

On Managing the Human Factors Engineering of Hybrid Production Systems

M. RAHIMI, P. A. HANCOCK, AND A. MAJCHRZAK

Abstract—In the transition toward total automation, contemporary manufacturing systems are predominantly composed of production equipment that is neither completely manual or automated. The development of these systems, identified as hybrid production systems, employ and integrate the capacities of human operators with intelligent machines. It is argued that human activities in hybrid automated systems are critical in achieving productivity gains. Given this importance, hybrid systems must be designed to optimize production. Optimal human factors engineering is possible only when engineers and their management are aware of the technical challenges, created by hybrid systems, and the range of options available for meeting these challenges. This paper describes these challenges and their possible solutions, specifically targeted to the management of engineering and technology-based organizations.

Index Terms—Human factors, robotics, human-computer interaction, resource utilization, human-machine interaction.

INTRODUCTION

AN EXAMINATION of the evolution of manufacturing systems depicts a continuing trend from manual to automated activity. At the birth of industrial activity, the human contribution was essential for the successful operation of both manual and automated systems. More recently, however, this trend has turned toward a goal of total computerized automation in which human contributions are purposely excluded. One stage of development toward such a goal is the installation of intelligent interactive work operations which we have identified as *hybrid systems*. In a hybrid production system, the human operator and machine interact, each as cooperative intelligent entities. As computerized automation progresses, managers of such hybrid operations need to understand how automation affects both the human operators of the hybrid system and overall productivity of the system. In addition, managers need to have a thorough knowledge of human factors engineering design issues in order to be more effective in evaluating performance as well as the potential effectiveness of different design options.

While completely automated factories may in the future be the standard facility in the manufacturing sector, given costs, technical, and managerial considerations they are not currently a feasible option for most factories. Progress toward factory automation has primarily consisted of introducing islands of automation (e.g., robots and computer numerically controlled machines). While this introduction appears to be viable, the effectiveness of the "islands" for meeting manu-

facturing needs is not automatically assured. With such "islands," shortcomings may result from poor integration of the human actions with machine functions. For example, the highest proportion of robots are used to automate isolated assembly and material handling operations [8]. The servicers of these robots perform setup, programming, inspection, and maintenance procedures. Ultimately, supervisors and managers are required to optimize such hybrid work environments. A number of issues characterize this optimization process: 1) the job responsibilities of the human, 2) the engineer's knowledge in design and redesign of the work layout for a hybrid workstation, 3) the software and hardware interfaces between computerized machines and other system components, 4) selection and straining requirements for new and already existing operators, 5) career development opportunities for operators, 6) safety and health of the operators, and 7) operator motivation. The immediate task of the manager is to weld these elements into a fully integrated system. This paper presents an approach toward the development, implementation, and evaluation of hybrid systems based on the interacting elements of humans and machines in high-technology systems.

In the sections which follow, focus is first directed toward the discussion of hybrid systems for automated work environments. Following this discussion, a generalized framework for analysis of the essential components of a hybrid system is presented. This qualitative analysis is based on a framework previously noted as the *problem factor tree* [51], [72]. This hierarchical tree structure enables one to conduct a simple analysis of the components making up a complex system. The tree is further decomposed into branches which identify individual factors of critical importance to the operations of hybrid systems. In the first level of decomposition of the system there are three branches. Further factor decompositions are treated in separate subsections. Each subsection presents the knowledge necessary for engineers and managers who need to integrate human and machine components of hybrid systems.

FOCUS OF HYBRID WORK SYSTEMS

Fig. 1 is a graphic depiction of the change in the relative degree of human physical (i.e., manual) and cognitive energetic contribution as a function of increasing automation. As the level of automation increases, the type of human interaction with the system clearly shifts from physical to cognitive contributions. Typically such cognitive contributions include pattern recognition capabilities and problem-solving capacities. Beyond a point of medium automation—a point at

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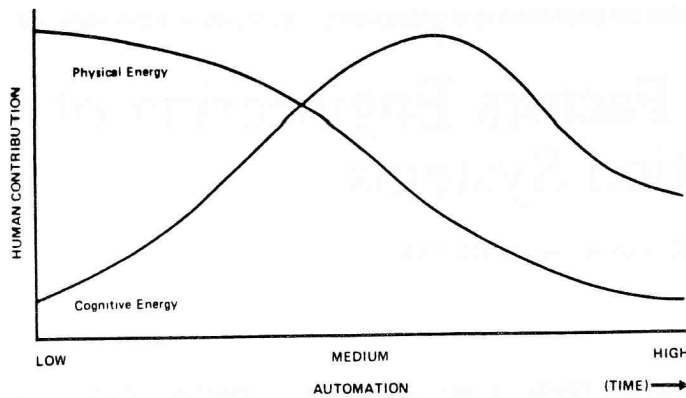


Fig. 1. A depiction of changes in human physical and cognitive contribution to work process with different levels of automation.

which many contemporary systems may now be characterized—the human cognitive contribution substantially increases. With further automation, the human cognitive contribution reaches a maximum and then declines; nevertheless, even in the most automated systems, the human role remains critical to the successful accomplishment of the operational goals [16]. In a highly automated factory, for example, where robots and computerized numerically controlled (CNC) machines perform most of the production operations, operators and engineers are involved in robot programming, teaching, maintenance, and trouble shooting, and supervisors are involved in production scheduling. However, it is not only the nature and level of the human contribution which is important. Equally important are the interactions between the human and machine components of automated systems.

