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ABSTRACT

An experimental tool is described for the investigation of the human control behavior for slow responding dynamic systems. The Program for Research on Operator Control in an Experimental Simulated Setting (PROCESS) is a simulation of a dynamic water-alcohol distillation system that can be used in research on operator training. In particular, PROCESS is designed to conduct research on fault management skills. PROCESS is described in detail, starting from a general model of control tasks; it enables the user to maintain the current status of more or less automatic systems or to change the state of the system. PROCESS is discussed from the perspectives of both the operator and the experimenter. The experimental configuration is then sketched, and ongoing research using PROCESS is reviewed. Recent research on control behavior for slow responding systems has suggested that training programs develop a set of fault management procedures to enable adequate control of the system. It is argued that, after sufficient practice, fault management procedures are cognitively represented as production rules that can yield quantitative predictors of performance. Information processing task analysis was used to determine the steps that build up fault management procedures. The focus of studies currently being conducted with PROCESS is the optimization of training programs for fault management skills, and the goal is the study of transfer of training. Six figures illustrate the PROCESS model. An appendix describes the equations governing PROCESS. (Author/SLD)

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

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CONTENTS

ABSTRACT[1]

This report describes an experimental tool for the investigation of human control behavior of slow responding dynamic systems. PROCESS (Program for Research on Operator Control in an Experimental Simulated Setting) is a simulation of a dynamic water-alcohol distillation system that can be used in research on operator training. In particular, PROCESS is developed to conduct research on fault management skills. 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; finally, the experimental configuration is sketched and a brief review of ongoing and future research using PROCESS is presented.

1 We thank Stef Breukel, Johan Sunter, and Diederik Waardenburg for doing an excellent job in engineering the software package for PROCESS and Service-station TOLAB for technical support. We also thank Jules M. Pieters, Ted N. White, and Jeroen J.G. van Merriënboer for their useful comments on a draft of this report

1. INTRODUCTION

Since Crossman and Cooke [5] 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., [12], [14]-[19], [21], [24], [25]).

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., [21], [26]). Fault management is generally conceived of as coping with system failures and at least incorporates the phases detection, diagnosis, and compensation. The operator has to notice that the system is not acting in conformity with expectations, or that an alarm occurs (acoustic and/or visual) which is pointing at an undesired state of the system (detection). After detection, the cause of the undesired state has to be found (diagnosis) and compensatory actions have to be taken in order to stabilize the system as fast as possible (compensation). Rasmussen and Lind [20] 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 report is addressed to operator training and some attention is indirectly 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 seldom used in scientific research on operator training. Morris *et al.* [17] 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 which 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 [22], FAULT [23], and PLANT [17]. 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., [14], [16], [17]).

To make the generalizability of these results plausible, Morris *et al.* [17] 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 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 these studies, it is seems necessary to use simulators with both a high psychological fidelity and a high physical fidelity. Therefore, we have developed PROCESS (Program for Research on Operator Control in an Experimental Simulated Setting). PROCESS is a dynamic simulation of a water-alcohol distillation system. 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 the simulated system 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.

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.

2. 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 Figure 1.

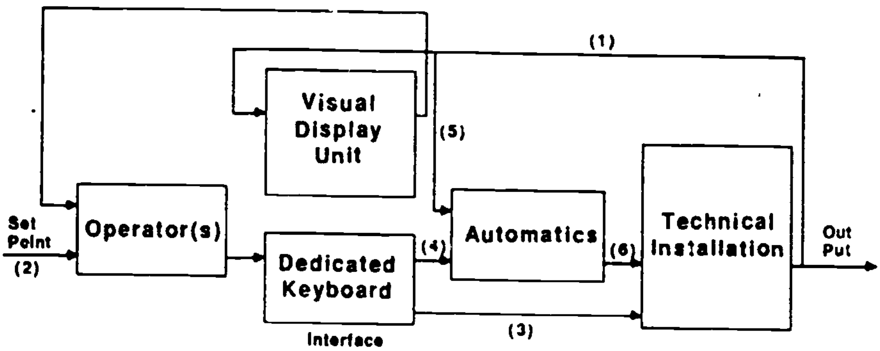

Figure 1. General model of control tasks

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 through automatics (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).

