Process: Program for Research on Operator Control in an Experimental Simulated Setting

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Abstract **—An experimental tool for the investigation of human control behavior of slow responding dynamic systems is described. Process (program for research on operator control in an experimental simulated setting) is a simulation of a dynamic water–alcohol distillation system that is especially useful in research on operator training. In particular, Process is developed to conduct research on fault management skills.**

INTRODUCTION

Since Crossman and Cooke [6] examined the behavior of operators who were asked to heat up a beaker containing water to a chosen set-point, and to keep the temperature steady, an increasing number of researchers have addressed or are currently tackling the problem of optimizing human control behavior of slow responding dynamic systems (e.g., [13], [15]–[20], [22], [25], [26]).

Over the past two decades, there was a shift in interest from human control behavior of manually controlled systems to automatically controlled systems. Nowadays, operators primarily monitor the behavior of automated systems and they are only actively involved with the system in cases of suboptimal production levels or system failures. Consequently, there is an increasing interest in one particular aspect of the operator's job, namely *fault management* (e.g., [22], [27]). Fault management is generally conceived of as coping with system failures and is thought to incorporate at least the phases detection, diagnosis, and compensation. Operators have to notice that the system is not acting in conformity with expectations, or they have to perceive an alarm signal (acoustic and/or visual) that is pointing at an undesired state of the system (detection). After detection, the cause of the undesired state has to be found (diagnosis). Finally, compensatory or corrective actions have to be taken to stabilize the system as fast as possible (compensation); usually, this means that the operators have to dispatch a repair crew to repair the system malfunction and, if possible, that they have to stabilize the system manually. Rasmussen and Lind [21] discern two lines of research directed to an improvement of fault management skills: 1) research on operator training, and 2) research on interface design. The present article is addressed to operator training in the first place; indirectly, some attention is paid to interface design.

The tendency to automate the direct control of production processes highly confines the possibilities for on-the-job training in normal operation. Process operators have little opportunity to practice fault management skills, because undesirable or potentially hazardous situations occur only occasionally in automated plants. The use of simulations of the system is often thought to be a solution for this training problem. Aircraft simulators are perhaps the best-known example, but simulators also exist for air traffic control, ship-navigation, supertanker steam propulsion plants, tanks, submarines, nuclear power stations, and petrochemical plants [4]. In addition, the use of simulations offers the advantage of high experimental control. But, although many sophisticated simulators exist, they are seldomly used in scientific research on operator training. Morris *et al.* [18] put forth some possible reasons for not using these so-called high-fidelity simulators in research. For instance, they mention the high costs involved in the exploitation of the simulators, the long training period required if the simulated system is complex, and the problem that in general the simulators can only be used for the training of actual operators of a plant that makes the potential subject-pool limited. Furthermore, if actual operators are used, then the experimenter may have inadequate control over the subjects' prior task-related knowledge because the number of available subjects is low.

To overcome these problems, less complex low-fidelity simulators have been developed to conduct research. Well-known examples are TASK [23], FAULT [24], and PLANT [18]. TASK and FAULT are representative for trouble-shooting tasks. Subjects have to find as quickly as possible a faulty element in a randomly generated network structure. The tasks are used to train some basic diagnostic skills that form an essential part of fault management. PLANT is a computer-based dynamic control task representing a generic production process. Subjects have to supervise the flow of fluid through a series of tanks interconnected by valves. The subjects' goal is to maximize the production of an unspecified product in the face of introduced system failures, for instance valve malfunctions. PLANT is used to train all three aspects of fault management (detection, diagnosis, and compensation). Although it should be noted that the reduction of fidelity may reduce the validity of results, studies using TASK, FAULT, and PLANT have provided interesting insights in human control behavior that eventually can be successfully applied to operator training. For instance, available research evidence suggests that the emphasis on theoretical aspects of system functioning in traditional operator training is disproportionate to the actual value of such knowledge. Instead, it is suggested that the content of instruction should be more directly related to what the operator may be required to do in interaction with the system. That is, the training program should be directed to develop a set of fault management procedures that enable adequate control of the system (e.g., [15], [17], [18]).

To make the generalizability of these results plausible, Morris *et al.* [18] suggest to interpret the concept of fidelity for low-fidelity tasks like TASK, FAULT, and PLANT in terms of *psychological fidelity* and not in terms of *physical fidelity*. Whereas physical fidelity pertains to the physical resemblance to an actual system, psychological fidelity refers to problem solving opportunities similar to those experienced in actually controlling the system. Nevertheless, they suppose that the use of low-fidelity tasks is probably most appropriate as a "front end" or "filter" for studies with higher face validity.

To conduct studies with higher face validity, it is necessary to use simulators with both a high psychological fidelity and a high physical fidelity. To meet these requirements, Process (program for research on operator control in an experimental simulated setting) was developed. Process is a dynamic simulation of a water–alcohol distillation system; Process's interface is based on a real-world process control environment.[1] A simulation of a distillation system was chosen because in process industry, distillation is a widely used technique to separate the components of a liquid mixture by making use of the differences in boiling point. In addition, the degree of automation of Process is in conformity with the degree of automation of modern plants. Hence, the results of studies using Process can be more easily generalized. In this respect, Process is an experimental tool that extends the possibilities for research on human control behavior of slow responding dynamic systems.

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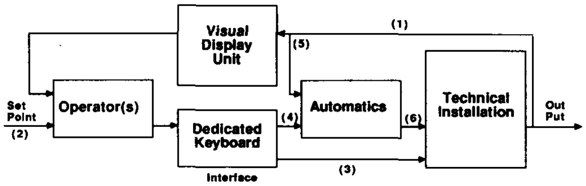


Fig. 1. General model of control tasks.

Starting from a general model of control tasks, Process is described in detail. First, Process is described from the operator's view; second, Process is described from the experimenter's view, which in fact reflects a description of the software package of the simulation program; finally, the experimental configuration is sketched and a brief review of ongoing research using Process is presented.