These human-computer interactions include on-line as well as off-line modes of operations. Such dynamic communication between humans and intelligent machines occur during different modes of operation. Consequently, the nature, scope, and allocation of functions between humans and machines during these interactions are also dynamic. Thus, to ensure optimal use of hybrid systems, better critical understanding of the effects of such interactions with automated and intelligent systems is required [27]. It is upon this premise that attention for the design of automated production systems centers on hybrid systems.

In summary, the hybrid system is composed of the following elements: a) a production system that is partially automated such as small component assembly, material handling, and robotic inspection, b) limited interaction and cooperation (e.g., communication) among groups of machines, c) operations in which learning is determined primarily by the human components of the system, and d) task performances which require substantial human sensory capabilities (i.e., information collection, processing, and feedback) rather than elaborate machine sensing. Considering the above points, *any evolution toward advanced automation must progress through a stage of a hybrid system.*

A FRAMEWORK FOR MANAGING THE DESIGN OF HYBRID SYSTEMS

Using the previously described hierarchical tree structure, Fig. 2 represents factors of importance in a hybrid work system. The apex of the structure represents overall produc-

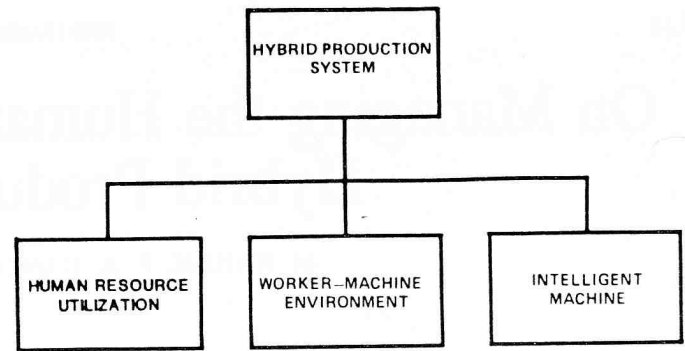


Fig. 2. The first hierarchical decomposition for a hybrid automated production system.

tion system. The system is decomposed into three major elements which relate to the worker-machine-environment, human resource aspects, and intelligent machine behavior. Concern for the latter factor is considered to be largely microengineering design, and beyond the scope of this paper. Further decomposition of the first two branch elements are discussed within the sections labeled worker-machine environment and human resource utilization.

Through the adoption of this hierarchy, the manager can use the simple structure we have presented to locate individual problem areas. For example, issues related to retraining of robot maintenance operators are discussed within the human resource utilization branch of this tree. These considerations can be then integrated into an ongoing picture of the transition process as it applies to a specific organization. Future developments of this framework should include any direct and indirect interrelationships among elements of this structure to be used for a manager's dynamic decision-making process.

WORKER-MACHINE ENVIRONMENT

Because hybrid systems have facilitated the growth of automated production, the manager's evaluation of performance, reliability, and safety of the system has become increasingly more difficult. This is primarily due to a high degree of integration among the elements of these hybrid systems. Engineers and managers of these systems must evaluate the individual and integrated reliability, in addition to considering the safety and performance issues. Specifically, engineers and managers need to be aware of four content areas subdivided in Fig. 3.

System Reliability

Software and Hardware Reliability: Software is becoming the dominant component of automated manufacturing systems. In the rapidly developing field of software engineering, universally accepted design concepts have yet to be established [25]. However, one principle that has been recognized is the importance of incorporating software reliability considerations into the initial stages of program design and development. That is, within a systems design approach, software development is an integral part of the overall system development process. Clearly, complex computing systems comprise interacting hardware and software elements which are subject to a wide spectrum of failure modes and errors [26]. The human contribution at this juncture is in the detecting and then

