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SIMULATION-AIDED DESIGN OF MAN/MACHINE INTERFACES IN AUTOMATED INDUSTRIES

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ABSTRACT

This paper describes the potential use of new computer simulation techniques for human factors designers in automated industrial process control. Problems in communications, operational procedures, and task allocation between the operator, computers and other machines can be identified from the simulation results and resolved. Also the simulation can show the system performance, individual operator workload with allocations of time into task classes, and provide the mechanism for testing sensitivities to learning, individual differences, motivation, environmental conditions, and job stress. Design strategies with computer simulation and coupled man-in-the-loop simulation are discussed.

1. INTRODUCTION

Automation has decreased the number of process control operators in industry but the importance of the remaining operators has significantly increased. Also the roles of these operators have changed dramatically from a direct process controller to that of a process or subprocess manager and a coordinator with other operators. As a manager and coordinator, the operator must perform more monitoring, communication, supervision, problem solving, and decision making. These role changes require the system designers to provide more organized information and decision aiding capabilities. As a consequence of these job complexities and the greater importance of the operators' jobs relative to system effectiveness, significantly greater demands are placed on system designers; particularly those who must deal with human factors problems. These demands on designers necessitate the use of new methodologies which can aid the design team in resolving these problems. A simulation-aided design strategy is described below to serve as part of these new methodologies.

Computer simulation of man-machine systems is not new (Siegel and Wolf, 1969; Wherry, 1969, 1971; Wortman, Duket and Seifert, 1977; Buck and Maltas, 1979; Ong and Buck, 1978). However, most computer simulations are naive in their descriptions of human operators and our ability to extract human factors design information from them is primitive. Recent endeavors to advance the state of the computer simulation art for industrial human factors applications are described below. Another feature to be described is the use of man-in-the-loop simulation as an adjunct and complementary technique to computer simulation. While man-in-the-loop simulation is also not new, advances in the software modularity and portability to mini-computers have greatly improved the capabilities of this technique (Buck, Alford and Deisenroth, 1978) so that it can be used for numerous jobs and quickly reconfigured between tests. Considerable design-aiding potential exists through a coupling of the improved man-in-the-loop simulation approach, with its high face validity, to a smarter computer simulation approach. This coupling requires a new form of design strategy in the interlacings of these techniques. Some elements of this strategy are described below.

A traditional human factors problem area has been called "function allocation". Fitts (1962) originated this term when he advocated that tasks should be assigned to either a person or

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a machine on the basis of which or who was the better performer of specific functions. The idea was simply to identify the principal function of a task and then use his list of functions where he compared man with machines in order to select the better performer. Unfortunately tasks to be performed may contain several indivisible functions where the allocation choice across all functions may not be consistent. Jordan (1963) also criticised the "Fitts List" approach because the approach ignored the graceful degregation of performance by people as compared to sudden machine failures. Whitfield (1967) further criticized this approach because it ignored other criteria than strictly function performance (e.g., flexibility, reliability, and repeatability). More recently the function allocation question has arisen again with the use of intelligent machines taking over tasks in some partnership with people according to various allocation strategies (Greenstein and Rouse 1980). Whether the allocation is a fixed or a situation-variable strategy, there is the "task communication problem" which must also be considered in the allocation decision (Buck, 1978). This communication problem arises because the need for information in task execution may be separated from the source of the information. If the information source is a sensor and a human operator needs the information to execute a task, then the sensor-collected information must be translated for communications to the operator. In the converse case of a human observer and a machine performing an associated operational task, translation and communications are again needed. However, the combining of the information collection and the execution of an attendant task can at times eliminate or at least minimize the translation and communication requirements. The result will likely improve task performance, and reduce the probability of errors in translations and communications, but the magnitudes of these effects are exceedingly difficult to estimate. Computer simulation provides an organized framework where these apparent subtleties can be captured and the effects on both the total system and the individual operator can be examined.

