MODELING, IDENTIFICATION AND CONTROL, 1989, VOL. 10, NO. 4, 185–202

The effective use of full scale simulators for training

doi:10.4173/mic.1989.4.1

TAHIR I. MALIK†

Keywords: *Dynamic process simulators, operator training, chemical engineering.*

A full scale process simulator is a type of simulator which is comprehensive in the details of the plant simulated, emulated or replicated. The experience of use of non-nuclear, full scale process simulators is relatively fresh. There is enormous scope for increased or more effective utilization through rationalized analysis carried out from different perspectives or points of view. It is argued that the chemical engineering perspective is of fundamental importance for process plants and may not have been given its due importance so far. The effective use of these, usually large investment, simulators for training is analysed from a chemical engineering viewpoint and resulting ideas and recommendations presented. Another perspective investigated is that of the simulator designer. The maximum utilization of the simulators will depend upon optimal use of the functions and facilities built in by the designer. The possible use by the instructor or the trainee of the simulator development tools and utilities is discussed. Two examples of full scale simulators are the Gullfaks and Oseberg Production Platform Simulators, operated presently be Statoil and Norsk Hydro respectively and designed and built by NorControl Simulation. These simulators are referred to in the paper as appropriate examples. The most obvious perspectives, that of the instructor and the trainee, are also touched upon. It is argued that human teachers or instructors remain critically important elements in training sessions carried out in the presence of full scale simulators. The effective use of the simulator will depend heavily on the proficiency of the instructors. Speculations are made into the future developments in the methodology of use of simulators.

1. Introduction

This paper is intended to look critically at how a class of real time, chemical process plant simulators defined as Full Scale Simulators (FSS) can be used most effectively for training purposes. The abbreviation FSS is used here to refer only to a chemical process simulator and not, for example, to a nuclear power plant or an aircraft simulator. The concept of the FSS will be first defined and developed so its characteristic may be appreciated. FSS represent considerable investment on behalf of the operating company. Their experience of use so far will be briefly reviewed. Future use of FSS for training is likely to grow and therefore it is appropriate to start discussion on their effective utilization.

There is a need for rationalized thinking, to raise various questions for discussion from different points of view; and to share these experiences with others. It will be valuable at least to motivate discussion on the matter and start the thinking process, if not provide all the answers here.

Received 1 August 1989.

† NorControl Simulation A/S, P.O. Box 1024, N-3191, Horten, Norway.

This paper was presented at SIMS '89 (Scandinavian Simulation Society), 31st Annual Meeting, Bergen, Norway, May 31–June 2, 1989.

The discussion is based upon different perspectives or points of view; these are naturally influenced heavily by the author's own personal experience, although an attempt is made to cover the simulator users (Fig. 1).

The first perspective considered is that of a chemical engineer. It is thought that not enough chemical engineering thinking has been applied to the making and running of FSS. Conversely, there is not enough realisation on the part of chemical engineers of the potential value of the FSS to their discipline. A discussion is therefore presented on the chemical engineering view of process operators, process dynamics and FSS before seeking specific recommendations from this point of view.

The second perspective considered is that of the simulator designer or manufacturer. Various discussion points will arise out of looking at the effective use of FSS from this angle. The third perspective, of the simulator user, will consider the importance of the human instructor, the effective use of malfunctions and will present other suggestions and discussions.

It is hoped that this will lead others to enter discussions and give ideas from their own perspective on how best to use FSS, which should be used with increasing frequency in the future.

2. Definition and key attributes of FSS

Gran *et al.* (1988) recently put forward a definition for a FSS in relation to a process plant. A FSS is a simulator reproducing both steady state and dynamic behaviour of a real process plant. To satisfy the full criterion, the simulator should contain models for all the main processes, or if there is more than one identical parallel process train, at least models for one of them; it should contain models for the bulk of the supporting utility, process and emergency systems, if not for all of them; it should have an emulation, replication or 'stimulation' of the operator system installed on the plant; it should have a replica of the man–machine interface functions of the real plant's central control room (CCR); and, in addition, a FSS will have an instructor's station backed by dedicated functions for the benefit of a tutor.

It is beneficial to make such a classification for a FSS. Clearly, the opportunities of such a device deserve some separate considerations from other products such as part task simulators, generic simulators, programmed instruction systems etc., some of which are also based on dynamic simulation. An FSS, in contrast to these other products, gives a very detailed and dedicated view of a given, real plant. It is designed to look like and give responses almost indistinguishable from those obtained from the real plant. FSS form part of the growing overlap between training related to chemical processes and dynamic simulation of chemical processes (Fig. 2).

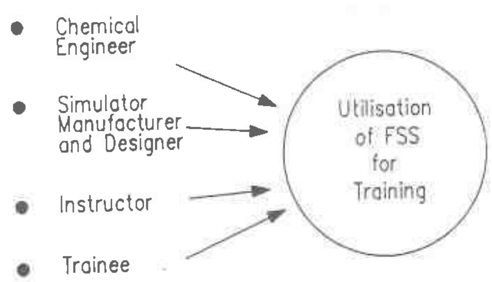

Figure 1. Users of full scale simulators.