3. PROCESS FROM THE OPERATOR'S VIEW

PROCESS fits to the presented general model of control tasks. Under normal conditions PROCESS is stable and well adjusted, it produces a liquid mixture of approximately 85% alcohol out of a liquid mixture of approximately 40% alcohol. The operator uses a visual display unit and a dedicated keyboard 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:

Overview

The overview (Figure 2) 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 catched 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.

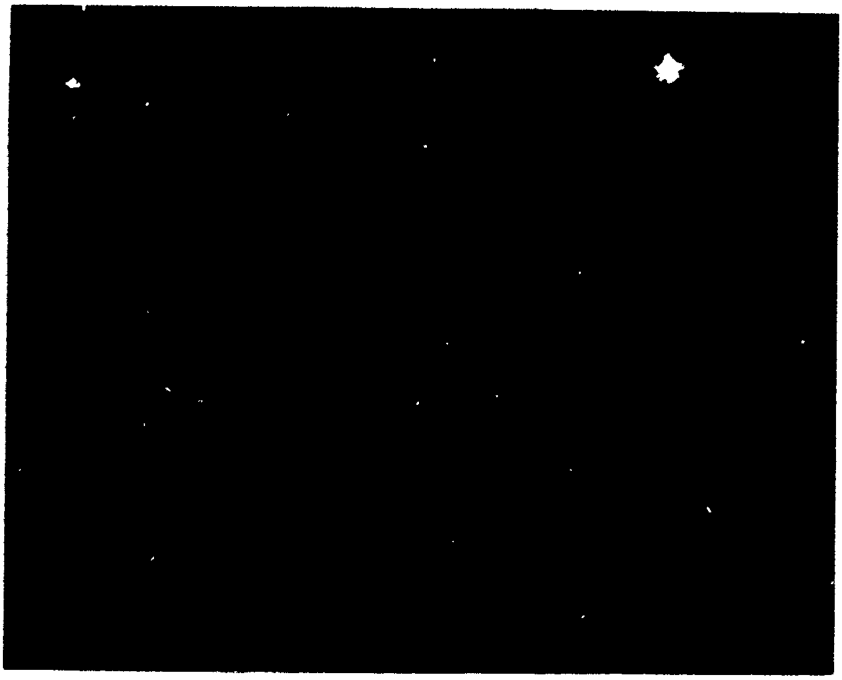

Figure 2. The overview

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 six seconds. 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. An additional visual alarm (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 can recognize a system malfunction by an unexpected 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, it is indicated which controllers are under repair.

Controller Information Display

After detecting a 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 (Figure 3). 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 minutes, 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 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.

Figure 3. The controller information display

In addition, the actual behavior of all controllers is displayed at the right part of the screen. So, at all times the operator 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 controllers 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 (Figure 4). The repair list provides information on the type of malfunction that is being repaired in a particular controller (e.g. leakage in controller FC3). In addition, the repair list displays the actual behavior on the controllers, the available function keys, and the message area.

Figure 4. The repair list

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:

- The Multifunction Keys Group (eight keys) 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 (four keys) is used to switch between various screen displays and to dispatch a fictitious repair crew to repair system malfunctions.
- The display Select Group (three keys) is used to select a particular screen display.
- The Data Entry Group (18 keys) is used to enter numeric values for PID adjustments, valve positions, set points, or alarm limits. In addition the Data Entry 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 (two keys) is used to cancel commands. This group is also used to temporarily freeze the distillation process, in order to create an opportunity to freely counsel a help system.
- The Acknowledge Group (two keys) is used to control the alarm system, for instance to stop the acoustic alarm in case of a system malfunction.

4. 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* for later analyses.