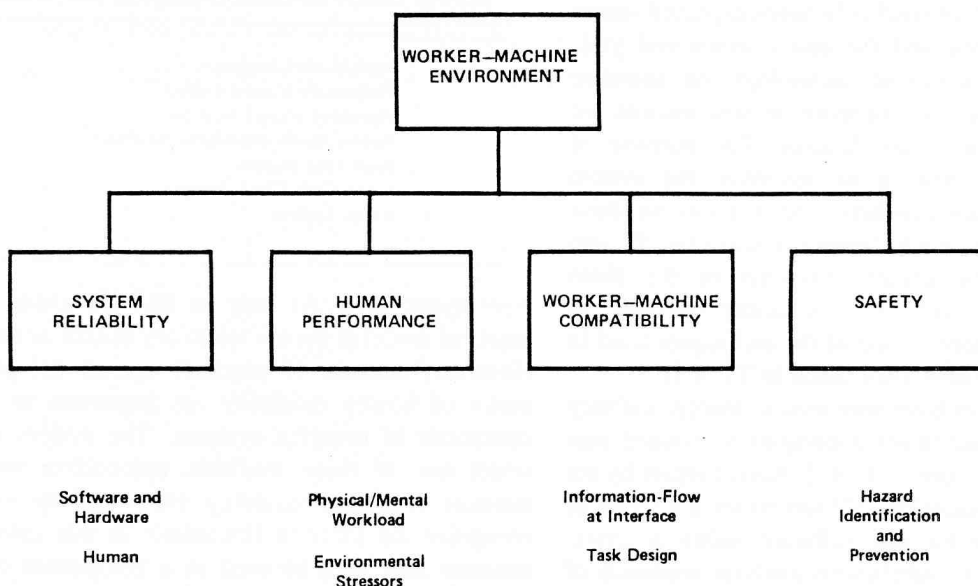


Fig. 3. Major components of a worker-machine environment and related subdivisions for human factors engineering considerations of hybrid systems.

correcting errors in software that may affect the performance of the system.

Software reliability, analysis, and evaluation continue through system analysis, software design, coding, testing, and system operation and modification. To identify and eliminate problems of unreliability the emphasis must be placed on the analysis and design where most of the software flaws and errors are introduced. It is estimated that 60 percent of all software errors are committed *before coding even begins* [44]. Therefore, it is recommended that, as early in the program as possible, managers expand the resources allocated for detecting and eliminating software errors and failures. Unless particular attention is given to each step of program development and efforts are made to reduce errors as well as improve reliability, the progressive stages of software development can result in a very inefficient and even hazard-producing operation [43]. The cost of software error detection and elimination steadily increases as the software is integrated into the system's operational phases. This growth is directly dependent upon the combinatorial interactions between components that characterize large and complex systems and their development [14], [43].

Reliable combined hardware/software systems are often developed using information based on subsystem failure rates; however, there are problems in extrapolating from the subsystem to the combined hardware and software system. For example, the knowledge obtained from hardware reliability and safety methodologies does not always apply to software subsystems [43]. Table I is a list of the major differences between hardware and software failures and reliability that have to be considered. The nature of these differences

emphasize the importance of considering safety and reliability issues within the early design stages.

In addition to applying subsystem failure principles to software design, system reliability can benefit from the application of system safety principles. System safety is the discipline that is concerned with the safety of humans as well

TABLE I
DIFFERENCES BETWEEN HARDWARE AND SOFTWARE RELIABILITY

- | | |
|----|--|
| a. | Software has no bathtub hazard rate curve. |
| b. | Software does not wear out. |
| c. | Software faults and failures are rooted in software design whereas, hardware failures are affected by design, production, operation and maintenance. |
| d. | Redundancy in software procedures, codes and commands may not have the same positive effect as hardware redundancy for reliability and safety. |
| e. | The long and complex process of software error elimination may itself generate the possibility of further error introduction. Without a process of continuing, error detection simple software correction may actually increase the possibility of system failure. |
| f. | Software components are highly interdependent. To maintain software reliability, software modularity must be incorporated. |
| g. | In software, Mean Time Between Failure (MTBF) relates to time between <u>detection</u> of errors not <u>occurrence</u> of undesired outcomes or failures. |
| h. | System failures are normally traced back through hardware first. For software dominant systems, this strategy is no longer valid. |
| i. | Software fault detection is a function of test time, type of test, and choice of test data. For complex systems, software fault diagnostic tests may be even more difficult to design than the original software. |

as expensive peripheral subsystems. System safety concepts and methodologies can be used to simultaneously identify and control faults (hazards) associated with system constituents [14]. This discipline is useful for determining the mechanism for considering software as a system constituent. The development of "software system safety" is emphasized in military standard MIL-STD-882B, which requires design of safety into military-contracted and subcontracted systems.

The discipline of system safety has identified that software system hazards are a result of conflict between expected versus actual machine instructions and the data encountered [63]. With the emphasis of advanced technology on software systems, the discipline has focused more on how hazards are generated through conflicts, not failures. The purpose of software system safety, then, is to determine the system elements that produce such conflicts, and to focus on those unexpected outputs which could become hazardous. System safety analyzes only the critical elements of the three subsystems of software, hardware, and human operator, in addition to their interactions. Some of the techniques used in software system safety analysis are listed in Table II.