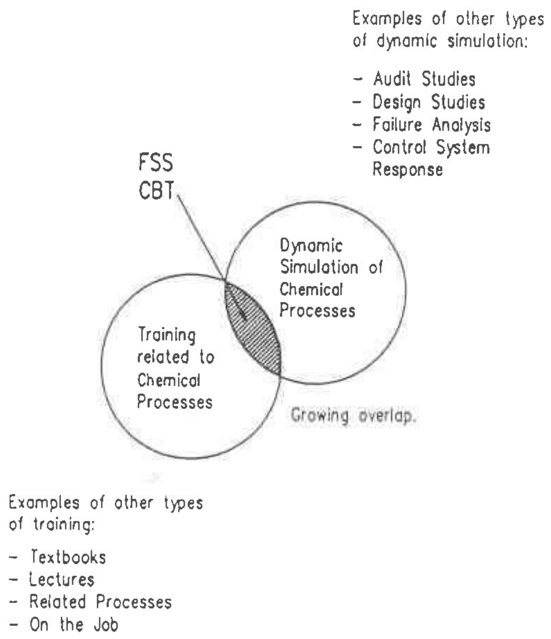

Figure 2. Overlap between dynamic simulation of and training related to chemical processes.

It is important to appreciate that a FSS would normally only be made with reference to a real process plant, whether already built and producing or going through one of the precommissioned project phases. FSS are expensive and it is unlikely that investment in one would be justified for a process that had only reached a conceptual stage. It is feasible, however, to modify an existing FSS to represent new conceptualized processes. The reconfiguration of a FSS is possible within the bounds of simulator system software and hardware.

An essential and fundamental feature of FSS is that they give dynamic as well as steady responses. The dynamic simulation of processes requires the solution of mixed systems of differential and algebraic equations, models for which will be contained in the simulator in one of the various sequential modular or equation-based strategies. The steady condition can be considered as a special occurrence of the more general system of equations when the differentials with respect to time become zero. Steady conditions may prevail on the simulator with respect to localized parts of the plant or for the entire system.

Another essential component of the FSS are the models of the discrete logical events, such as the activation or deactivation of a process switch, in addition to the continuously, smoothly varying quantities. These components help to give the FSS a very close resemblance to the real plant.

Figure 3 gives the scope of process systems typically modeled, Fig. 4 shows the typical essential components of a FSS and Fig. 5 gives a typical list of models coming under the category of process control and instrumentation (see also Clare and Malik 1986).

3. Experience of use of FSS

There has been interest in the use of FSS for a number of years, Exxon for example started to use training simulators for some of their plants as long as 25 years ago (Silver

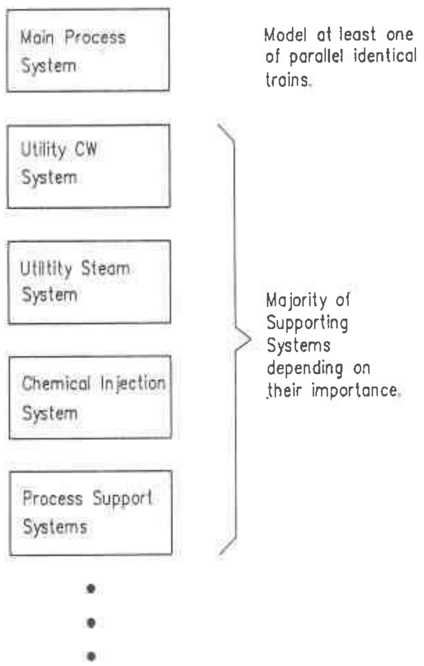

Figure 3. Scope of systems modeled in a full scale simulator of a chemical process plant.

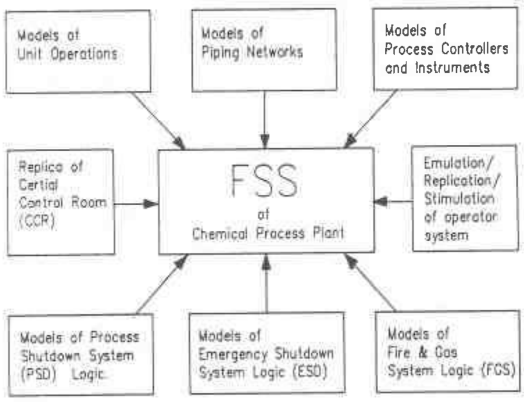

Figure 4. Typical components of a full scale simulator of a chemical process plant.

and Zamwalt 1983, Demena *et al.* 1984), but the total number of true FSS built to date and the experience of use of FSS in the mainstream process industry remains limited. There is unanimous agreement in the literature about the great benefits derived from training on FSS (Gran *et al.* 1988, Silver and Zumwalt 1983, Demena *et al.* 1984, for example), but relatively little is mentioned on the methodology employed by the given user to implement training programmes on them.

The occurrence of use of FSS is likely to grow over the next few years as hardware costs tumble and precise and powerful software tools become available. Exxon now includes a process training simulator in most of its own plant projects (Silver and

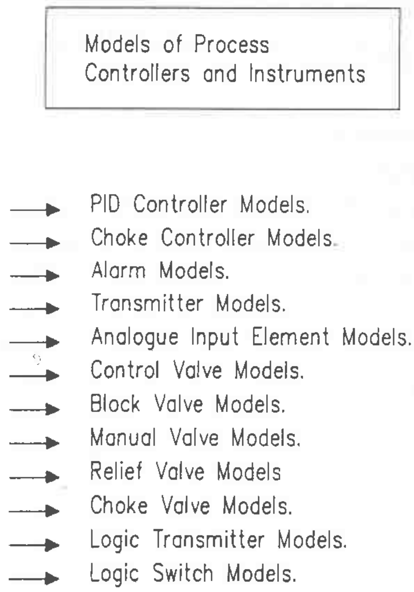

Figure 5. Examples of models of process controllers and instruments.