General Model of Control Tasks

In general, the operator's task is to supervise and maintain the current state of a more or less automated system or to change the system's state into a new desired direction, whether with or without intervention of automatics. The general structure of control tasks is outlined in Fig. 1.

In modern plants, output from the technical installation is usually presented to the operator on a visual display unit [1]. With the information presented, the operator compares the current state of the system with its desired state [2]. If the deviation is unacceptable, the operator will intervene in the technical installation usually by means of a dedicated keyboard. His control actions may change the system's state directly [3], that is, the system is manually controlled, or indirectly [4], that is, the system is automatically controlled. The part of the system's control that goes without intervention of the operator depends upon the degree of automation of the system [1], [5], and [6].

Process from the Operator's View

Process fits to the presented general model of control tasks. Under normal conditions, Process is stable and, if well adjusted, it produces a liquid mixture of approximately 85% alcohol out of a liquid mixture of approximately 40% alcohol. As shown in Fig. 2, the operator uses a visual display unit and a dedicated keyboard that are both built into a console-table to optimize the production process and to detect, diagnose, and compensate system failures.

The Visual Display Unit

The operator can select one out of three screen displays in order to retrieve particular information on the state of the production process. In order, these displays are the *overview*, the *controller information display*, and the *repair list*.

Overview: The overview (Fig. 3) displays a schematic representation of the distillation system. The distillation process is carried out continuously. That is, feed is introduced continuously into the distillation column. Before entering the column, the feed is preheated up to its initial boiling point by means of a closed steam pipe. The feed is introduced into the column at a place where the composition of the vapor/liquid mixture is about the same as that of the feed. The reboiler section underneath the column is provided with a heating system for the vaporization of the liquid mixture in the column. A condensor cools the vapors and the resulting condensate is caught in a reflux tank. The levels of liquid mixture in the distillation column and in the reflux tank are represented dynamically. Part of the condensate is drawn off as distillate, the remainder being returned to the column as reflux. The higher-boiling components in the feed are removed as a residue stream.

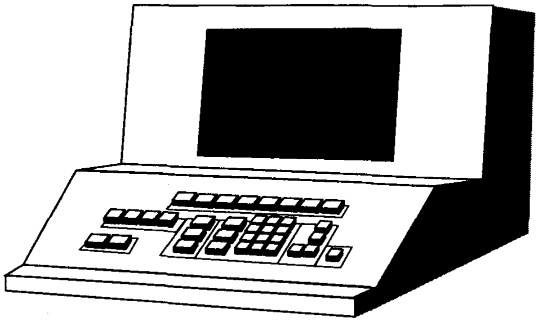


Fig. 2. Console-table.

Process is automatically controlled by six proportional integrative differential (PID) controllers: three flow controllers (FC), two level controllers (LC), and one temperature controller (TC). In the available displays, the controllers are represented by a blue rectangular frame. Inside these frames, the controller type (FC, LC, TC), the controller mode (AUTOmatic/MANual), the set-point (SP), the actual process value (PV), and the actual valve position (VP) are displayed, the latter two being refreshed every 6 s. The controllers have the following functions:

- FC1 controls the feed supply to the column
- TC2 controls the entrance temperature of feed in the column
- FC3 controls the residue flow
- FC4 controls the reflux flow
- LC5 controls the level of condensate in the reflux tank
- LC6 controls the level of liquid mixture in the column.

If the alarm system functions well, system malfunctions are indicated by means of an acoustic alarm signal. An additional visual alarm signal (a red flickering frame and a red flickering representation of the process value) shows in which controller the process value exceeds the alarm limits. If the alarm system itself fails, the operator may recognize that the system functions suboptimally by perceiving an unusual large difference between process value and set-point. Finally, at the lower middle part of the screen, the available function keys and a message area for system messages are displayed. Furthermore, in case reparations are done to controllers, it is indicated which controllers are under repair.

Controller Information Display: After detecting a possible system malfunction, the operator needs detailed information on the behavior of the controller in which the out-of-bounds condition occurred, in order to diagnose the cause of the malfunction. This information is provided in the controller information display of the controller in question (Fig. 4). Two trend graphs display information on the behavior of the controller. The upper graph displays the alarm limits, the set-point, the process value over the past 15 min, and the actual process value, represented by the "$<$" symbol. The actual process value and the graph are refreshed after a variable amount of seconds that is to be defined by the experimenter. If the trend graph scrolls, a new point is added to the graph and the old points shift to the left. In the same way, information on the valve position (expressed in percentages) is displayed in the lower graph.

In addition, the actual behavior of all controllers is displayed at the right part of the screen. So, at all times, operators can inspect the behavior of the rest of the controllers. The controller under study is indicated by means of a white arrow. Furthermore, the controller information display indicates which con-

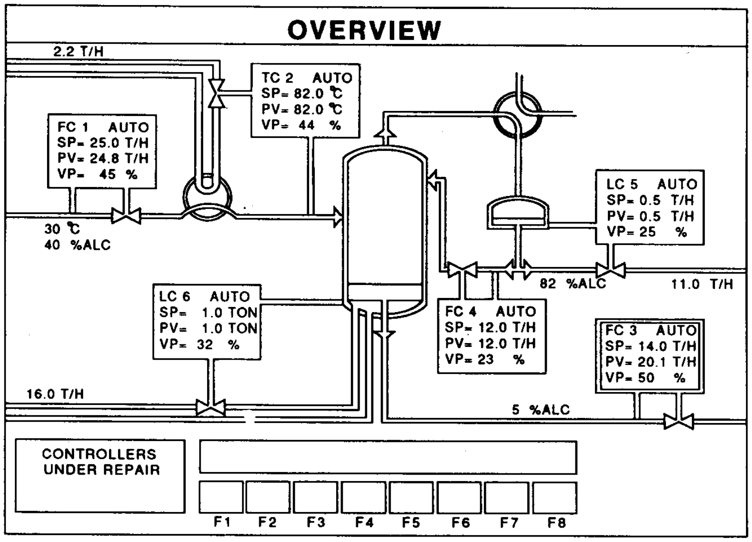


Fig. 3. Overview.