Some of these techniques have been used to analyze military software subsystems which involve complex automated machines used by human operators [9], [41]. Also, a report by the Electronic Industries Association [17] has outlined a series of recommendations for performing software safety analysis. This report emphasizes a multifaceted analysis approach of management considerations, technical aspects, and detailed procedural considerations for reliability and safety of a technological system. For this reason, system safety managers often assemble multidisciplinary engineering teams to study and analyze software reliability and safety issues early in the design process.

Human Reliability: To enhance productivity in hybrid operations, the manager must assist the system analyst to provide an estimate of overall system reliability. The key to this global estimate is to accurately assess human reliability, then incorporate this factor when estimating overall system reliability. Human reliability estimates are difficult to obtain. There are two distinct approaches to this problem, each of which has generated some controversy. One approach holds that human reliability is measurable in a manner similar to that of machine reliability. Therefore, estimates of the reliability of the human component may legitimately be inserted into overall system reliability calculations and appropriate system reliability estimates derived. The alternate approach proposes that the human must be treated as a *qualitatively* distinct component, since human behavior varies not only in numerical magnitude but also in fundamental content from machine reliability. Under this latter perspective, the simple combination of two qualitatively different functions (one of the human and the other of the machine), leads to problems of increasing complexity and difficulty in producing an effective estimate of overall system reliability. The interested reader may wish to examine the controversy in more detail and should refer initially to the review work of Adams [1]. The first approach, emphasizing the direct incorporation of human reliability when estimating system reliability, can be found in the work of Swain [70].

The major problem in estimating and predicting human reliability is the lack of a coherent theory of task performance error. Human reliability estimates must be based on a taxonomy of human task performance by which task errors can be predicted. With our present state of knowledge, there is little consensus on what constitutes an elementary unit of a task or on what taxonomy might describe the plethora of human

TABLE II
SYSTEM SAFETY METHODOLOGIES FOR SOFTWARE ANALYSIS

Fault Hazard Analysis
Preliminary Hazard Analysis
Operating Hazard Analysis
Failure Modes and Effects Analysis
Fault Tree Analysis
Safety Cross-Check Analysis
Sneak Analysis

error types [29]. As long as this consensus is lacking, a practical model of human reliability cannot be developed fully. However, because of practical operational pressures, estimates of human reliability are important in managing the operations of complex systems. The system analyst has to select one of these available approaches and provide an estimate of system reliability. However, the manager should recognize the inherent limitations in this information. This estimate may then be used as a component of productivity indices for managerial decision-making.

Human Performance

Human performance involves numerous information processing capacities. We have chosen to focus on the concepts of workload and stress response as critical characteristics in interacting with intelligent machines.

Physical and Mental Workload: Workload may be divided into its two constituent components; namely, its physical and mental characteristics. Hybrid work systems are expected to transfer the emphasis from physical workload to mental workload. In a hybrid cell, the physical workload will be transferred largely to the more capable machine (e.g., robot) component, while elements such as problem-solving will be initially allocated more to the human worker. Given this shift in workload, it is becoming more important to be able to measure the degree of mental workload in a task in order to avoid overloading the human operator. This is somewhat unfortunate because, although we have well-defined procedures for measuring physical workload, the assessment of mental workload remains problematic [39]. Recent work [33], [34], [50], [73] has underscored difficulties encountered in this area of quantitative evaluation of mental workload.

For example, it has been found that excessive or insufficient mental workload may be instrumental in causing either long- or short-term dysfunction of the human worker (e.g., information overload and/or boredom) [33]. It is also possible that an instantaneous mental overload can cause performance degradation that may result in accidents [61], as is the case in process control, where a long period of underload may be interrupted by an emergency state. The emergency causes the demands to swing suddenly, thus creating an extreme overload situation [32].

To overcome this problem, Hancock and Chignell [11], [30] have sought an approach by which productivity may be optimized while human mental workload is maintained within acceptable limits. This is accomplished through a knowledge-based adaptive mechanism whose principal component is an intelligent interface. This interface produces a dynamic task

allocation strategy which optimizes system performance. The allocation and reallocation of tasks within this constraint is accomplished through reference to a knowledge base containing information about the characteristics of both the machine and the operator. The instantaneous status of each of these components is also provided to the interface at a rate determined by assessments of operator mental workload and system resource usage. The adaptive mechanism thus optimizes the usage of each entity without violating the maximal capabilities of the respective components.

Many restrictions concerning speed of operation are inherent in human limitations while flexibility of goal-directed action acts to curtail automated machine abilities. It is the purpose of the hybrid system to utilize the strategy of the knowledge-based adaptive mechanism, which employs the best capabilities of each element, while eliminating the potential limitations intrinsic to their individual functioning. To achieve this harmonious and efficient long-term state, on-line quantitative evaluation of mental workload is necessary. The *adaptive* or intelligent interface, which applies this information, uses artificial intelligence techniques that are based on an expert system superimposed on an appropriate knowledge base [31].