Zumwalt 1983). FSS have been built for operator training for North Sea oil installations. In the Norwegian sector, NorControl Simulation (NCS) has been primarily responsible for making 3 major FSS of offshore oil platforms. The first was commissioned for Statoil for the Gulfaks Production Platform, prior to the start of production on the real platform in 1987 (NorControl 1984, Strand 1988). The second, the Oseberg Platform Simulator, was delivered to Norsk Hydro in 1987 and was used for training well before the real platform startup in 1989 (Gran *et al.* 1988, NorControl 1986). The third is the Veslefrikk platform simulator which has gone through factory acceptance tests in April 1989 and will be used by Statoil (NorControl 1988a, Strand 1988). The Gullfaks, Oseberg and Veslefrikk simulators are all located in Sandsli-Bergen, also the venue for SIMS 89 conference.

4. Chemical engineers' viewpoint

4.1. *Its relevance*

The discipline of chemical engineering, since its inception in the 1920s (Coulson and Richardson 1970), has become fundamental to all types of process plant investigations. Before the 1920s the technologies for various processes were considered to be substantially independent from each other with little reliance on common underlying principles. Modern day chemical and process plants make full use of experiences gained on other plants of the same type as well as on plants making other products. This experience is carried forward through formulation into chemical engineering principles and later on their application to new and revamped projects.

The application of chemical engineering technology has led to leaps in the complexity of process plants. The process plants today contain a high degree of internal integration and employ sophisticated control systems and operation strategies. The effective operation of these plants depends on the sound understanding and use of chemical engineering principles as do the development, design and construction of them. It follows that the effective use of FSS for training will also benefit by reference to chemical engineering concepts, viewpoints and philosophies.

4.2. *Its view of process operator function*

Before considering the view on training using FSS, it is desirable to elucidate the chemical engineering view on the function of the process operator. Not much emphasis has been placed in the past on describing the role of the process operator in chemical, engineering literature. Standard works (Coulson and Richardson 1970, Perry and Chilton 1973, for example), contain very little on the human operator within the process plant. This does not mean that there is not an important role implied by the chemical engineering discipline.

It is asserted here that an essential component of chemical engineering is the relationship and interface betwen processes, on the one hand, and man, on the other, in various contexts. Numerous processes taking place in nature are of no immediate interest to chemical engineers (theoretical considerations excluded) as they are not practically utilized by man. As soon as a process is harnessed by man for economic gain, or intended to be so, chemical engineering science and technology become very relevant to its consideration. Chemical engineering, unlike pure science, is directly concerned with human values and desires and all interfaces between man and chemical engineering systems.

Normally, the primary human objective of running a process plant is to make economic gain in a safe and environmentally acceptable manner. This will also be the primary chemical engineering objective for the same plant. It is attained through optimal design and efficient operation of the plant. It is also known to the process operating and control system, in the form of setpoints for closed loop controllers, programmed logic for decision making during normal and abnormal operation and various additional supervisory control functions. An operating plant, like any real process, may have an infinite number of steady or dynamic states, which may be desired, undesired but stable, unsafe or even explosive. The automatic control system is designed to steer the plant through optimal, safe and environmentally acceptable states at all times during startup, normal operation and shutdown.

Human operators ensure that satisfactory, or if possible optimal, but certainly safe states are maintained by manual intervention in the event of inadequate or incapacitated performance of all or parts of the control system. The operator is the final link on the human side in the chain of management and technical personnel responsible for the plant. As such, he communicates the human requirements to the plant. Apart from intervention during maloperation, the operator will have several other tasks to perform such as selecting equipment for duty, standby or maintenance.

The increase in the degree of automation of plants has meant that manual action required for routine tasks is now minimal. The operator tasks are increasingly of a cognitive nature rather than merely perceptual. Also, the operator function is increasingly concentrated in the hands of less personnel. The large scale process industry has long been a highly capital intensive venture compared to other industries but the recent advances in microprocessor applications have made it much more so. The capital invested in an offshore platform per CCR man at a given time runs into hundreds of millions of dollars.

The likely trend in the future is for increased sophistication, although not necessarily increased physical scale for all the processes. The capital invested per CCR man is also likely to grow both for the traditionally large scale processes such as offshore oil production, ammonia synthesis or ethylene production and for the more speciality and high value added chemicals plants.

The chemical engineering requirements on the standard and proficiency of the operators are therefore very high. There is an increasing demand that the operator, particularly the supervisor, should be qualified to a high educational and professional standard. In the long run the requirement could emerge that the operators of chemical plants should be academically and professionally qualified as chemical engineers.

It is asserted here therefore that the chemical engineering perspective of the process operator is of a highly trained, educated, experienced and judicious individual with substantial cognitive as well as perceptive abilities. This view of the operator is a corollary to the way application of chemical engineering technology seeks to engineer modern plants and the consequential demand on operators that arises.

4.3. *Its view of process dynamics*

It is stated (Chemical Engineering 1989) that traditionally dynamic simulation has been an activity for control engineers whereas chemical engineers have concentrated on steady state flowsheet simulation and process design. However, this imbalance has been due to the high costs of dynamic simulation in the past and not because chemical engineering is not concerned with process dynamics. Chemical engineers have always been interested in dynamic as well as steady performance of real plant. The critical phases of startup and shutdown and other plant upsets are of as much concern to chemical engineers as efficient, steady plant performance. Dynamic behaviour is also of interest for design purposes, as in the sizing of relief valves and relief flare systems.