2. COMPUTER SIMULATION AS A DESIGN AID

In the early days of computer simulation, each individual problem being faced required a new computer program. The programming effort was very considerable and so this analytical technique was rarely employed unless there was extensive justification and available design funds. Since then special simulation software languages and programs have been developed which greatly reduce the required programming effort. Systems Analysis of Integrated Networks of Tasks (SAINT) is such a methodology. As its name implies, SAINT uses a network of nodes and branches to describe the parallel and serial tasking effects (Wortman, Duket and Seifert, 1977; Wortmen, et al., 1978) which provides an intuitive vehicle for obtaining direct designer inputs, rather than inputs via a programmer, and it provides a means for verifying the existing operations as well as verifying the practicality of alternative operations with system operators, engineers, and managers. While the early version of SAINT was based on the GASP II language and only discrete tasking was possible, the latest versions are now GASP IV based (Pritsker, 1974), so that both discrete and continuous processes can be handled.

Strengths and weaknesses in using SAINT approach to simulating large industrial processes are shown in Buck and Maltas (1979) and Ong and Buck (1978). These two case studies demonstrated that parallel, cascade, and probabilistically varying industrial processes (i.e., hot strip mills and basic oxygen furnace shops) with numerous human operators could be captured by SAINT. Further, these studies demonstrated that a wide variety of statistics could be obtained for use in assessing workloads on individual operators, implying specific design changes, and total system effects for evaluations of the design changes. Also multicriterial effects could be examined through the computer simulations so that tradeoffs could be considered and progressive experiments could be made toward an optimum design. However, this computer simulation described machine and people behavior alike except for the specified different parameter values added to the simulation package.

Wherry (1979, 1971) showed the need for creating simulation models of human behavior as distinct from machine behavior. This concept led to the development of the Human Operator Simulator (HOS) which was tailored for simulating aircraft pilots. It was also this concept and the limited application of HOS which motivated our recent efforts to start the development of Smart SAINT which would combine many of the human behavioral features with the more-generally applied simulation package SAINT. This development is discussed below.

Man-in-the-loop simulation (MILS) is a distinctly different technique from computer simulation but highly complementary for design aiding. The later technique is performed strictly within the computer while MILS uses one or more people as part of the actual simulation activities. This feature provides a greater face validity of the results because actual people are used rather than computer program models of people. However, man-in-the-loop simulation entails the real time use of a compouter, with perhaps some acceleration from real time so long as the time effects are compatible to the human operator. In the case of specific types of aircraft where training and safety are very expensive and paramount issues, large dedicated computers are practical for MILS. With varied human control tasks in industry, such computer systems are economically impractical. Limitations of minicomputers and the need for flexibility to meet the high variability of different industrial jobs both pose a problem. While not all of these problems are eliminated, recent technological advances in minicomputer hardware and software concepts and techniques (Buck, Alford, and Deisenroth, 1978, Gist, Buck and Deisenroth, 1978) have made the man-in-the-loop simulation technique feasible for many applications. This technique can also be used for purposes of skill maintenance of personnel after the design is completed and the system is in operation.

3. SMART SAINT AS A DESIGN AID

As described in the previous section, SAINT was chosen as the vehicle through which to demonstrate the effects of man-machine activities on total system performance. SAINT is a process-oriented simulation technique designed for modeling man-machine systems. It is both a powerful and flexible design aid, capable of capturing the essence of complex industrial systems in a form suitable for the simulation of design alternatives. Where SAINT is unique is in the flexible operator representation provided for by the simulation package. Other simulation languages exist that are specialized to process representation, or operator modeling in specific non-industrial settings (such as aircraft). SAINT provides the process modeling capabilities needed to represent complex industrial systems and include a simple machine-like representation for the system operators, as a standard computer package. The capability for "smarter" representation of the operator functions exists, but is left to the user to model through FORTRAN subroutines. Thus users of this simulation technique are not restricted to operator models specific to a given application or industry, and are free to include whatever level of representation of the operator function is appropriate for their needs.