Environmental Stressors: Environmental stressors, in the context of hybrid production, are facets of the surrounding physical environment which act to disturb the output efficiency of the operational cell. Environmental stressors can encompass physical characteristics such as temperature, vibration, radiation, and variations in the gaseous constituency or pressure of the atmosphere. Environmental conditions are as liable to impact the efficiency of the human as they impact the machine (e.g., robot accuracy is affected by environmental dust or electromagnetic noise).

However, the stressors' impact on humans is often ignored in hybrid system design. By ignoring their impact, human stress tolerance standards are often not set and thus inadvertently exceeded. In the work of Hancock and Chignell [31], adaptability criteria for setting human stress tolerance standards have been defined. These principles advocate establishing stress levels that do not violate individually scaled adaptive ranges. In this work, normal, transitional, and failure operational modes of activity are modeled. Thresholds of adaptability are also modeled which provide the mechanism through which stress monitoring can be achieved. For example, the human operator generates significant performance errors at the point where the homeostatic capability of the individual is superceded. In analogy, this would indicate that the quality of a machined product would become unacceptable at the point at which production speed exceeds the control capability of the unit. Through the use of the concept of comfort, it is suggested that stress levels should not violate the subjectively sought zone of comfort of the human operator. In hybrid production

ms, where operators are normally faced with machine-paced production [38], assessing and maintaining such "stress-comfort" zones becomes essential if optimal work productivity is to be achieved. Consequently, the manager must monitor operators, keeping in mind that any sign of job dissatisfaction or worker behavioral stress could be an

indication that the combined activity of the hybrid cell is overtaxing the human component. This information should be subsequently used to adjust the task allocation procedure.

Worker-Machine Compatibility

For hybrid workstations, task design and information flow between workers and machines must be compatible. Design of a hybrid task and ways of transmitting critical information between human and machine are important for the successful accomplishment of hybrid system objectives.

Information Flow at the Interface: One immediate problem in the development of hybrid production systems is the nature and method of information transmission across the interface between operator and automated machine. Typically, robot/machine structures have been and are being developed independently of interactive considerations. Important questions have been left unanswered: how is the machine to present information? Should there be visual, verbal, tactile, or multichannel transmission? Is this information to be presented in parallel with the operation at hand or serially, contingent upon task completion of each constituent of the cell? Both the physical and cognitive interfaces need to consider the principle of *compatibility* in order to minimize potential operator-machine information handling conflicts. The principle of compatibility states that the different forms of information transfer to and from human operators (visual, auditory, etc.) require minimal inconsistency [22]. For example, spatial information is best conveyed via a graphic medium which implies a visual display, while text is compatible with auditory input. This does not ignore the value of redundant presentation or multimodal displays. However, compatibility may be optimized by matching the nature of the information to the characteristics of the sensory system at hand. With current technology there are a number of stereotypes (e.g., manual entry of commands, as compared with difficult to translate information between forms of presentation, voice entry) that are difficult to dissolve. Operators have come to expect data in a certain format and are uncomfortable with changes (e.g., computer-aided training versus hardcopy material). An example of redundancy in the interface is the use of easily recognizable alphanumeric characters together with graphics on a video display terminal, since these characters reduce the probability of operator error and thus system malfunctioning [7].

Compatibility should be both physical and cognitive. Physical compatibility in hybrid systems is achieved through the use of direct manipulators. These prosthetics simply replicate the movement of the operator at a remote point. In this case, the operator and the machine represent essentially one entity with the prosthetic *slaved* to the movement of the human. The question of integrating information flow at the interface concerns how to physically realize this level of direct and compatible interaction while retaining cooperation between the two intelligent entities.

When the somewhat mechanistic problems of the physical interface are resolved, there remains the larger and less tractable questions concerning the cognitive model of the operator and the intelligent machine interaction. It is important

that, as the flexible machines adapt to interactions with the operators, these adaptations reflect operator performance through changing states of learning [11]. Therefore, interactive processes are required for both operator and machine learning. This learning process increases in importance as the operator becomes progressively more familiar with the capability of the system at hand. The eventual goal is optimal production with the active cooperation of highly *skilled* entities. It is not common to consider a robot as skilled, especially as at least to a cursory inspection it may replicate only a deterministic movement path. This predetermined movement path is, of course, necessary for task completion. However, skill and learning enter into the picture when considering the actions of the cooperative system, which is of superordinate importance for increasing productivity [68]. When human operators are involved in operating a robot work cell, the cell should be viewed as a flexible *problem-solving team*. The need for a problem-solving team arises when tasks are not sufficiently simple and well-defined or do not involve repetitions of the same response sequence. Such tasks can be viewed as a series of problems that need to be solved for a successful outcome to occur. The cognitive solution to these problems would be a direct result of cooperation between operator and machine, while the physical action to achieve success is delegated largely to the machine.