At a mathematical level, chemical engineers are used to dealing with both steady state and dynamic correlations. Equation (1) below is a typical, steady design type correlation. It applies to heat transfer to a cooling fluid inside a tube by the mechanism of forced convention. In such a correlation averaged, bulk variables are used. The temperature used to calculate the dimensionless numbers is taken as the average of the inlet and outlet temperatures for the bulk fluid (as opposed to that in the film). The coefficients and indices for such correlations are determined experimentally, at steady conditions, for given constraints. Equation (1) is valid for the ranges $0{\cdot}7 < \mathrm{Pr} < 160$ and $\mathrm{Re} > 10000$. Equation (2) also applies to heat transfer, it is for unidirectional heat conduction and its solution covers time varying conditions. It will be noted that Equation (1) is an algebraic correlation whereas Equation (2) is a partial differential equation. Both types have long been of fundamental chemical engineering interest.

$$Nu = 0{\cdot}023\,\mathrm{Re}^{0{\cdot}8}\,\mathrm{Pr}^{0{\cdot}3} \tag{1}$$

$$\partial T/\partial t = \mathrm{DH}\,\partial^2 T/\partial x^2 \tag{2}$$

Chemical engineers employ fundamental laws of heat, mass and momentum transport, fluid mechanics and thermodynamics and, in addition, empirically determined correlations, in order to explain behaviour of seemingly different processes. Diverse operations such as spray drying, fluidization and distillation are explained using these methods for both steady and dynamic conditions. The understanding of these operations would only be partial if the transient effects were left out. The relative lack of dynamic simulation carried out in the past by chemical engineers, in comparison to steady state simulation, is therefore indicative of the practical difficulties and costs encountered and not of low requirements.

4.4. *Its view of the FSS*

From a chemical engineering viewpoint the FSS should be regarded as a new generation tool with vital fresh attributes, not all present in previous tools. These are:

(*a*) enormous detail.
(*b*) dynamic and steady response.
(*c*) continuous and discrete, logical events.
(*d*) real time performance.
(*e*) fully interactive facilities.

Some have been present in previous chemical engineering tools such as flowsheeting packages, performance analysers, equipment designers and CAD systems but their simultaneous availability occurs for the first time in an FSS. The FSS is the only other place, apart from the real plant where so many subsystems are integrated with each other in an orderly way to form a complete plant system. The FSS therefore offers enormous opportunities from a chemical engineering and process systems engineering point of view and its full exploitation along these lines has yet to take place.

Cheaper availability of these simulators in the future will give additional power to chemical engineering methods and to some extent alter the way in which chemical engineering work is carried out. It is possible, for example, that the synthesis of a FSS could start as early as the design process and be completed when the detailed design is finished. The integrated use of FSS in process engineering would also depend on how related new computer based chemical engineering technologies develop (Egol 1989, Geo *et al.* 1987 a–d).

4.5. *Its view of training with FSS*

It is possible to train an operator according to chemical engineering demands by the use of a FSS. A FSS brings the task of operator training right into the fold of chemical engineering applications, in this sense it closes an important, previously unfilled gap. Operator training can now be carried out in a systematic, scientific manner with the backing of powerful facilities and need not remain an uncertain art.

Some general thoughts arise from a chemical engineering perspective with regard to effective use of FSS for training:

4.5.1. *Run FSS for longer periods.* Chemical engineers are very conscious of the capital invested in their real plants. Large scale process plants usually run round the clock to ensure speedy financial return and to avoid wearing, time consuming shutdown and startup cycles. FSS are also expensive and capital intensive. By analogy, there may be a case of making greater use of the FSS simply by running it for a longer period. There is certainly a case for considering two 8 hour shifts if not round-the-clock use. It may be thought inconvenient to train at night, but it should be remembered that real plants also run at these times.

4.5.2. *Keep FSS closely tuned to real plant.* It is important to keep some of the snapshots on the FSS closely tuned to the characteristic of the real plant, if it has started production. Changes in the plant occur due to wear and tear, corrosion, scaling and resultant modification to transfer process rates, catalyst decay and renewal and equipment being replaced, among other causes that are beyond operator's direct control.

The operator actions such as modifications to controller setpoints and instrument settings will also result in changes to the plant behaviour. Also, the correction of design faults on the plant, for example in sequencing logic (NorControl 1987) will leave the simulator not updated. It could also be that the simulator was built when all design data was unavailable which would lead to differences between the simulator and the later erected plant. It is very important to remove these differences as far as is possible.

Much improvement is required along these lines for both the Gullfaks and Oseberg FSS. To the author's knowledge, relatively little tuning has been carried out on these simulators up to now with feedback from the real plant.

4.5.3. *Make operators responsible for updating FSS.* A possible suggestion is to make the operators themselves responsible for keeping the simulator fully tuned to the status of their plant. The actual implementation onto the simulator may be carried out by expert programmers under their direction. It is believed such a responsibility would increase the awareness and interest of the operator with regard to the FSS. Different operators could be responsible for keeping different subsystems on the simulator tuned, for example one operator could be assigned the task for the steam system while another operator could be responsible for part of the main process.

As far as the author is aware, there has been no such role given to the operators on Gullfaks, Oseberg or any other FSS.

4.5.4. *Integrate training with other activities.* The possibilities of integrating operator training with other chemical engineering tasks should be carefully examined. Operators may carry out the following, for example, on the FSS:

(*a*) tune individual control loops.
(*b*) try out new relief valve set pressures.
(*c*) tune complete subsystems on the FSS.
(*d*) work out material and energy audits with help from the simulator.
(*e*) try out new startup or shutdown strategies.
(*f*) identify operating bottlenecks on the plant.
(*g*) carry out MMI reviews and studies.