PROCESS Initialization File

In the PROCESS Initialization File, the following six categories of parameters are specified (See also the appendix):

- System input parameters for the equations governing the behavior of each of the six PID controllers.
- Tables specific for the distillation process of a water-alcohol liquid mixture.
- System input parameters for the equations governing the situation in the lower, middle, and upper part of the distillation column.

- System input parameters for the equations governing the situation in the reflux tank.
- 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.
- 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. The introduction of a system malfunction in one of the controllers can also be specified on-line. The rest of the parameters cannot be specified on-line. By creating a command file in which several cases are 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:

- 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. Additional identification parameters can always be specified within parentheses.

- PROCESS specification. In this category the following parameters can be specified:
  a) PROCESS start-up from zero or the more common situation that PROCESS is already running.
  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 the subject is presented a next case as soon as he has solved the present case. If a subject cannot solve a 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 unlocked:
     - change PID adjustment
     - change controller mode
     - change alarm limits

- change set point
- change valve position

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. When a PID controller malfunctions, the valve is no longer automatically controlled. Eventually an out-of-bounds situation will occur (but, see option j). If the valve functions well, PROCESS can be manually controlled.
- 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. When a valve malfunctions, it gets stuck in a particular position and eventually an alarm situation will occur (but, see option j). The valve position cannot be changed during reparation, neither manually nor automatically.
- Leakage. In case of a leakage, 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 position 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 malfunction can be specified in seconds.

j) Specification of valve positions. In case the controller mode is initially set to manual (option c), or/and if a valve malfunction is specified (option g), or/and if a PID controller malfunction is specified (option g), a particular valve position should be specified in advance. The specification of a particular valve position is necessary to ensure an out-of-bounds situation.

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:

- Subject identification. The parameters specified under tho 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.
- 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. If the experimenter choose to make a keydump, the keydump may serve as input for the *PROCESS Demonstration File*, for instance,

to replay a subject's control behavior. In training, the PROCESS Demonstration File could be easily used to give a subject instructional feedback.

- 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 non existing 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.

5. PROCESS' EXPERIMENTAL CONFIGURATION

Figure 5 schematically presents the experimental configuration of the simulator PROCESS[2].

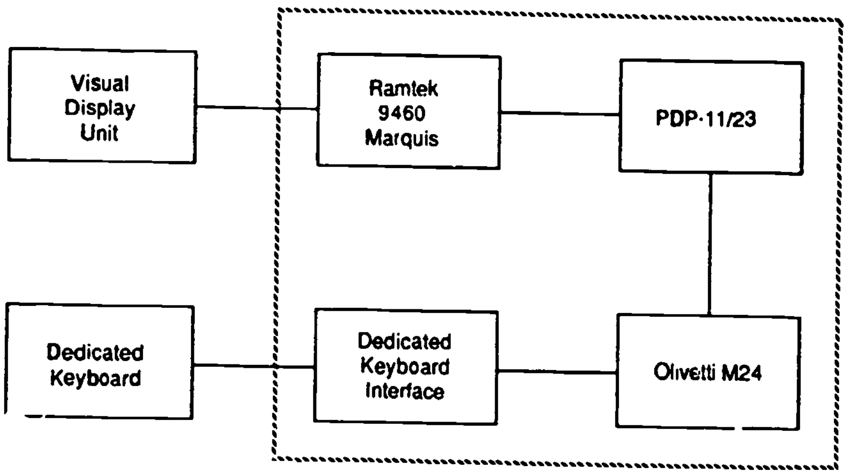

Figure 5. The expenmental configuration of PROCESS

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 unc‿ MS-DOS. A RS-232 Interface connects the Olivetti to a

2 A new version of PROCESS is being implemented on a personal computer with a 22-inch high-resolution color monitor.

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 introduces system failures on-line). 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 the Ramtek to the visual display unit. A DEC LSI-11 Series Interface links the PDP to the General Purpose Interface of the Ramtek.

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.