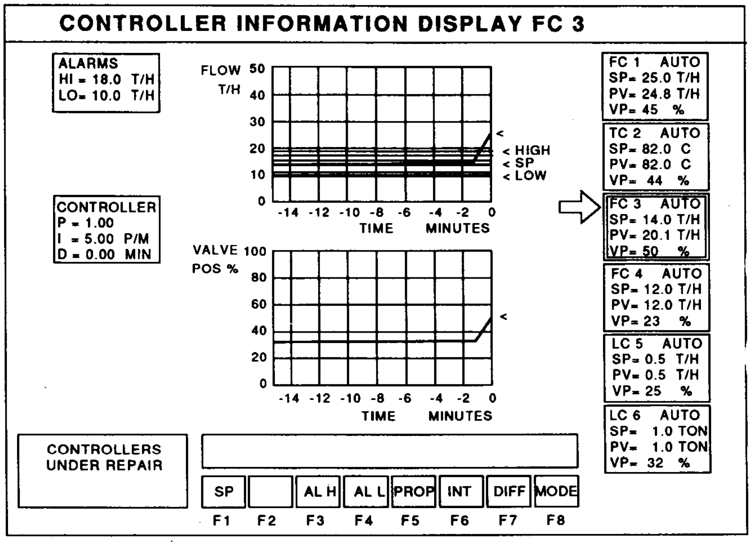


Fig. 4. Controller information display.

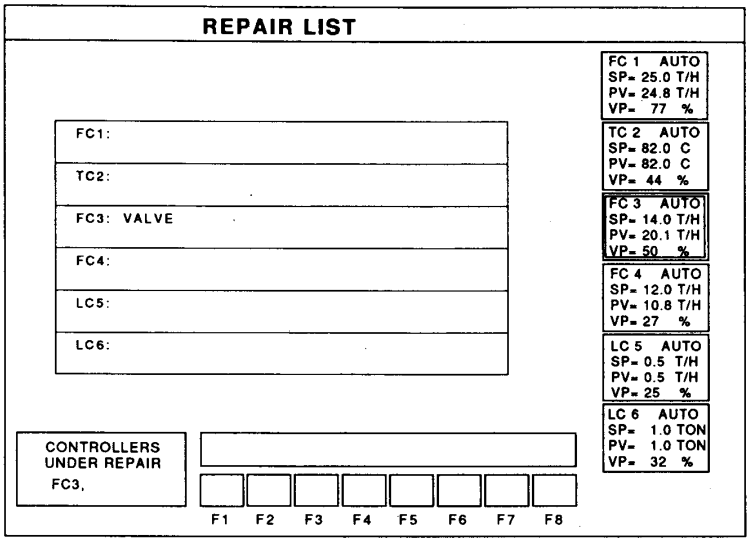
trollers are under repair, it displays numerically the PID adjustment and the alarm limits, and it displays the real time. Finally, as in the overview, the available function keys and the message area are displayed.

Repair List: To minimize the consequences of a system malfunction, the operator must report the malfunction as quickly as possible so that the malfunction can be repaired. Whenever a reparation is carried out, the operator can select the repair list (Fig. 5). The repair list provides information on the type of malfunction that is being repaired in a particular controller; for instance, Fig. 5 shows that the valve of controller FC3 is currently under repair. In addition, the repair list displays the actual behavior of the controllers, the available function keys, and the message area.

The Dedicated Keyboard

The dedicated keyboard comprises 37 keys that are used to carry out particular control actions. The keys are divided among six different function groups (Table I). Some control actions, for instance the selection of screen displays, can be carried out in a fast way or in a more roundabout way; in the former way, system messages are used less frequently than in the latter way.

The *multifunction keys group* is used for various functions, such as changing set-points, changing valve positions, or changing controller modes from automatic to manual. The *associated display group* is used for a "fast-switch" between various screen displays; this group is also used to dispatch a fictitious repair crew to repair system malfunctions. The *display select group* is used to select a particular screen display. Selection of screen displays is supported with relatively many system messages. The *data entry group* is used to enter numeric values for PID adjustments, valve positions, set-points, or alarm limits. In addition, this group is used to select the diagnosed system malfunction from a list of possible system failures, such as valve malfunctions and leakages. The *change message area group* is used to cancel commands. This group is also used to temporarily freeze the distillation process, in order to create an opportunity to freely



FC 1 AUTO
SP= 25.0 T/H
PV= 24.8 T/H
VP= 77 %

TC 2 AUTO
SP= 82.0 C
PV= 82.0 C
VP= 44 %

FC 3 AUTO
SP= 14.0 T/H
PV= 20.1 T/H
VP= 50 %

FC 4 AUTO
SP= 12.0 T/H
PV= 10.8 T/H
VP= 27 %

LC 5 AUTO
SP= 0.5 T/H
PV= 0.5 T/H
VP= 25 %

LC 6 AUTO
SP= 1.0 TON
PV= 1.0 TON
VP= 32 %

Fig. 5. Repair list.

TABLE I
FUNCTION GROUPS AND NUMBER OF KEYS PER FUNCTION GROUP OF THE DEDICATED KEYBOARD

Function Groups	Number of Keys
1) Multifunction Group	8
2) Associated Display Group	4
3) Display Select Group	3
4) Data Entry Group	18
5) Change Message Area Group	2
6) Acknowledge Group	2

counsel a help system. Finally, the *acknowledge group* is used to control the alarm system, for instance to stop the acoustic alarm in case of a system malfunction.

PROCESS FROM THE EXPERIMENTER'S VIEW

The experimenter determines the way in which Process is presented to the subjects. For instance, the degree of automation of process is under the experimenter's control, which makes it possible to use Process both as a manually controlled system or as an automatically controlled system. In fact, two input files are available to define a particular run of Process. In the *Process initialization file*, the initialization values of the parameters of the mathematical model of Process are specified. In the *Process control file*, a particular case, to be solved by the subjects is defined. The input files can be defined easily by the experimenter. Control performance of subjects participating in an experiment is expressed in a number of dependent variables that are registered in the *Process result file*; the obtained data can be used for later analyses.