Previous work demonstrated the process modeling capabilities of SAINT and used simple operator representations to examine task allocations between different operators and between operators and machines. Increasingly complex levels of industrial automation has changed the role of the supervisors and operators of such systems to the point where such simple representations are not longer adequate. Recent efforts have concentrated on developing models of operator behavior suitable for use in simulation modeling. Smart SAINT is the regular SAINT package with a collection of models representative of different types of task performance behavior found in industrial systems. A designer can select those models appropriate to a given application and include them in the computer simulation. A preliminary design of the system could then be simulated and analyzed. Critical aspects of the man-machine interface can be examined through man-in-the-loop simulation from which specific performance parameters can be determined.

The varieties of operator behavior available for modeling are limitless. In assembling a set of models useful for designers of industrial systems, this range of behavior was examined and reduced to a limited set of behaviors covering the essential aspects of operator performance. It is felt that this basic set of models provides reasonable guidance to the simulation modeler for inclusion of the many aspects of man-machine performance in models of the total system.

The models of operator performance developed to date have been grouped into two categories -- factors affecting task performance (operator individual differences), and task types. They are discussed separately as follows.

3.1 Factors Affecting Task Performance

Variability in task performance can be due to a number of operator related causes. Individual differences between operators and an operator's changing performance over time both result in performance differences. The following is a summary of the factors considered for inclusion in Smart SAINT.

Learning. The time for a new operator to learn a task is parametrically modeled. The effects of various levels of operator training before coming on-line can be represented along with system performance effects due to an operator "in training."

Individual Differences. Final performance level due to operator training, experience, and innate abilities is described for the population being considered. Differences due to age, sex, personality and physical and mental abilities are modeled.

Motivation. Such factors as wage structure, supervision, safety for oneself and others, boredom due to monotonous or repetitive type tasks, and the time during a work shift, may have a significant impact on operator task performance. Parametric descriptors of motivation are included.

Environment. The many physical aspects of the task environment, such as noise, temperature, ventilation and illumination affect operator performance to various degrees. Protective clothing may restrict movement, vision, or hearing. Thus communication and decision making may be affected as well as physical task performance. These potential effects are included.

Stress. Inadequate time to perform all of one's assigned tasks affects attitudes and hence the performance time. Strenuous physical tasks result in short-term operator fatigue that must be alleviated by adequate rest periods. Mental fatigue due to mental processing and attention type tasks causes performance to deteriorate with time unless rest is provided or alternative tasks are available to break the routine. Visual fatigue in the form of eye strain results from long-term use of CRTs. These effects, too, may be included in Smart SAINT.

3.2 Task Types

Human operators are typically involved in several types of activities. Representation of these activities in SAINT simulation modeling is a matter of proper structuring of SAINT task nodes. In some cases these nodes are a basic part of the process representation, but more often additional nodes are used to represent operator activites. The following is a summary of the task types considered for inclusion in Smart SAINT.

Cognitive. Perception, detection, monitoring and decision making are modeled. Monitoring and inspection tasks have become an increasingly large part of the operator's task assignment.

Communicative. Communication between operators, or between operators and machines, are modeled. This includes visual and auditory communication (e.g., direct voice or phone communication) as well as interaction with electronic systems.

Motor. Large amounts of data (such as the Motion Time Measurement System) are available on basic motor task times for operators. Modeling of combined motor/information processing type tasks is being developed, but absolute performance times are beyond the current state-of-the-art. Models of continuous manual control are available in the literature.

Dual Tasking. Human information processing models are available in several levels of complexity. SAINT assumes use of operators that perform tasks serially -- one task at a time. More recent parallel processing and combined serial/parallel processing representations are being explored for use with Smart SAINT. A hybrid model is currently being used to model monitoring. The operator scans many process variable values (in parallel) in search of non-normal readings. Upon finding an out of range reading, the operator changes to a serial sequence of tasks used to correct the problem and then monitoring is resumed.

SAINT has no automatic provision for operator communication or decisionmaking. These aspects of operator performance must be included as part of the user-written portion of the computer simulation. However, Smart SAINT does combine the modeling of the various tasks performed by the operator, with individual operator effects on process performance, to serve as a guide for use of SAINT as a man-machine system design aid. Furthermore, Smart SAINT provides a task-type profile of the different human operators as a means for describing job changes which result from alternative designs, operating procedures, or conditions being examined.