6. CURRENT RESEARCH USING PROCESS

As stated before, recent research on human control behavior of slow responding dynamic systems suggests that training programs should be direct.d to develop a set of fault management procedures that enable adequate control of the system (e.g., [14], [16], [17]). Based on recent developments in cognitive psychology that describe the human cognitive architecture in terms of declarative and procedural knowledge [1], [2], [9]-[11], we argue 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 [11] have shown that production rules can yield quantitative predictors of performance. For that purpose, we have used information processing task analysis methods to determine the individual steps, or individual production rules, that build up particular fault management procedures. Starting from the six possible system malfunctions that can be introduced in PROCESS we have constructed *PROCESS' Procedure Network*. 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 may be some overlap between two distinct fault management procedures, that is, they have particular individual production rules in common. One complete procedure is illustrated in Figure 6.

IF	THEN
an acoustic and visual alarm occurs.	acknowledge acoustic alarm; acknowledge visual alarm; select the Controller Information Display of the malfunctioning controller.
the process value exceeds the alarm limits	check the Repair List.
the controller is not under repair	check the controller mode
the controller mode is automatic	check trend information on the process value.
the alarm situation is not caused by fluctuations in the process value	check trend information on the valve position
the process value can not be brought within alarm limits by changing the valve position	conclude that a leakage has occurred; report the malfunction

Figure 6. An example of a fault management procedure in PROCESS

Several studies are currently conducted with PROCESS. The focus of these studies is the optimization of training programs for fault management skills. It needs no explaining that it is implausible that all possible fault management procedures are specifically practised in a training program. Therefore, our studies are aimed at transfer of training,

[6], [7], [8]. 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 our studies, subjects are required to counsel the *PROCESS Help System* in order to acquire a selection of particular fault management procedures. We have used TAIGA (Twente Advanced Interactive Graphic Authoring system; [12]) to implement the PROCESS Help System on a separate personal computer (Olivetti M24). The help system is based on PROCESS' Procedure Network. The condition sides of each production rule are presented in a question format and the action sides are presented 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 System correctly, they are able to detect, diagnose, and compensate any system malfunction.

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 advise. Another line of research is addressed to the issue of how interactive video can be used as a training tool in acquiring fault management procedures. Bijlstra and Jelsma [4] suggest that the costs of training could be reduced if interactive video is used 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.

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APPENDIX

Five categories of equations govern the behavior of PROCESS. Tables, specific for water-alcohol mixtures, that contain boiling temperatures as a function of alcohol concentration and vapor alcohol concentrations as a function of fluid alcohol concentration serve as input for the state equations.

Equations (1), (2), (3), and (4) govern the behavior of the PID controllers.

(1)	Vp(n+1)	= Pc + d(n+1) + Ic * SimStep * SUM(n+1) + Dc * {d(n+1) - d(n)} / SimStep
(2)	d(n+1)	= {SP - pv(n)} / maxpv
(3)	SUM(n+1)	= d(n+1) + SUM(n)
(4)	Fl(n+1)	= Fl(n) + {MaxFl * Vp(n+1) - Fl(n)} * CFilter

where.

CFilter	= filter constant, 0 ≤ CFilter ≤ 1
Fl(n)	= flow through valve of controller
Pc	= proportional constant
Ic	= integrational constant
Dc	= differential constant
d(n)	= relative difference
maxpv	= maximum process value
MaxFl	= maximum flow through valve of controller
pv(n)	= controlled process value
SP	= set point of controller
SimStep	= timestep, i.e. time between (n) and (n+1)
Vp(n)	= valve position, 0 ≤ Vp ≤ 1

Equations (5) and (6) govern the behavior of the preheater.