Process Initialization File

In the Process initialization file, the following six categories of parameters are specified (see also the Appendix):

1) System input parameters for the equations governing the behavior of each of the six PID controllers.
2) Tables specific for the distillation process of a water–alcohol liquid mixture.
3) System input parameters for the equations governing the situation in the lower, middle, and upper part of the distillation column.
4) System input parameters for the equations governing the situation in the reflux tank.
5) System input parameters for the equations governing variations in the input of the water–alcohol mixture into the distillation system and the variations in steam pressure for the preheating section and the reboiling section underneath the column.
6) General parameters for specifying for instance the time between two display refreshments and the time between two trend graph refreshments in the various controller information displays.

Process Control File

In the Process control file, a number of parameters is specified to define a case, for instance a particular malfunction that is to be detected, diagnosed, and compensated by the subjects. By creating a command file in which a series of cases is defined, the experimenter can compose a complete training session consisting of a number of cases that are subsequently presented to the subjects. In this way, the experimenter can create different practice schedules and investigate their effects on control performance. In the process control file, the following two categories of parameters can be specified:

1) *Subject identification*. A number of parameters can be specified to identify subjects participating in an experiment. These parameters comprise the subject's number, the training condition, the part of the training that is carried out, a particular system malfunction to be solved, and the controller in which the system malfunction will occur. Further, if necessary, the experimenter can add additional information that is relevant to the experiment to be conducted.
2) *Process specification*. In this category the following parameters can be specified:
   a) Process already running or process starting-up from zero.
   b) The available time to solve a particular case. The time is either variable, that is, solving a case is subject-paced or the time is fixed, that is, a subject is given limited time to solve a case. It is also possible to specify a variable time under the condition that a certain maximum has not been reached. If this option is chosen a subject is presented a next case as soon as the current

case has been solved. If a subject is unable to solve the case within the maximum time specified, which implies that Process has not been stabilized, the next case is automatically presented. Then, in the Process result file, it is registered that Process has not been stabilized.

c) Controller mode. Each of the six controllers can be initially set to manual or to automatic.
d) Alarm limits. Within a particular range, the alarm limits can be specified for each of the six controllers.
e) Function availability. For each of the six controllers the following functions can be blocked or unblocked:
    - change PID adjustment
    - change controller mode
    - change alarm limits
    - change set-point
    - change valve positions.
f) Acknowledged alarms. A case can be defined with or without an alarm situation that has been acknowledged already. This situation might occur with a shift of operators controlling Process.
g) Start time of system malfunctions. For each of the six controllers, the start time of a particular system malfunction can be specified in seconds. There are seven kinds of system malfunctions possible within the Process environment:
    - PID controller malfunction. If a PID controller malfunctions, the valve is no longer automatically controlled. Then, in the automatic mode, the valve stops in a particular position (see option j). As a consequence, an out-of-bounds situation will occur. In the manual mode, Process can be manually controlled under the condition that the valve itself is not defect.
    - Incorrect PID adjustment. If the PID adjustment is incorrect, discrepancies in actual process value and set-point are not correctly compensated. As a consequence, amplitudes of fluctuations in process value will increase and eventually oscillations will occur that cause repeatedly out-of-bounds situations. Again, if the valve functions well, Process can be manually controlled.
    - Valve malfunction. If a valve malfunctions, it gets stuck in a particular position and, as a consequence, an alarm situation will occur (see option j). The valve position cannot be changed during reparation, neither manually nor automatically.
    - Leakage. In case a leakage occurs, fluid flows out of the normally closed distillation system. That is, the sum of the amount of distillate and the amount of residue is less than the amount of feed. Naturally, the PID controllers will try to avoid an out-of-bounds situation by closing or opening a valve. However, because a leakage cannot be compensated, the valve will eventually reach its minimum (0%) or maximum (100%) position.
    - Alarm failure. In case the alarm system fails, no acoustic signal (horn) is sounded and no red flickering indication in one of the controllers is displayed when an out-of-bounds situation occurs. Naturally, an alarm failure can only be detected in combination with another malfunction.
    - False alarm. In case of a false alarm, an acoustic horn signal is sounded and a red flickering indication in one of the controllers is displayed, although the process value does not exceed the alarm limits.
    - Tank rupture. A tank rupture cannot be introduced by the experimenter but may occur in consequence of inadequate control of Process. For instance, under certain circumstances the distillation column may boil dry or the column or the reflux tank may overflow. In any case Process is automatically shut down.
h) Controllers under repair. A case can be defined with or without controllers that are currently under repair. As with acknowledged alarms, this situation might occur with a shift of operators controlling Process.
i) Duration of reparation. Except for a tank rupture that cannot be repaired within a particular run of Process, the duration of reparation for each of the remaining six possible system malfunctions can be specified in seconds.
j) Specification of valve positions. In order to ensure an out-of-bounds situation, the experimenter has to specify which position the valve should take if the controller mode is initially set to manual (recall option c), or/and if a valve malfunction is specified (recall option g), or/and if a PID controller malfunction is specified (recall option g). If, for the aforementioned cases, a particular valve position is not specified in advance, an out-of-bounds situation might never occur. This is possible if the valve accidently stops in a position that does not seriously disturb the production process.

