at the BASF Antwerp site, a “parking lot” sequence concept has been developed. The aim of this sequence is to support the operator in case of a serious plant disturbance and to bring the plant quickly to a safe and stable state (“parking lot”). This allows a faster recovery to normal load and avoids a full trip of the plant. When the full “parking lot” sequence is activated around 150 variables (setpoints, valves, ...) are triggered to reach a desired position. The full concept was first implemented on the HiFi OTS to verify its correct operation. The HiFi OTS environment is used as an accurate digital twin allowing for full dynamic response evaluation of the plant in case the sequence is activated. In addition the operators were trained on the OTS on what to expect in case the sequence is activated. Only after these steps, the final version of the “parking lot” sequence was implemented on the real plant. This approach (validation and training on OTS first) assures a “first time right” implementation in the real plant and on top a very high

acceptance of the operators since they feel confident that the sequence and logics will work as expected. In the years the “parking lot” sequence has been implemented it was activated a couple of times working as expected. This allowed the plant to stabilize and recover to normal plant load quickly, minimizing production losses.

Greenfield OTS: a digital twin for a new plant

Building an OTS for a greenfield plant (greenfield OTS) is especially beneficial to assure a smooth and efficient start-up of the plant due to different reasons.

The OTS can be used to train the operators extensively in order to improve and speed up significantly the understanding of the new process and how to handle it (e.g. start-up/shut-down) before the actual plant is started up. Having the OTS already available before the start-up of the plant will allow the start-up/shut-down procedures to be validated thoroughly and where required adjusted. Having the OTS available in this stage of the project allows as well to validate in detail the control concepts (DCS) and safety logics (SIS) in more detail compared to the typical FAT (factory acceptance testing) protocols applied for the DCS and SIS. The OTS allows full dynamic testing of the interaction of all the controls and logics in all different states of the process. The control concepts and logics can be improved based on the outcome of these detailed dynamic tests. Stable and dynamic behavior of the process is also related to the tuning of the PID controllers in the DCS. The OTS serves as digital twin and is the ideal test bank to provide appropriate initial values for the PID tuning. The PID parameters obtained during the testing and training on the OTS can be transferred to the life system before start-up. Sometimes conceptual design errors are identified during greenfield OTS projects that require equipment changes. An example from one of the greenfield OTS projects is the wrong sizing and positioning of an outlet nozzle on a drum not allowing to collect sufficient liquid in the drum to operate properly in all circumstances.

As illustrated above, the use of a greenfield OTS as a digital twin facilitates the early detection of all kinds of design errors (equipment, controls, procedures, ...) which leads to a smoother start-up and significantly reduced start-up times. Due to the OTS training before start-up, operators are familiar with the procedures and feel much more confident to start up their greenfield plant.

OTS MAINTENANCE

Plants are subject to modifications continuously, either to improve process efficiency or for safety reasons, equipment, piping, controls and logics are changed throughout the lifetime of a plant. Keeping the OTS aligned with the real plant is important for operators to experience the actual plant's state properly on the OTS.

Training of operators on an outdated OTS system (OTS not fully in line anymore with the real plant) significantly reduces the effectiveness of the training. To avoid this degradation of the OTS training experience, regular maintenance on the OTS is required. The maintenance includes model changes (to reflect, e.g., equipment and piping changes) as well as control and logic changes (to reflect changes in DCS&SIS). Typically, maintenance is performed by a process control engineer (e.g., model changes, control and logics changes) together with the instructor (validating the applied changes in the OTS). The maintenance frequency depends on the number of plant modifications in the real plant but typically ranges from twice to once a year. Typical bigger maintenance activities on OTS are related to turn around (TAR) activities of the real plant in which major modifications are implemented on the real plant. Again, here the OTS can serve as the perfect test bank (digital twin) for changes to be applied during the TAR by implementing and testing the OTS relevant changes before the TAR takes place.

CONCLUSION

OTS systems have become a vital tool for training starting as well as experienced operators within BASF. At BASF Antwerpen, the deployment of both High Fidelity (HiFi) and Mid Fidelity (MiFi) OTS has enabled to differentiate and tailor these training tools to different types of plants, enabling a wider adoption. The presence of a dedicated instructor is critical for the effective implementation and utilization of an OTS, ensuring consistent and impactful training. Furthermore, regular maintenance of an OTS is imperative to maintain the alignment with real plant conditions, thereby preserving its relevance and efficacy as training instrument. Beyond their primary training function, OTS also serve as digital twins, facilitating the testing and validation of modifications in the DCS&SIS or the plant itself of both green/brownfield plants.

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