Some of these tasks will only be appropriate for experienced and not new operators. The novice may repeat the exercise without taking results back to the plant. Also, the inferences from the FSS will only be valid if it is closely tuned to the plant and the models are of sufficient fidelity.

The main point is that the operator would interact with the simulator in a different context from the normal and thereby become familiar with certain new aspects of the plant. Also, the thinking required to solve the problem would enhance his understanding of the plant. It may also be more interesting for the operator to know that he is solving a real problem rather than only going through a training exercise. In a way, this would be 'on the job' training except that it would be carried out without risk to the real plant.

4.5.5. *Plant manager and simulator manager.* At least when the simulator is on the same site as the real plant, which is not usually the case with offshore platforms, there is a case for integrating the plant operation management with the simulator operation management in order to maximize the use of the simulator by plant personnel and to help to make the simulator a problem-solving resource for the plant. An investigation will be required on the implications of making the plant manager also the simulator manager for each given situation. The training sessions would continue to be directed by the instructor and thus a desired degree of separation between the plant and the simulator could still be maintained.

4.5.6. *Use FSS to train on other plants.* A FSS gives the possibility for individuals to attain hands-on experience of processes that they will not directly work on themselves. Experienced or highly professional operators would welcome the opportunity of trying out another type of process or operator system from the one they are familiar with. The novice operator will appreciate the context of his intended process better if he has been introduced to a few different ones.

On sites with clusters of plants, operators can be made familiar with the operation of their neighbouring plants. In the fertiliser complex context, for example, the ammonia plant operators would gain by trying out the urea or ammonium nitrate process and vice versa. The same applies to interacting offshore oil platforms, Gullfaks A and Gullfaks B, for example (NorControl 1989 a).

4.5.7. *Use FSS to train on markedly different plant states.* Apart from training on FSS of other plants, exercises should be available on FSS of the same plant with a characteristic markedly different, but attainable, from the then status of the real plant. These exercises will be available on different snapshots of the same FSS and will not require new installations. It is of course important not to confuse the new operators by giving them too many variations and to plan such sessions with care, with the trainee fully aware that he is referring to a different mode. Such exercises will introduce the trainee to a broader operation band of the plant than might be present on the plant at that time.

The trainee can be given different cases in rapid progression to make him appreciate the differences between them. As examples, consider cases with

(*a*) selected catalysts near to end of life.
(*b*) fresh catalysts.
(*c*) plant near to shutdown for scheduled maintenance.
(*d*) plant fresh after scheduled maintenance.
(*e*) plant running with a single synthesis train.
(*f*) plant running with multiple synthesis trains.
(*g*) plant running towards the lower end of permitted inventory range.
(*h*) plant running towards the upper end of permitted inventory range.
(*i*) plant running at normal ambient conditions.
(*j*) plant running at severe ambient conditions.

Various combinations of the above cases may also be tried. For example, fresh catalyst may be combined with plant running at the upper end of permitted inventory range to initiate a challenging operations task.

4.5.8. *Desired chemical engineering attributes from process operators.* The question of what makes a good operator is very complex and will require considerations from other disciplines, particularly human psychology. From a chemical engineering point of view, the following are some suggested attributes to aim for. He should:

(*a*) have good familiarization with the process (the static flowsheet and the dynamic behaviour).
(*b*) develop a good understanding of the principles behind the process.
(*c*) appreciate the relative importance of the different parts of the process and hence be able to estimate the degree of production loss caused due to malfunction or removal from service of given equipment or section of plant.
(*d*) should be able to assess the state or 'health' of the plant by observing a few selected indicators quickly without going through the masses of information on display.
(*e*) be familiar with functions of individual unit operations.
(*f*) appreciate the desired product specification and constraints.
(*g*) appreciate the constraints and operating limits within which the system needs to operate.
(*h*) be able to diagnose malfunctions and faults quickly.
(*i*) be familiar with startup and shutdown procedures.
(*j*) be familiar with emergency procedures.
(*k*) be able to cope with masses of information during crisis and select the correct items to concentrate upon.
(*l*) have developed judgement on the reliability of data during instrumentation failures, a time when operator actions are of critical importance.

5. Simulator designers' viewpoint

The simulator designer is rarely a single person, more likely a multidisciplinary team who put together the simulator from information provided by the customer, dedicated simulation tools, standard hardware and software tools and specialized hardware for CCR displays, panels and furnishings. The designer will naturally be most aware of the comprehensive features contained in the FSS. Discussion points arise on how to effectively use the FSS from this point of view:

5.1. *Make good MMI design for instructor station*

The effectiveness of the instructor depends on his ease of interfacing with the simulator. The keyboard is the main medium for instructors inputs and is complex because it will require both operator function keys and instructor function keys. There should be a clear distinction between the instructor keys and operator keys if they are combined on the same keyboard. Individual keys should be present for obtaining snapshot directory, malfunctions list and FODs menu. Preferably, a detailed description of each key's function should be available close to the instructor station. In case of more than one numbers pad on the same board it should be obvious which one is applicable for a given input from the instructor.

There are lessons to be learned from existing instructor stations on Gullfaks and Oseberg.

5.2. *Make full use of range of instructor functions*

Full use should be made of the range of functions designed into the instructor system. Some of the facilities are rarely used. For example, logs on student actions are possible but rarely kept. Use of logging can help towards the development of a scientific way of instructing. Moreover, the trainee can be informed exactly about his errors.