Process Result File

In the Process result file, a subject's control performance is registered. The Process result file is composed of the following three parts:

1) Subject identification. The parameters specified under the heading subject identification of the Process control file are registered in the Process result file. In addition, the number of times a particular system malfunction occurred is registered.
2) Subject-system interactions. The starting time of all system actions and all subject actions and the time differences between them are registered. Furthermore, all system actions and all subject actions are briefly defined so that a complete record of a subject's performance is available. In addition to that, all individual key presses are recorded in a so-called keydump file. This keydump file serves as input for the *Process Demonstration File*. The Process Demonstration file may be used to replay a subject's control behavior. In training, the Process demonstration file could be easily used to give a subject instructional feedback.
3) Summary of results. In the summary of results a number of dependent variables, that represent a subject's control efficiency, is kept. In order, the following data are registered:
    a) Whether a subject did or did not succeed to stabilize Process after occurrence of a system malfunction.
    b) The time it took to detect, diagnose, and compensate a system malfunction.
    c) The number of keys pressed.
    d) The number of wrong conclusions, that is, the number of times a subject made a faulty diagnosis and dispatched a repair crew to repair a nonexisting system malfunction.
    e) The number of times a subject has interrupted Process.
    f) The total time that Process was interrupted.
    g) The number of out-of-bound situations during a run of Process.
    h) The alarm integrals for all of the six PID controllers.

PROCESS' EXPERIMENTAL CONFIGURATION

Fig. 6 schematically presents the experimental configuration of the simulator Process.[2]

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[2] A PC-version of Process is available from Bijlstra & Van Merriënboer, Training Consultancy and Development, P.O.B. 217, 7500 AE Enschede, The Netherlands.

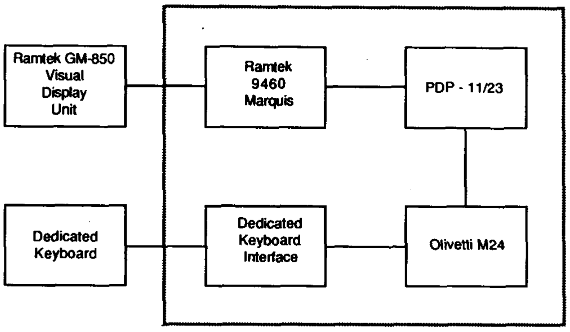

Fig. 6. Process' experimental configuration.

As described under the heading "Process from the operator's view," a visual display unit (Ramtek GM-850, 22-inch ultra-high resolution CRT) is used to display information on the state of the simulated system and control actions are carried out on a dedicated keyboard. The simulation program is in TURBO PASCAL and runs on an Olivetti M24 personal computer under MS-DOS. A RS-232 Interface connects the Olivetti to a dedicated keyboard interface.[3] If the simulation program is started, a communication program is sent to the Dedicated Keyboard Interface. With this communication program, key presses entered on the dedicated keyboard by the operator can be read and sent to the Olivetti. The Olivetti interprets those key presses. The Olivetti also interprets commands entered on the Olivetti keyboard by the experimenter (for instance, in case the experimenter wishes to introduce system failures on-line instead of by means of a command file). Finally, the Olivetti logs particular parameters that are used to create the process Result file later on. A second RS-232 Interface connects the Olivetti to a PDP-11/23 minicomputer. The PDP creates graphic displays for a Ramtek Graphic Display System (RM 9460 Marquis) and controls the output of this system to the visual display unit (Ramtek GM-850). A DEC LSI-11 Series Interface links the PDP to the general purpose interface of the Ramtek.

CURRENT RESEARCH USING PROCESS

As stated before, recent research on human control behavior of slow responding dynamic systems suggests that training programs should be directed to develop a set of fault management procedures that enable adequate control of the system (e.g., [15], [17], [18]). Based on recent developments in cognitive psychology that describe the human cognitive architecture in terms of declarative and procedural knowledge [1]–[3], [10]–[12], it is argued that after sufficient practice fault management procedures are cognitively represented as production rules. Production rules are condition-action pairs (IF–THEN statements) that form the basic elements of procedural knowledge. The production rules test for the presence of various conditions in the declarative knowledge (static representation of facts, concepts, etc, in the form of a propositional network), and either manipulate the declarative representation or produce behavior. Practice collapses individual production rules into larger production rules which considerably speeds up their application.

Kieras and Bovair [12] have shown that production rules can yield quantitative predictors of performance. Based on their information processing task analysis method, the individual steps, that build up particular fault management procedures, were determined. Starting from the six possible system malfunctions that can be introduced in Process, the *Process' Procedure Network* was constructed. The network is a production system format representation of all possible procedures and combinations of procedures that can be followed to detect, diagnose, and compensate particular system malfunctions. Naturally, there will be some overlap between two distinct fault management procedures, that is, they have particular individual procedural steps in common. One complete procedure is illustrated in Table II.

TABLE II
EXAMPLE OF FAULT MANAGEMENT PROCEDURE

IF	THEN
1) Alarm signal occurs	– Acknowledge acoustic alarm – Acknowledge visual alarm – Select CID[a] – Check trend information on PV[b]
2) PV exceeds alarm limits	– Check repair list
3) Controller is not under repair	– Check controller mode
4) Controller mode is AUTO	– Check trend information on PV
5) No fluctuations in PV occur	– Check trend information on VP[c]
6) VP is adjusted to compensate deviation PV-SP[d]	– Check trend information on PV
7) PV is not approaching SP	– Check trend information on VP
8) VP has reached/is going to its utmost position	– Conclude: leakage – Report malfunction

[a] Controller Information Display
[b] Process Value.
[c] Valve Position.
[d] Set-Point.

Several studies using Process have been conducted or are currently carried out. The focus of these studies is the optimization of training programs for fault management skills. With respect to this, it needs no explaining that it is implausible to specifically practice all possible fault management procedures in one training program. Given the theoretically infinite amount of possible faults, operators of Process must be able to handle faults, or combinations of faults, that they have not encountered before. Therefore, the studies are aimed at transfer of training [5], [7]–[9]. Transfer of training is the term used to describe the benefit obtained from having had previous training or experience in acquiring a new skill or in adapting an already mastered skill to a new situation. Transfer of training is of special interest for process operators, because they are frequently confronted with situations not previously encountered.