4. AN EXAMPLE DEMONSTRATION OF SMART SAINT

A steel industry process control simulation is currently being developed to demonstrate simulation-aided design of industrial process systems involving significant man-machine interaction. Fig. 1 shows a model of the process.

This ingot processing example was chosen because of its complexity and the significant impact of the operators on the productivity of the system. The basic process starts with molten steel, which is poured (teemed) into molds and allowed to solidify. The ingot molds are later removed (stripped) from the ingots and the ingots are placed in one of many large furnaces (soaking pits) where they are reheated to achieve a uniform high temperature for rolling. The ingots are removed from the furnaces several hours later and sent on to the rolling operations next in the process sequence, to be made into slabs. Scheduling of the soaking pit operation is critical to efficiency and productivity of this process. The decisionmaking, monitoring, and communication aspects of this process are modeled along with more routine operator functions such as crane operation, as an example of the use of Smart SAINT in design aiding. By modeling, and collection of statistics on the various operator functions, effects on the process of operator individual differences and decision strategies can be systematically examined.

Davis and Buck (1980) contains a detailed description of the example process, along with discussions on factors affecting operator task performance. A variety of task types performed by operators in this system are discussed and modeled. A series of experimental demonstrations are included to demonstrate the use of Smart SAINT as a design aid, as follows:

Illustration 1	-	Component Tasks Within an Operator's Job
Illustration 2	-	Sensitivities to Individual Operator Differences
Illustration 3	-	Planned Down Times
Experiment 1	-	Operator Learning Effects
Experiment 2	-	Decision Strategy Analysis: Changing/Removal Priorities
Experiment 3	-	Decision Strategy Analysis: Assignment of Pit Territories to Pit Cranes

Fig. 2 shows two simplified examples of SAINT node structures used for modeling individual differences and monitoring/decisionmaking. For the purpose of illustration, Fig. 2a, b shows a work effort labeled "TASK 1", and its associated FORTRAN subroutine, used to determine which operator is performing that task node, and how the task time assigned at the start of the simulation should be modified to reflect performance by a particular operator. Fig. 2c shows a work effort labeled "Monitor", in which the monitoring action occurs at a given interval until an out-of-bounds system condition is detected, at which time an intermediate action (such as communication, adjustment, alarm sounding) is performed and then monitoring is resumed. These SAINT node diagrams are included here to illustrate the two methods used for implementing increased operator modeling fidelity through Smart SAINT - that is 1) modification of task time or quality of performance at a single node, to reflect performance characteristics of a particular operator, and 2) use of a group of nodes to model a complex series of operator actions with fidelity beyond that achievable with a single node. Use of Smart SAINT largely involves a determination of the fidelity of operator representation required for a given application, and incorporation of that representation (through the two methods discussed above) in an overall model of the process or system being simulated.

The steel industry ingot processing example is being used to further explore and develop simulation methodologies for man-machine system design and analysis. Development of Smart SAINT is an on-going development activity. As further models of operator effects and behavior become available, they can be incorporated into Smart SAINT for use in current and future simulation