5.3. *View the knowledge contained in FSS*

There is large amount of process knowledge buried in the models which is invisible to the operator. Creating dynamical effects from the models does not bring into view all the process knowedge which they are based upon. For example, the exit temperature in a process stream leaving an air cooler will be displayed but the user will not see the particular heat transfer correlation valid at the time. Similarly, all the modeled logic is contained in the simulator, but the operator will only view the opening or closing of a valve or bringing in or removal from service of equipment. Methods are being developed (Thrane 1988) to index the knowledge and to provide easy access to it.

At the present time, computer literate instructors could benefit additionally from a FSS through their ability to navigate through the models' software and thereby view the knowledge contained.

5.4. *Make use of manufacturer's tools*

Other simulator designer tools will also become available to the sophisticated user. A tool for easily emulating operator systems and operator pictures, called Emula, has been developed by NCS in cooperation with IFE with partial funding from Statoil (NorControl 1988). Another facility being developed by NCS and IFE is the configuration engine (NorControl 1989), which will allow the user to create and store simulations on a colourgraphic terminal from library based standard modules, in an interactive manner, with windows of initial value and typical value sets available to aid the modeler.

The manufacturer's willingness to release his proprietary tools will depend upon the given relationship with the client.

5.5. *Improve FSS quality significantly through change proposals*

The quality of a FSS can be significantly enhanced by implementing relatively small change proposals. The correct identification and timely implementation of the changes can have a marked influence on the effectiveness of training. All FSS benefit from feedback from the user to the designer and the consequent adjustments, no matter how well FSS have initially been designed.

The management of change proposal implementation is therefore an important task requiring good judgement on the selection of the best desired alternatives.

5.6. *Use correct model fidelities*

Careful consideration should be given to the fidelity of the FSS as a whole and those of individual models. If there is a specific requirement for specialized training on a given unit, then it is required to provide the desired fidelity, which may be higher than the general simulator. The possibility of providing the same model to two different extents of rigour should also be borne in mind. In this way the real time CPU budget can be satisfied by using the lower fidelity version when none of the other models can be switched off from the execution queue, while the higher fidelity version remains available for specialized training. No extensive use of models with multiple fidelity versions appears to have been made so far.

5.7. *Choose correct degree of replication*

The degree of replication will be an aggregate function composed of the degrees of replication of various components in the FSS. The cost of making a FSS goes up exponentially as the degree of replication approaches 100%. It is therefore practical to design for a few points away from 100%, particularly if the FSS is for training alone. The responses from the simulator will remain almost indistinguishable from the real plant until the degree of replication is well below 100%.

6. Simulator users viewpoint

The primary users of FSS in training sessions will be the instructor and the trainee operators. Irrespective of how well the simulator is designed or integrated with chemical engineering concepts, the effective use will depend heavily on the way these personnel perform.

6.1. *Proficiency of instructor*

The instructor is the leader of the training session and apart from personal qualities, some particular requirements are made of him.

(*a*) He should be an expert operator, if possible, on the actual plant. He should remember the locations of control loops, safety logic loops, key manual, control, ESD and relief valves etc. apart from insight into the main process units. He should have all the attributes of the ideal operator himself that have been mentioned in section 4.5 above.

(*b*) He should be proficient in reading and explaining engineering documents, particularly process flow diagrams, piping and instrument diagrams, safety cause and effect charts, sequence flowcharts and logic diagrams.

It is important to supplement exercises on the simulator with explanations given by the instructor from various documents. The instructor will not be so effective if he himself cannot fully comprehend the documents.

(*c*) He should be fully conversant with the functionality of the instructor system, including malfunctions system, alarm handling system, student monitoring functions, field operated devices and snapshot handling.

(*d*) He should, it is highly recommended, have an insight into the process models system and be able to make simple modifications, such as to parameter values in the database, turn individual models on or off, or use alternative physical property data. He should be aware of the simulation method used and know the sequence and the relative frequency of individual models execution. He should be familiar with real time concepts and have a proper understanding of the integration time step. He should be aware of the scope of different process models.

Figure 6 shows 3 different model execution mechanisms. Figure 6a is a sequential scheme where all models of the same type are executed together, for example all the PID controllers are evaluated in a single model, one after another, before another type of instrument is handled. The strategy was used in both Gullfaks and Oseberg simulators. Figure 6b also represents a sequential scheme but the different types of models are repeatedly interspersed, so a given set of transmitter, PID controller and control valve may be evaluated one after another before other sets or models are handled. This scheme has been

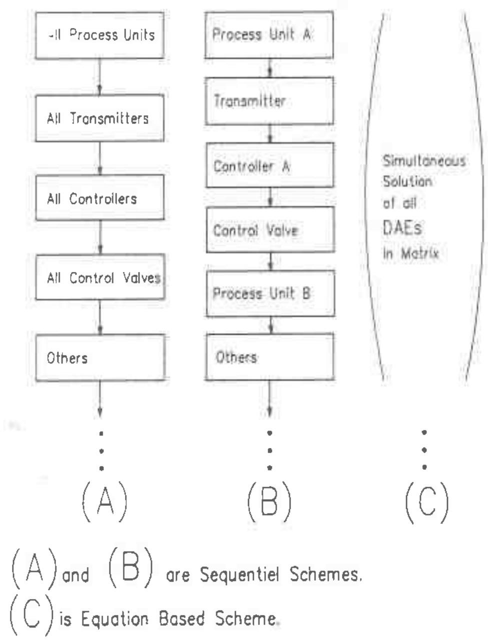

Figure 6. Various model execution strategies for full scale simulators of chemical processes.

primarily used in the Veslefrikk simulator except that the piping network model has been implemented using simultaneous computation (Endrestøl *et al.* 1989). Figure 6 c shows a matrix which should contain all the equations for the simulated system. The simultaneous solution of all the equations gives an equation based simulator, such as SPEEDUP (Perkins and Sargent 1982).