In the studies conducted, subjects are required to counsel the *Process Help System* that supports them in acquiring a selection of particular fault management procedures. The Taiga (Twente Advanced Interactive Graphic Authoring system; [14]) was used to implement the Process Help System on a separate personal computer (Olivetti M24). The system is based on Process' procedure network. The condition sides of each procedural step are presented to the subjects in a question format and the action sides are presented to them in an action format. A single question, a single action, or a combination of several actions (never more than four) is presented on one page of the computer screen. If subjects answer a question, the screen displays either a next question or instructions to carry out particular actions. In order to avoid interference with Process' dedicated keyboard, Process Help System is completely mouse-controlled. If subjects follow the procedures suggested by the Process Help

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[3] For information on the technical specifications, contact Geert Wijnands, University of Twente, Department of Education, Service-station TOLAB, P.O.B. 217, 7500 AE Enschede, The Netherlands.

System correctly, they are able to detect, diagnose, and compensate any system malfunction.

From the results of a recent study of Jelsma and Bijlstra [9], it appears that Process is a relevant experimental tool for the understanding of human interaction with dynamic systems. To conduct their study, Jelsma and Bijlstra [9], selected an exemplary sample of four faults and their related procedures out of Process' procedure network. Using Process control file, it was possible to predefine the selected types of faults and the time at which they should occur in the simulated process. In this way, the experimental conditions for all subjects were kept similar. The selected faults were introduced in the simulation and their related procedures were extensively practised under different instructional conditions. Roughly, subjects had to practice about eight hours to attain mastery level, that is, to be able to relatively quickly and error free detect, diagnose and compensate the introduced faults. The goal of the study was to identify the effects of two types of practice schedules on first-shot transfer performance in fault management (constant versus variable practice). On the transfer test, subjects had to detect, diagnose and compensate several types of faults that were not practised. Those "new" faults were predefined in Process Control File as well. Process Result File registered subjects' fault management performance individually and the obtained data were later statistically analyzed (see for a detailed description of the study and obtained results, [9]). In general, the results of the study indicated that constant practice facilitates large gains in performance in the initial stages of training and quickly leads to mastery. However, transfer performance is relatively low. Variable practice, on the other hand, produces small gains in performance during the initial stages of training and mastery level is attained more slowly. However, transfer performance is relatively high. Jelsma and Bijlstra [9] concluded that this trade-off between training for rapid acquisition and training for transfer which their study revealed, is of practical relevance in the design of training programs for operators of dynamic systems.

Another line of research, in which Process is used as an experimental tool, is attributed to the issue of how interactive video can effectively be utilized in acquiring fault management skills. Bijlstra and Jelsma [4] suggest that the costs of fault management training could be reduced if interactive video is used, for instance as a preparatory training tool preceding the expensive training in high fidelity simulators, or in cases where simulators are not used, in the real work environment. To optimize the instructional design of videodisc-based fault management training, Bijlstra, Jelsma, and Van Merriënboer [5] set up an experimental study to investigate the effects on transfer of training of different types of information presentation (audio-visual versus textual–visual) prior to and during the training at Process. The presented information contained a concrete model of the distillation process and a general approach to fault management (i.e., the phases detection, diagnosis, and compensation). The results of the study indicated that the audio-visual presentation of this information led to a significantly better transfer performance than the textual-visual information presentation (see for a detailed description of the study and obtained results, [5]).

Based on the results of various experimental studies and given the relative large potential for installing Process, it may be expected that Process can be easily scaled up to reasonable-sized problems that occur in real-life. Future research using Process pertains the integration of Process and the Process' help system in order to investigate the effects of on-line assistance during the training of fault management procedures on transfer to procedures not previously performed. On-line assistance could considerably improve the acquisition of fault management procedures, because, if subjects are not acting optimally or make particular errors, the system immediately provides them with advice.

APPENDIX

PID Control in Process

Each of the six PID controllers in the system continuously tries to equalize a process value to a given set point by adjusting the position of a valve in one of the stream pipes. This valve position determines a flow that in turn affects the process value under consideration. A function $D(t)$ is defined

$$D(t) = \left(x_{sp} - x(t)\right)/x_{\max}$$

with $x(t)$ the process value at time t. This value may stand for a flow ([tons/h]), for a temperature ([°C]) or for a liquid level ([tons]). The symbols x_{sp} and $x_{\max}$ denote the set point and the maximum process value, respectively.

The function $D(t)$ is evaluated at each time t_n, the result of which determines the valve position at the next time t_{n+1} according to

$$P(t_{n+1}) = C_p D(t_n) + C_i \int_0^{t_n} D(t)\,dt + C_d \left[\frac{dD(t)}{dt}\right]_{t=t_n}$$

with $0 \leqslant P(t) \leqslant 1$. Here, C_p, C_i and C_d are a proportional, integrational and differential constant, respectively, which have specific values for each PID controller. The corresponding flow through the valve is now given by

$$Fl(t_{n+1}) = Fl(t_n) + C_f\left[Fl_{\max} P(t_{n+1}) - Fl(t_n)\right]$$

with $Fl_{\max}$ the maximum flow possible through that valve and C_f a filter constant $(0 \leqslant C_f \leqslant 1)$ which introduces a finite reaction time of a flow with respect to an altered valve position.

Mass and Heat Balance in Process

The boiling temperature, specific heat and vaporization heat of a water–alcohol mixture, either fluid or vaporized, are all expressed as functions of the alcohol concentration. The vapor alcohol concentration is given as a function of the fluid alcohol concentration. All these functions are evaluated according to empirical rules.