Task Design: The consideration of human operators in the design and development of automated systems has raised new questions related to the design of production units and tasks. A procedure for integrating the tasks of humans and machines is given by Sanders and McCormick [64]. This procedure advocates:

- 1) Statement of task objectives,
- 2) separation of functions,
- 3) allocation of tasks to:
 - a) human,
 - b) hardware,
 - c) human/hardware interface,
- 4) system integration.

This is a textbook approach for technologically simple components and devices. With the introduction of automation (e.g., robots, flexible manufacturing systems, and CAD/CAM), a layer of complexity is added to this task design scheme [6], [53], [54]. This complexity has been handled with a series of lists indicating advantages and disadvantages of humans versus robot capabilities. "Robot-man" charts have been developed which compare abilities in the categories of 1) action and manipulation, 2) brain and control, 3) energy and utilities, 4) interface, and 5) miscellaneous factors. Kamali *et al.* [38] have extended the robot-man chart into a table comparing the abilities of automation, robots, and humans as part of a framework to aid the engineers in designing tasks for hybrid robotic systems. These robot-man charts have not received widespread application to the present time. They tend to oversimplify the problems by assuming that robots' and humans' capabilities are static and can be differentiated across all tasks. For example, the memory capability of a robot processing unit may be much greater than a human operator.

However, the human flexibility in utilizing memory capacity make this simple comparison potentially misleading and practically untenable.

Given the problems of the robot-man charts, a more complex model for task allocation between human and intelligent machines is needed. This model should contain mechanisms by which variabilities of human performance and flexibility of computerized automated machines are included as the degree of automation increases. This model should be able to respond to the following issues on hybrid system task allocations:

- Is the software compatible with human operators' cognitive problem solving approach?
- What are the structured methods for information transfer between automated machines and the human input/output?
- What are the requirements for operators' jobs in tasks such as maintenance, trouble shooting and diagnostics, backup and recovery, inspection, and repair?
- What should be the nature of interaction between human operator and computerized decision support systems?
- What is the optimal allocation of function between machines and humans in an automated work cell, with particular concern for the extent of the human supervisory responsibilities?

The solution to these problems will clearly involve a high degree of human reasoning and logic. Advances in artificial intelligence provide a framework to increase the intelligence of the machine within a hybrid system. The primary contribution of a task design and allocation model, then, is to indicate how and to what extent human *and* machine reasoning are integrated. For example, is it sufficient for the operator to simply follow a set of operational rules? Probably not, since, for the hybrid cell to operate in a problem-solving mode, rule-based operation would provide insufficient flexibility to allow the generation of novel solutions. Instead, the hybrid cell would be enhanced if operator's skills and knowledge were derived from operations rather than rules. Such operations are not merely the procedure of the operation monitored by the operator, but also include interactions of the machine with the human entity.

Safety

Previous discussion concentrated on issues which enhance design and productivity of hybrid systems. Since hybrid systems are complex and expensive, an important overriding issue is how to integrate safety of humans and expensive machines (and peripherals) in the operational life cycle of the system. Events such as Chernobyl nuclear accident, the Challenger explosion, and the Cerritos plane crash clearly indicate the potential for increase in severity of injuries and damages within largely automated and computer controlled systems.

Hazard Identification and Prevention: Due to the complexity of hybrid systems, traditional seat-of-the-pants approaches are not adequate in identifying potential hazards related to hardware, software, operational procedures, and human interactions. As an example, let us consider a hybrid

work system involving robots for assembly and material handling. A number of studies have pointed out the importance of identifying factors which cause robotic accidents [4], [23], [58], [69]. Ironically, the introduction of robot automation to eliminate human involvement in production has led to a series of accidents involving humans. Since one severe injury or death may seriously affect the viability of a production facility, more rigorous analysis to identify, control, and prevent hazards is needed for the hybrid work systems. A description of causes of robot-related accidents can help managers and users of these automated systems plan for safe hybrid workstations.

Table III contains a list of potential sources of robot accidents [59]. To resolve some of the safety problems listed in Table III, traditional safety engineering approaches have been partially modified [58]. Some combination of the following four approaches are suggested to improve safety of hybrid systems:

- Developing a complete robot sensory capability for detecting the presence of humans and non-humans in the work area.
- Improving hardware and software reliability and control modules for design of robotic hybrid systems.
- Incorporating ergonomic considerations for appropriate layout and material flow design of hybrid workstations to prevent collision.
- Developing a comprehensive safety training program for individuals involved in robot operation and maintenance.

Prior to implementing a combination of these approaches, it is essential to identify specific factors that might contribute to potential hazards for the particular workstation. While Table III includes a list of potential causes, methods are needed to systematically identify "root" causal factors. Several system safety methodologies have been suggested to model and analyze potentially dangerous factors contributing to robotic accidents [58], [62]. One such methodology is energy barrier analysis [58]. In energy barrier analysis, any physical damage is explained to have a kinetic energy source producing the damaging force. Prevention of human injury, therefore, can be achieved by blocking transfer of this undesired energy from the source to the human component of the hybrid system. Other potentially useful techniques for robotic safety are listed in Table IV.