The instructor should be well aware of the scheme of execution for this FSS and should know the implications of altering sequences or removing or inserting models to the list.

Knowledge of the modeling system will give certain additional powers to the instructor. It will be necessary to have some control on this so as to avoid corruption of the models or the configured system. It is appropriate to link the permission to alter system to the instructor's understanding and abilities. There is a strong case for the instructor to be at least moderately familiar with the modeling system terminology.

6.2. *The effective use of malfunctions*

The demands on the operator are greatest when an instrument or equipment fails. The effective use of FSS very much depends upon the effective introduction and removal of malfunctions. Good malfunction application and handling on the FSS will require a skilled instructor with premeditated strategy. The aim should be to expose the student to a wide variety of realistic malfunctions at the right time.

A malfunction is an undesired state in one or more of the subsystems. Also the individual sybsystems could be running correctly but their given combination could be undesirable. Malfunctions can build up gradually or they can occur suddenly or even catastrophically. Some malfunctions will lead to total failure while others will only cause partial loss. Reduced thermal or other efficiencies may also be looked upon as undesirable states. Some malfunctions, such as electricity failure, have an instantaneous global effect, while the effect of others will slowly percolate through the process.

In real life, it is usually a combination of more than one unlikely malfunction or operator error which results in a catastrophe of scale such as Piper Alpha, Bhopal or Chernobyl. A FSS provides an excellent opportunity to experiment with combinations of malfunctions which could cause serious accidents and to train to deal with these situations quickly. However, careful planning will be required to select the cases and analysis will be required on what should happen as a consequence of the applied malfunctions.

It is important to close the safety loop on the FSS so there is feedback from the process to applied malfunctions. It will be of little training value to create a FGS alarm on the FSS if it is not registered by safety logic which automatically initiates fire fighting devices and orderly shut down of the plant.

6.3. *Use instructors early in simulator projects*

The instructors should be employed in the early part of the simulator project to liaise with the manufacturer, provide expert guidance on the process and ensure correct information is released to the manufacturer as soon as it is available. This activity also benefits the instructor by familiarising him with the plant documents at an early time. Statoil have made good use of instructors in this way for the Gullfaks and Veslefrikk projects.

6.4. *Make instructors visit plant frequently*

Once the plant is operating, it is recommended that the instructors should make frequent visits to it, to be aware of the changing plant environment and new problems as they arise.

6.5. *Allow trainees to work alone on FSS*

Although a FSS is designed for instructor-trainee sessions, gains can be made by trainees spending time alone on the simulator. A simulator cannot easily be damaged by inexperienced users, providing they follow simple instructions and common sense rules. If a given run is spoiled for some reason, the simulator can always be given a warm restart. In solitary sessions, the trainee can familiarise himself with the plant through the simulator and carry out simple operations. Trainees should be encouraged to use the simulator in this way after the termination of normal classes.

There may be benefits in attempts by one trainee to run the whole plant on his own, where normally a few operators would be used in reality, as long as it is understood to be just an exercise. Such exercises will enable the operator to gain an overview of the whole process, which he may not obtain in his normal job.

6.6. *Allow groups of trainees to run FSS*

Considerations should also be given to allowing groups of a few trainees to carry out exercises on the simulator without the instructor. One of the trainees may for example act as the supervisor and also be in charge of the instructor's terminal. This way the students would devise their own problems. While this will be no substitute for the sessions with the instructor, it will help in the problem formulation, self organisation and cognitive skills of the trainees. As far as the author is aware, such uses of FSS have not normally been considered.

6.7. *Make documentation on FSS specifically for trainees*

FSS come with a comprehensive set of documents for the instructor but relatively little is normally written for the trainee. Trainees should be presented with a standard package giving an easy to follow description of the simulator, simple user instructions and timetables and planned schedules for sessions. A booking system should be used where authorized individuals may reserve the simulator for their own use. This will also be important in relation to changes to the simulator that were implemented by modeling or system experts in between live training sessions. The important point is that everyone should know about the availability of the simulator in a simple and nonconfusing manner. It will save time.

6.8. *Leave some snapshots free for current users*

It is recommended that free snapshots should be available for each trainee. This way the student may keep returning to the simulator and tuning, upgrading or playing with his own snapshot.

7. *Future*

The future methodology of use of FSS depends on the way the architecture of FSS develops and how they are integrated with process engineering in general and other artficial intelligence and expert system based tools being developed currently. It would be natural to carry out trials of some of the other computer based products on FSS before applying to the real plant, similar to the way that MMI studies can be carried out on FSS today.

Following this and further discussion, it should be possible to greatly increase the effectiveness of use of FSS so that operator training becomes firmly established along scientific lines and the operator role is fully recognised as central to the chemical engineering profession.

The integration of various process engineering functions will mean that several of the other tools are amalgamated into the FSS. It may happen that the training use for FSS will have to compete with other uses which would be followed up more vigorously. In that event, it will become more important to make longer use of the FSS each day and to have an effective booking system.

8. *Conclusions*

(*a*) FSS are a valuable addition to the repertory of chemical engineering tools. Chemical engineers should look at them as such and make full use of the opportunities they present.