Before entering the distillation column the initial water–alcohol mixture (the feed) with alcohol concentration f_{in} is preheated up to a temperature:

$$T_{in}(t_n) = \min\left(T_B(f_{in}), T_{liq}(t_n)\right)$$

with

$$\begin{aligned} T_{\text{liq}}(t_{n+1}) &= T_{\text{liq}}(t_n) \\ &\quad + C_t\left[T_{\text{sup}} + Fl_{st}(t_n)c^{\text{vap}}/Fl_{in}(t_n)c^{spc}(f_{in}) - T_{\text{liq}}(t_n)\right]. \end{aligned}$$

Here, $T_B(f)$ is the boiling temperature and $c^{spc}(f)$ the specific heat of a water–alcohol mixture with alcohol concentration f. The temperature T_{sup} is the temperature of the water–alcohol mixture before it has passed the preheater. The flow $Fl_{st}(t)$ is the steam flow through the preheater and $Fl_{in}(t)$ the flow of the feed at time t. A constant C_f $(0 \leqslant C_f \leqslant 1)$ is introduced to simulate the effect caused by the finite time required for the heat exchange. Finally, c^{vap} is the vaporization heat of water.

For the description of the mass balance in the distillation system the following functions are defined:

$$S_i(t_n) = \int_{t_n}^{t_{n+1}} Fl_i(t) f_i(t)\,dt \qquad i = \text{in}, 1, 2, 3, \text{ref}, \text{out}.$$

For $i = 2, 3$, $Fl_i(t)$ is the liquid flow at time t from level i to level $i-1$ in the distillation column (the lower, the middle and the upper part of the column are labeled with numbers 1, 2, 3, respectively). The flow $Fl_1(t)$ is the residue stream from the lower part of the column, $Fl_{in}(t)$ is the feed entering the middle part of the column, $Fl_{\text{ref}}(t)$ is the stream from the reflux tank into the upper part of the column and $Fl_{\text{out}}(t)$ is the distillate stream out of the reflux tank. The fluid alcohol concentration of the various flows is denoted by $f_i(t)$ (note that f_{in} remains constant and that $f_{\text{ref}} = f_{\text{out}}$!). The function $S_i(t_n)$, therefore, describes the amount of alcohol transported between t_n and t_{n+1} in the flow $Fl_i(t)$. The analogous vaporized alcohol transportation is described by the function:

$$S_{v,i}(t_n) = \int_{t_n}^{t_{n+1}} V_i(t) f_{v,i}(f_i(t))\,dt \qquad i = 1,2,3.$$

For $i = 1,2$, $V_i(t)$ is the vapor flow at time t from level i to level $i+1$ in the distillation column. The flow $V_3(t)$ is the vapor flow from the upper part of the column to the reflux tank. The vapor alcohol concentration is denoted by $f_{v,i}$ that is a function of the fluid alcohol concentration $f_i(t)$. In the evaluation of the functions S_i and $S_{v,i}$ the flows as well as the concentrations are assumed to remain constant between t_n and t_{n+1}.

The amount of alcohol in the three parts of the distillation column and in the reflux tank can now be expressed as

$$\begin{aligned}
m_1(t_{n+1})f_1(t_{n+1}) &= m_1(t_n)f_1(t_n) - S_1(t_n) \\
&\quad - S_{v,1}(t_n) + S_2(t_n) \\
m_2(t_{n+1})f_2(t_{n+1}) &= m_2(t_n)f_2(t_n) - S_2(t_n) - S_{v,2}(t_n) \\
&\quad + S_{in}(t_n) + S_{v,1}(t_n) + S_3(t_n) \\
m_3(t_{n+1})f_3(t_{n+1}) &= m_3(t_n)f_3(t_n) - S_3(t_n) - S_{v,3}(t_n) \\
&\quad + S_{\text{ref}}(t_n) + S_{v,2}(t_n) \\
m_{\text{ref}}(t_{n+1})f_{\text{ref}}(t_{n+1}) &= m_{\text{ref}}(t_n)f_{\text{ref}}(t_n) - S_{\text{ref}}(t_n) \\
&\quad - S_{\text{out}}(t_n) + S_{v,3}(t_n)
\end{aligned}$$

with $m_i(t)$ the liquid level at time t.

For the description of the heat balance in the distillation system the following functions are defined

$$Q_i(t_n) = \int_{t_n}^{t_{n+1}} Fl_i(t) c^{spc}(f_i(t)) T_i(t)\,dt \qquad i = \text{in}, 1, 2, 3, \text{ref}, \text{out}$$

$$\begin{aligned}
Q_{v,i}(t_n) = \int_{t_n}^{t_{n+1}} V_i(t)\big[c^{\text{vap}}(f_{v,i}(f_i(t))) \\
+ c^{v,sp}(f_{v,i}(f_i(t)))T_i(t)\big]\,dt \qquad i = 1,2,3.
\end{aligned}$$

Here, $c^{spc}(f_i)$ is the specific heat of a fluid water–alcohol mixture with alcohol concentration f_i. Furthermore, $c^{\text{vap}}(f_{v,i})$ and $c^{spc}(f_{v,i})$ are the vaporization and specific heat, respectively, of a vapor water–alcohol mixture with alcohol concentration $f_{v,i}$, which is itself a function of the fluid alcohol concentration f_i. Finally, $T_i(t)$ denotes the temperature at level i at time t (note that $T_{\text{ref}} = T_{\text{out}}$!). In the evaluation of the functions Q_i and $Q_{v,i}$ the flows as well as the concentrations and the temperatures are assumed to remain constant between t_n and t_{n+1}.

The heat balance in the three parts of the column and in the reflux tank can now be described as

$$\begin{aligned}
&m_1(t_{n+1})c^{spc}(f_1(t_{n+1}))T_1(t_{n+1}) \\
&\qquad - Q_1(t_n) - Q_{v,1}(t_n) + Q_2(t_n) \\
&m_2(t_{n+1})c^{spc}(f_2(t_{n+1}))T_2(t_{n+1}) \\
&\quad = m_2(t_n)c^{spc}(f_2(t_n))T_2(t_n) - Q_2(t_n) - Q_{v,2}(t_n) \\
&\qquad + Q_{in}(t_n) + Q_3(t_n) + Q_{v,1}(t_n) \\
&m_3(t_{n+1})c^{spc}(f_3(t_{n+1}))T_3(t_{n+1}) \\
&\quad = m_3(t_n)c^{spc}(f_3(t_n))T_3(t_n) - Q_3(t_n) - Q_{v,3}(t_n) \\
&\qquad + Q_{\text{ref}}(t_n) + Q_{v,2}(t_n) \\
&m_{\text{ref}}(t_{n+1})c^{spc}(f_{\text{ref}}(t_{n+1}))T_{\text{ref}}(t_{n+1}) \\
&\quad = m_{\text{ref}}(t_n)c^{spc}(f_{\text{ref}}(t_n))T_{\text{ref}}(t_n) - Q_{\text{ref}}(t_n) \\
&\qquad - Q_{\text{out}}(t_n) + Q_{v,3}(t_n)
\end{aligned}$$

with $Fl_{st}(t)$ the steam flow in the reboiler section and c^{vap} the vaporization heat of water.