(5)	Ftemp	= SupplyTemp + Fl * VapHeat(0) / {Fl * SpecHeat(SupplyConc)}
(6)	DFtemp	= Min{BoilTemp(SupplyConc),Ftemp}

where:

BoilTemp(c)	= boiling temperature of a fluid water-alcohol

		mixture with concentration c
DFtemp	=	displayed temperature of feed
Fl	=	fluid quantities in column
Ftemp	=	temperature of feed
SpecHeat(c)	=	specific heat of a water-alcohol mixture with concentration c
SupplyConc	=	concentration of incoming watero-alcohol mixture
SupplyTemp	=	temperature of incoming water-alcohol mixture
VapHeat(c)	=	vaporization heat of a water-alcohol mixture with concentration c

The distillation column is supplied with two trays that divide the column in a lower, middle, and upper part. The situation in each part is governed by equations (7), (8), and (9).

(7) $FConc_1(n+1) = (Mass_1(n) * Fc_1(n) + Fl_2(n) + FConc_2(n) - Vap_1(n) * VConc_1(n) - Fl_1(n) * FConc_1(n)) / Mass_1(n+1)$

(8) $VConc_1(n+1) = VapConc[FConc_1(n+1)]$

(9) $Temp_1(n+1) = (Fl_1(n+1) * (SimStep/60) * VapHeat(0) + Mass_1(n) * SpecHeat[FConc_1(n)] * Temp_1(n) + Fl_2(n) * SpecHeat[FConc_2(n)] * Temp_2(n) - Vap_1(n) * SpecHeat[VConc_1(n) * Temp_1(n) - Fl_1(n) * SpecHeat[FConc_1(n) * Temp_1(n)) / [Mass_1(n) * SpecHeat[FConc_1(n+1)]]$

Levels 2 and 3 are calculated analogously.

where:

$FConc_i(n)$	=	fluid concentration at level i
$Fl_i(n)$	=	fluid quantities in column at level i
i	=	part of the distillation column, $1 \leq i \leq 3$
$Mass_i(n)$	=	mass at level i
SimStep	=	timestep, i.e. time between (n) and (n+1)
SpecHeat(c)	=	specific heat of a water-alcohol mixture with concentration c
$Temp_i(n)$	=	temperature in column at level i
VapConc(c)	=	concentration of vapor of a water-alcohol mixture with fluid concentration c
VapHeat(c)	=	vaporization heat of a water-alcohol mixture with concentration c
$Vap_i(n)$	=	vaporized quantities in column at level i
$VConc_i(n)$	=	vapor concentration in column at level i

Equations (10), (11), (12), and (13) govern the situation in the reflux tank.

(10)	TankLevel(n+1)	=	TankLevel(n) + Vap_3(n) - Out(n+1)
(11)	Out(n+1)	=	OutFlow * SimStep
(12)	TankConc(n+1)	=	(Tanklevel(n) * TankConc(n) + Vap_3(n) * $VConc_3$(n) - Out(n+1) * TankConc(n)) / TankLevel(n+1)
(13)	TankTemp(n+1)	=	(TankLevel(n) * SpecHeat[TankConc(n)] * TankTemp(n) + Vap_3(n) * * SpecHeat[$VConc_3$(n)] * BoilTemp[$VConc_3$(n)] - Out(n+1) * SpecHeat[TankConc(n)] * TankConc(n)) / [Tanklevel(n+1)*SpecHeat[TankConc(n+1)]]

where:

BoilTemp(c)	=	boiling temperature of a fluid water-alcohol mixture with concentration c
Out(n)	=	amount of fluid that streams out of the reflux tank, i.e. amount of fluid that flows to controller 4 and 5
OutFlow	=	amount of fluid that streams per time unit out of the reflux tank
SimStep	=	timestep, i.e. time between (n) and (n+1)
SpecHeat(c)	=	specific heat of a water-alcohol mixture with concentration c
TankConc(n)	=	concentration in reflux tank
TankLevel(n)	=	amount of fluid in reflux tank
TankTemp(n)	=	temperature in reflux tank
Vap_i(n)	=	vaporized quantities in column at level i
$VConc_i$(n)	=	vapor concentration in column at level i

Finally, a set of sinusoide equations govern the variations of flow, temperature, and concentration of the feed and of the variations of flow and temperature of steam for the preheating section and the reboiling section underneath the column.

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