Strengths and weaknesses of each methodology when applied to other hybrid systems must be considered. For certain developmental aspects, such as the design of safety sensors, the initial step should involve developing evaluation criteria. Included in these criteria are degree of human and machine protection, degree of human interaction within the machine danger areas, and type of operator task assignments. The criteria set is under development for an array of robot operations [57], [58].

The hybrid system designer must consider not only the human-machine environment, but also the environment in which the worker is encouraged, motivated and developed—in short, utilized. Systems designed in ignorance of such issues may be unproductive not because of inadequate technology or

TABLE III
POSSIBLE SOURCES OF ROBOT ACCIDENTS

<u>Machine Related Factors</u>	
-Robot component failures (mechanical, electrical, etc.)	
-Software control inadequacy, error, and reliability	
-Unexpected halts and stops	
-Improper design of teach control panel	
-Inadequate safety devices and sensors	
-High speed of robot arm	
-Human-robot work environment	
<u>Operator Related Factors</u>	
-Entering danger zone of a halted robot for:	
. trouble shooting	
. repair	
. testing	
. maintenance	
. teaching	
-Improper initial robot start-up procedure	
-Work-piece adjustment and positioning	
-Operator unaware of robot movement	
-Intentional disabling of safety devices	
-Collision path for robot and human tasks	
-Lack of training	

TABLE IV
SYSTEM SAFETY METHODOLOGIES FOR ROBOTIC SAFETY ANALYSIS

Preliminary Hazard Analysis
Subsystem Analysis
Failure Mode and Effect Criticality Analysis
Critical Incident Technique
Task Analysis
System Simulation
Fault Tree analysis
Management Oversight and Risk Tree Analysis

an improperly designed interface, but because workers are insufficiently attentive, knowledgeable, or motivated to keep the equipment running. Therefore, in designing hybrid systems, it is important to understand how such systems can change the way humans are used. With this knowledge, the manager may then choose the hybrid system which expected more or less from the human, or more or less from the organization in developing the human.

HUMAN RESOURCE UTILIZATION

There are five major issues to consider under human resource utilization. These five, depicted in Fig. 4, are job responsibility, selection, training, personnel policies, and organizational climate.

Job Responsibilities

In a hybrid system, responsibilities of operators' jobs will change dramatically from their responsibilities when working with less intelligent machines [48]. Since more computer-automated machines are often capable of responding to immediate feedback about the status and quality control. For example, Pullen surveyed 99 manufacturing cells and found 67 percent of them have operators responsible for their own inspection [56].

Since hybrid workstations with intelligent machines are

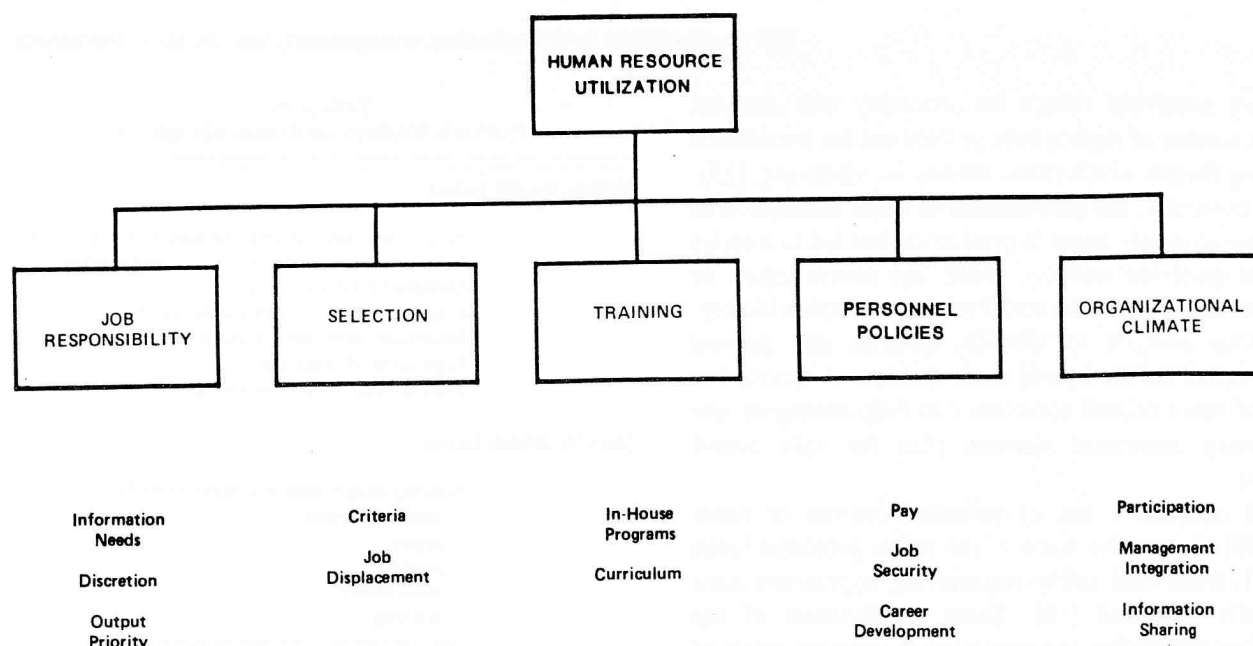


Fig. 4. Major components of human factors in management and related subdivisions for hybrid systems.