REFERENCES

[1] J. R. Anderson, "Acquisition of cognitive skill," *Psych. Rev.*, vol. 89, pp. 369–406, 1982.

[2] J. R. Anderson, *The Architecture of Cognition*. Cambridge, MA: Harvard Univ. Press, 1983.

[3] J. R. Anderson, "Production systems, learning, and tutoring," in *Production System Models of Learning and Development*, D. Klahr, P. Langley, and R. Neches, Eds. Cambridge, MA: MIT Press, pp. 437–458, 1987.

[4] J. P. Bijlstra and O. Jelsma, "Some thoughts on interactive video as a training tool for process operators," *Programmed Learning and Educational Technology*, vol. 25, pp. 28–35, 1988.

[5] J. P. Bijlstra, O. Jelsma, and J. J. G. van Merriëboer, "*Effects of Audio-Visual Information Presentation on Transfer of Fault Management Skills*," manuscript submitted for publication.

[6] E. R. F. W. Crossman and J. E. Cooke, "Manual control of slow response systems," in *The Human Operator in Process Control*, E. Edwards and F. Lees, Eds. London: Taylor and Francis, pp. 51–66, 1974.

[7] O. Jelsma and J. M. Pieters, "The structure of practice schedules and transfer of training," in *Regulation of Learning*, P. R. J. Simons and G. Beukhof, Eds. The Hague: SVO/Selecta, pp. 177–190, 1987.

[8] O. Jelsma and J. M. Pieters, "Practice schedule and cognitive style interaction in learning a maze task," *J. Appl. Cognitive Psych.*, vol. 3, pp. 73–83, 1989.

[9] O. Jelsma and J. P. Bijlstra, "Training for transfer in learning to detect, diagnose, and compensate system failures," in *Proc. 7th Eur. Annu. Conf. Human Decision Making and Manual Contr.*, pp. 256–262, Paris, France, Oct. 1988.

[10] D. E. Kieras, *The Role of Cognitive Simulation Models in the Development of Advanced Training and Testing Systems*. University of Michigan, tech. rep., no. 23, 1987.

[11] D. E. Kieras and S. Bovair, "The role of a mental model in learning to operate a device," *Cognitive Sci.*, vol. 8, pp. 255–273, 1984.

[12] D. E. Kieras and S. Bovair, "The acquisition of procedures from text: A production-system analysis of transfer of training," *J. Memory and Language*, vol. 25, pp. 507–524, 1986.

[13] H. Kragt, *Operator Tasks and Annunciator Systems: Studies in the Process Industry*. Eindhoven University of Technology, The Netherlands, Ph.D. thesis, 1983.

[14] E. F. Laagland, "TAIGA, a graphic authoring system," in *Proc. 27th Int. Conf. Assoc. for the Development of Computer-Based Instructional Systems* (*ADCIS*), pp. 84–89, Washington, Nov. 1986.

[15] T. L. Mann and J. M. Hammer, "Analysis of user procedural compliance in controlling a simulated process," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-16, no. 4, pp. 505–510, 1986.

[16] N. Moray, P. Lootsteen, and J. Pajak, "Acquisition of process control skills," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-16, no. 4, pp. 497–504, 1986.

[17] N. M. Morris and W. B. Rouse, "The effects of type of knowledge upon human problem solving in a process control task," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-15, no. 6, pp. 698–707, 1985.

[18] N. M. Morris, W. B. Rouse, and J. L. Fath, "PLANT: An experimental task for the study of human problem solving in process control," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-15, no. 6, pp. 792–798, 1985.

[19] G. L. Myers and A. D. Fisk, "Training consistent task components: Application of automatic and controlled processing theory to industrial task training," *Human Factors*, vol. 29, no. 3, pp. 255–268, 1987.

[20] J. Rasmussen, "Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models," *IEEE Trans. Syst. Man Cybern.*, vol. 13, no. 3, pp. 257–266, 1983.

[21] J. Rasmussen and M. Lind, "Coping with complexity," in *Proc. First Eur. Annu. Conf. Human Decision Making and Manual Control*, H. G. Stassen and W. L. T. Thijs, Eds. Delft Univ. of Tech. pp. 69–91, 1981.

[22] J. Rasmussen and W. B. Rouse, *Human Detection and Diagnosis of System Failures*. New York: Plenum Press, 1981.

[23] W. B. Rouse, "Human problem solving performance in a fault diagnosis task," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-8, no. 4, pp. 258–271, 1978.

[24] W. B. Rouse, "Experimental studies and mathematical models of human problem solving performance in fault diagnosis tasks," in *Human Detection and Diagnosis of System Failures*, J. Rasmussen and W. B. Rouse, Eds. New York: Plenum, pp. 199–216, 1981.

[25] W. B. Rouse and S. H. Rouse, "Analysis and classification of human error," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-13, no. 4, pp. 539–549, 1983.

[26] T. B. Sheridan and G. Johannsen, Eds. *Monitoring Behavior and Supervisory Control*. New York: Plenum Press, 1976.

[27] W. L. T. Thijs, "*Fault Management*," Ph.D. Thesis, Delft Univ. of Tech., The Netherlands, 1987.