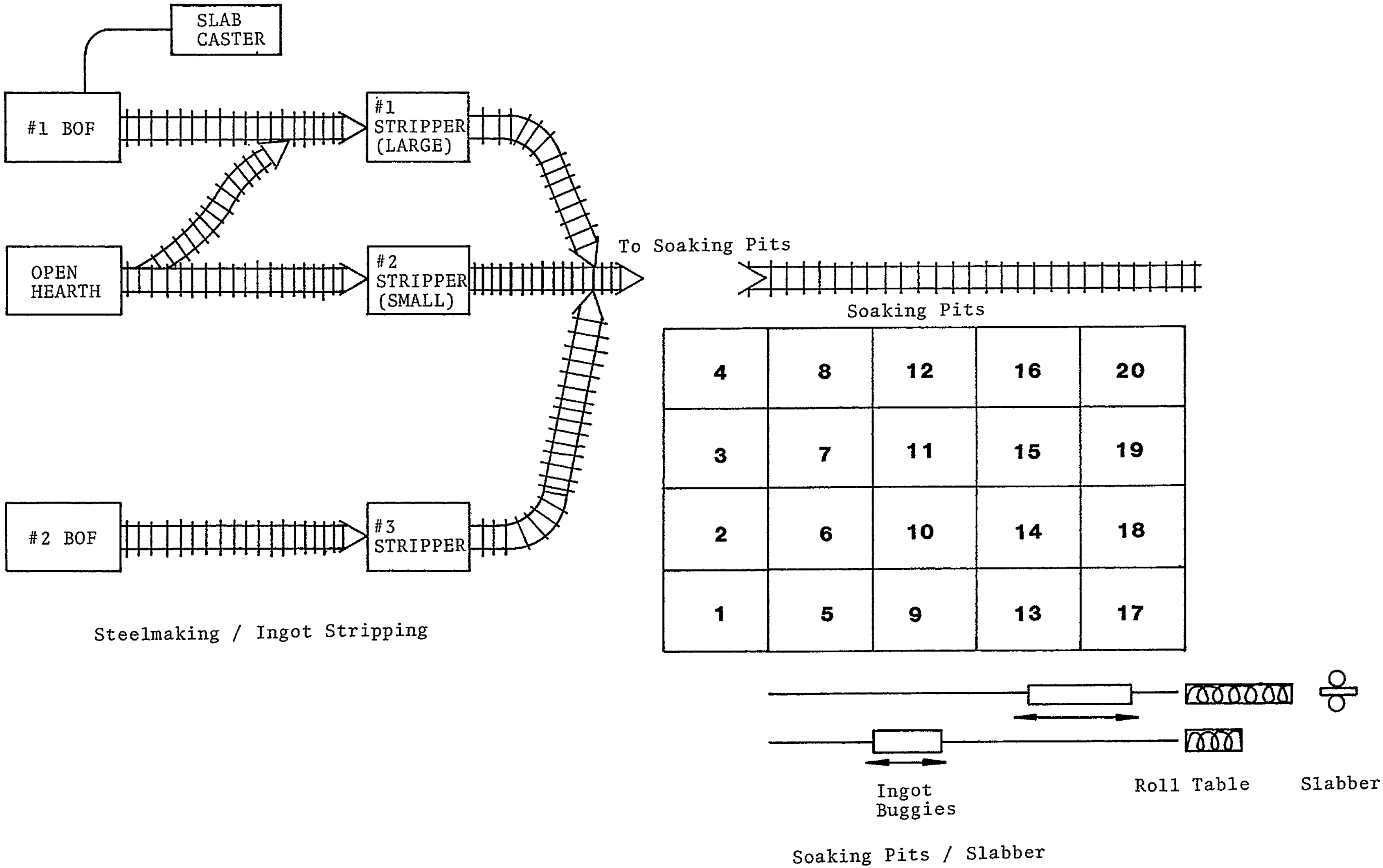
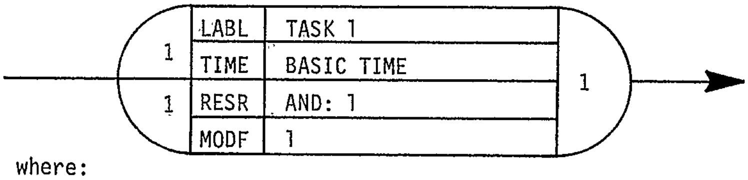


Fig.1 Ingot Processing Model



where:

BASIC TIME = task time without influence of operator performance factor

Fig. 2a

Saint Model Illustrating Moderator Function Specification Used To Model An Operator Performance Factor

```
      SUBROUTINE MODRF (MFN,NNODE)
C
      COMMON/COM22/TTIME,PFIRB
C
C****  EXAMPLE OPERATOR PERFORMANCE FACTOR MODEL
C
C**    SET PARAM1 TO THE OPERATOR RESOURCE ATTRIBUTE (RA)
C**    CONTAINING THE PERFORMANCE FACTOR
      CALL GETRA(NRE,NAT,VALUE)
      PARAM1=VALUE
C
C**    CALCULATE NEW TASK TIME
      TTIME=TTIME*PARAM1
      RETURN
C
      END
```

where:

NRE = number of the resource (operator) performing the task

NAT = number of the resource attribute affecting the performance of operator NRE

Fig. 2b

Subroutine for Model Shown in Fig. 2a

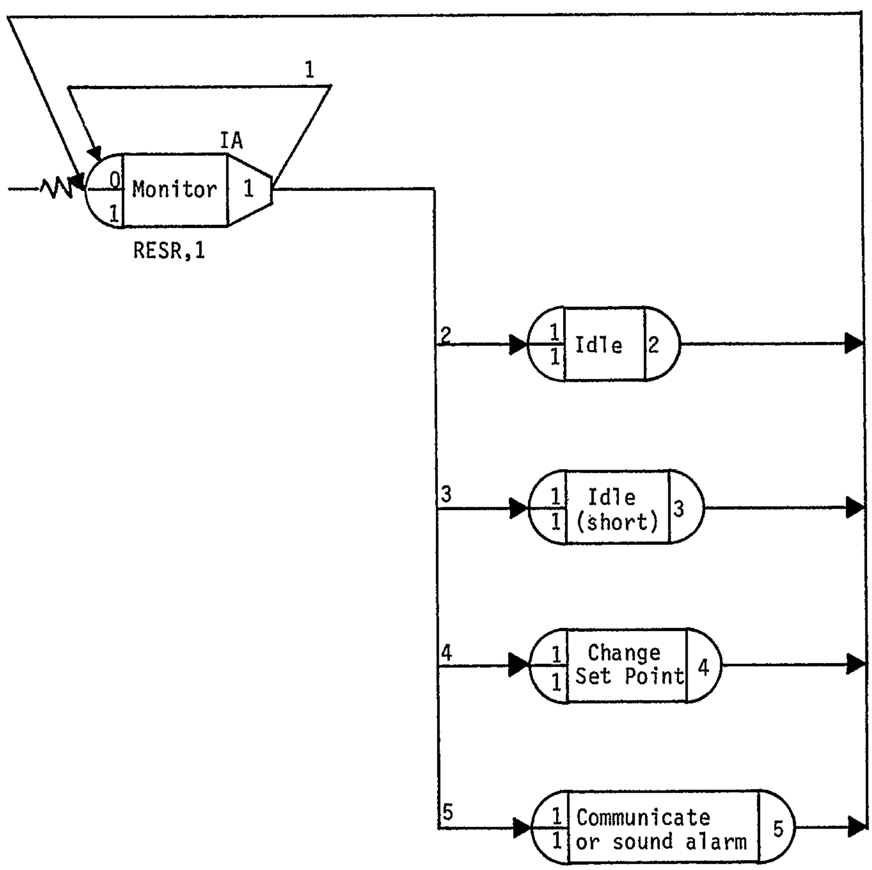


Fig. 2c

Monitoring of a Continuous Process

studies. Thus the man-machine modeling capabilities of SAINT adapt to operator models of increasingly greater fidelity and widespread application.

5. A MAN-MACHINE SYSTEM DESIGN STRATEGY

The discussion above shows many features of the development of Smart SAINT as a design methodology . Computer simulation is relatively inexpensive, particularly the marginal costs for experimentation. Moreover, computer simulation is fast so that several experiments could be done each day. Accordingly, this technique appears to be most useful during the early stages of design when many of the large contemplated changes are under scrutiny.

Man-in-the-loop simulation, MILS, provides a complementary methodology to computer simulation. However, MILS is more expensive, slower, but with more face validity. This later feature of man-in-the-loop simulation makes it particularly useful for determining performance parameters to be used in the computer simulation and for validating the results of critical jobs. The higher relative cost and time required to perform man-in-the-loop simulation limits its use to critical jobs and to situations where the experimental extrapolations of computer simulation appear to provide promise as a design, but there is question as to the assumptions used in the computer simulation. When these assumptions are scrutinized in a man-in-the-loop simulation, the results can then be transferred to the computer simulation for determination of system effects. As such, we feel that computer simulation should provide the primary experimental technique during all but the final design phases, with man-in-the-loop simulation playing a lesser but increasing role as these design phases evolve.