(*b*) The chemical engineering discipline places growing importance on the role of plant operator. It should be possible to train and refresh the operators to the high standards demanded by effective use of FSS.

(*c*) There is a need for vigorous discussion on alternate strategies on the best way to use FSS for training. Some ideas and discussion have been presented in this paper from the points of view of the chemical engineer, the simulator designer and the simulator user. Further ideas from these and other disciplines are required to be reported.

(*d*) The human element will remain as important in the effective use of the FSS as it is in the effective running of the real plant. There are high demands on the expertise and proficiency of the instructor. It is thought that the effectiveness of use of FSS can be greatly increased by using instructors who can make some adjustments to the process models systems and variables database.

(*e*) Cheaper prices will mean more widespread use of FSS in the future process plants. The precise course of events will depend on how FSS relate to the new technologies of integrated process engineering.

9. *List of symbols and abbreviations*

CAD	computer aided design.
CCR	central control room (of a process plant).
CSS	compressor supervisory system.
ESD	emergency shutdown system.
FOD	field operated device.
FGS	fire and gas system.
FSS	full scale simulator (of a process plant).
IFE	Institute for Energy Technology, Halden and Kjeller, Norway.
MMI	man–machine interface.
NCS	NorControl Simulation A/S, Horten, Norway.
PID	Proportional Integral Derivative (Controller)
T	temperature.
x	distance.
t	time.
DH	thermal diffusivity.
Re	Reynold's Number.
Pr	Prandtl's Number.
Nu	Nusselt's Number.

References

Chemical Engineering (1989). *Accelerating interest in dynamic simulation*, Newsfront article, Feb. 1989, 30–33.

Clare, R. and Malik, T. I. (1986). *Aspects of simulating process control systems of an offshore oil platform*, Proc. 2nd Europ. Sim. Cong. Antwerp, September 1986.

Coulson, J. M. and Richardson, J. F. (1970). *Chemical Engineering*, Vols 1, 2, 3 (Pergamon Press, London), reprinted 2nd edition.

Demena, H. F., Litwiller, J. A., Simpson, M. P. and Unruh, W. (1984). Nitrogen complex: ammonia plant operator training simulator, *Chemical Engineering Progress Technical Manual*, Vol. 24.

Egol, L. (1989). Simulation and process control, *Chemical Engineering*, Feb., 161–163.

Endrestøl, G., Sira, T., Østenstad, M., Malik, T., Meeg, M. and Thrane, J. (1989). Simultaneous Computation Within a Sequential Process Simulation Tool. SIMS 89, Conference on Simulation & Scientific Computation, 1989, Bergen, Norway. *Modeling, Identification and Control*, **10**, 203–211.

Gran, E., Malik, T. and Næss, L. (1988). *Process systems engineering opportunities presented through real time, full scale simulation of plants*, PSE 88 conference, September, Sydney.

NorControl Simulation Document (1984). *Detailed functional specification, Gullfaks A Simulator Project*, Horten, Norway.

NorControl Simulation Document (1986). *Detailed functional specification, Oseberg Simulator Project*, Horten, Norway.

NorControl Simulation Document (1987). *Unit Development Folder, CSS Logic System*, Oseberg Training Simulator Project, Horten, Norway.

NorControl Simulation Document (1988 a). *Detailed functional specification*, Veslefrikk Training Simulator Project, July, Horten, Norway.

NorControl Simulation Document (1988 b). *Undersøkelse av operatør stasjoner i kontrollrom, emulerings stasjoner og program verktøy for emulerings prosjektet*, Dok. no. s-0309-1.

NorControl Simulation Document (1989 a). *Unit Development Folder, Logic and Control System*, Water Injection System Extension, April, Horten, Norway.

NorControl Simulation Document (1989 b). *Configuration Engine Design Specification*, Ref. No. PDP/NCS-056, NCS/SAST Prosim Development Project, March.

Perkins, J. D. and Sargent, R. W. H. (1982). SPEEDUP—A computer program for steady state and dynamic simulation and design of chemical processes, *A.I.Ch.E. Symp. Series*, **78**

Perry, R. H. and Chilton, C. H. (1973). *Chemical Engineers Handbook*, 5th edition (McGraw-Hill Kogakusha Ltd, Tokyo).

Silver, R. E. and Zumwalt, R. W. (1983). *Interactive dynamic simulation package promotes efficiency in simulation development and use*, Summer Computer Simulation Conference, Vancouver, Canada, July 1983.

Stephanopoulos, G. (1987 b). *Expert systems and computing environments for process systems engineering*, L.I.S.P.E. meeting, MIT, June.

Stephanopoulos, G. (1987 c). *Computer aided chemical process control*, L.I.S.P.E. meeting, MIT, June.

Stephanopoulos, G. *et al.* (1987 a). *An artificial intelligence perspective of process engineering*, L.I.P.S.E. meeting, MIT, June.

Stephanopoulos, G., Johnston, J., Kriticos, T., Lakshmannen, M., Mavrovouniotis, M. and Siletti, C. (1987 d). Design-kit: An object orientated environment for process engineering, *Comput. chem. Engng*, **11**, 655–674.

Strand, A. (1988). *Statoil og Simulatorbruk*, Simsem 88, 6-7 October, 1988, Soria Moria Hotel, Norway.

Thrane, J. E. (1988). *Modelling Engine Detailed Design and Implementation*, Ref. No. PDP/NCS-UWD2.5, Nor Control Simulation Document, June 1988.