Smart SAINT provides additional capabilities over the earlier versions of SAINT so that sensitivity analysis can be better performed. Learning effects, individual differences, motivation differences, environmental, and stress effects can be evaluated both from the viewpoint of the individual operator and from the total system viewpoint. Most persons with much simulation experience recognize that systems are usually very sensitive to a few factors and highly insensitive to most others. Human factors designers need to know sensitivities to learning in order to assess training requirements. Sensitivity to individual differences necessitates better personnel selection. Motivation sensitivity implies a need for improved supervision or job enrichment. And the list goes on! It is, however, clear that sensitivity analysis serves an important human factors role in industrial system design; especially when automation is a significant aspect of the new design.

A few years ago Carroll, et al. (1976) came forth with suggested guidelines for industrial man-machine system design. Most of these guidelines consisted of checklists of questions which those authors felt were important considerations. Most experienced designers would likely agree with most of these guideline questions. If these guidelines fall short, it is probably due to the fact that this report does not tell users how to analyze the situation toward an appropriate resolution of the questions. We suggest that Smart SAINT is an appropriate technique for many of the more perplexing questions.

Other design methodologies have arisen in recent years which are valuable adjuncts in the design process. A variety of computer graphic techniques have been developed for improving the layout of controls and displays. Human Engineering Computer Aided Design, HECAD (Topmiller and Aume, 1978), is an example which employs a synthetic time system to aid in an evaluation of alternative layouts. While deficiencies admittedly exist in the synthetic time system, the time evaluation concept is very important and efforts are underway to improve deficiencies in synthetic time systems (Payne and Buck, 1979; Buck, Ings and Lehto, 1980). Another graphical computer-aided design technique is SAMMIE (Bonney et al., 1972) which aids in providing a dynamic anthroporphic analysis. These computer graphic aids will undoubtedly become more prevalent in the future. In fact, an interactive computer graphic approach to modeling Smart SAINT would represent a further improvement to the ergonomics design process, especially if algorithmic computer assistance were added (Pulat and Ayoub, 1979).

Problems still remain in devising highly faithful computer simulation models for man-machine systems designers. Most of these problems are our lack of knowledge about supervisor and operator behavior. In those cases assumptions are made. For example, if a discrete task is started and another higher priority task arises so that the current task is interrupted, then the time taken to complete the interrupted task is typically assumed to be the same as if the task were started anew. In cases where information transfer is part of the task and that part was finished prior to the interruption, then the information will not always be forgotten and that part of the task will not be repeated, thereby reducing the required performance time. Task interruption theory has not been developed to help here as yet. Other assumptions are frequently made about performing one discrete task at a time (Broadbent, 1958) and that the time required to perform a discrete task is unaffected by performing a continuous control task simultaneously. While there are a number of dual tasking theories (Norman and Bobrow, 1975, Kantowitz and Knight, 1978; Navon and Gopher, 1979), there are no predictive models which allow one to specify a priori the effects of the simultaneous continuous control task on the discrete task. The prediction of forgetfulness is another area where not enough is known, and most computer simulation models carry the assumption that nothing is forgotten. Until research can provide answers to these and other missing gaps in behavioral knowledge, computer simulation and mathematical models of behavior will be naive to many aspects of real life and their results suspect. Accordingly, HOS, Smart SAINT, and similar computer simulation models will of necessity be evolutionary.

6. CONCLUSIONS

Computer simulation has been shown to be a timely and cost effective design aid for human factors designers in automated industries. The increasing complexity of industrial process control has made necessary new approaches to the design of the operator function in such systems. Computer simulation and man-in-the-loop simulation provide designers with the ability to determine in advance the effects of operator behavior on system performance. This ability in turn allows the process interface to be structured so as to provide for efficient operator decisionmaking, monitoring, and control. Simulation-aided design over the past decade has advanced from strictly modeling the machine aspects of industrial processes to include limited aspects of operator behavior. Much work remains to be done in the development of "smarter" operator models, but design using these models is expected to be a more important part of future system design.

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