often engaged in producing a multitude of different parts using a range of raw and processed material input, the operator also becomes responsible for learning about the machine's efficiency in handling the variation in processing. For example, in an automated paper mill, one pulp digester seemed to be particularly efficient with certain kinds of wood fiber. By ensuring that all operators knew of this equipment idiosyncrasy, different materials could be properly routed through the different digesters [13, p. 447].

An operator's third responsibility is to work closely with maintenance personnel and supervisors [3]. Production halts, within different stages of automation and implementation, necessitate such close cooperation. These halts are frequently the result of a complex interaction of raw materials, the manner in which the materials were processed earlier in the production sequence, equipment idiosyncrasies, or equipment wear. Generally, the workstation operator is the only individual sufficiently observant of the equipment to identify important information to help distill the causes of various breakdowns. Therefore, the operator often becomes a key source of information to maintenance personnel and supervisors [4], [65]. These new job responsibilities of diagnosing quality, understanding equipment idiosyncrasies, and working with other staff to identify causes of production problems results in a demand for more information than that which is needed in the case of less intelligent machines.

In addition to more information, operators in hybrid systems tend to have more autonomy than operators working with predominantly traditional machines in manual production tasks. The amount of discretion needed to keep the equipment running is often underestimated according to a recent study of managers implementing flexible manufacturing systems (FMS) [27]. This increased operator discretion over production, inspection, and rework stems primarily from the production process being significantly more complex and costly. To facilitate machine uptime, some operators also have discretion

over, and responsibility for, maintenance tasks [4] as well as debugging computer programs [2], although these latter two responsibilities vary with the organization. Other areas over which operators often have discretion include internal distribution of tasks and governance of their own performance [28].

Another change in operators' jobs is that output priorities often shift from a focus on quantity to a focus on quality. For example, at a Ford plant, the implementation of hybrid systems caused management to refocus priorities on quality, giving operators the right to refuse to run bad parts [10].

For the manager responsible for selecting designs for hybrid systems, these new operator responsibilities mean that more is expected of the operator. To meet these new job responsibilities of increased information needs, more discretion, and a focus on quality, new job designs are often needed. These new job designs often include workgroups, overlapping job responsibilities among different workers, and broader more flexible job classifications [45]. The designs of the system, therefore, must allow for the flexibility and worker interaction inherent in such obscure designs. This can be accomplished through the careful design of equipment layouts, control panels, and expectations about areas of worker discretion.

Selection

Operators of hybrid systems need to be selected according to their perceptual and cognitive skills, rather than their muscular capacity and motor skills. In addition, for operators to effectively help with maintenance problems, their skills for diagnosing causes of complex interactions must be assessed [36]. Moreover, since more coordination is needed, operators must be selected based on their "human relations" skills, e.g., communication and "team-player" skills as well as an ability to adjust to unique problem-solving circumstances [45].

Given the extensiveness of the new selection criteria, it is likely that only a small portion of the existing workforce can meet all of these criteria. Moreover, fewer operators are often

needed with hybrid systems. As a result, some job displacement will occur. The amount of displacement, however, will depend more on other factors than simply the needed skills, the speed of equipment installation, new production requirements, and equipment reliability. For example, as an increased number and variety of products will be produced with the new equipment, the labor force can be assigned greater responsibility for the production processes, and the equipment can be installed at a sufficiently slow pace to allow a measured transition to evolving employment conditions [45]. The hybrid system designer, then, needs to consider the job displacement ratio, selection criteria, and available recruiting pool. It may be possible, for example, to design the system in modules that can grow in complexity as operator knowledge increases or can be installed at a slow enough pace to allow for absorption of displaced workers.

Training

Most training today for hybrid systems is being done as unstructured on-the-job training (OJT) [37], [45], [49]. Problems with this approach to training abound [52]. These problems include inadequate and biased information dissemination and loss of efficiency due to production disruption caused by the trainee. Thus, instead of unstructured OJT, a training strategy that combines in-house and external resources is needed [45]. Such a strategy would involve sending critical personnel to receive initial vendor training, then bringing in-house training expertise. The in-house training program would provide off-the-job classroom training followed by a supervised period of OJT experience. The training should be individualized, and would offer the same courses repetitively as new trainees are transferred into the line. The trainers would be trained supervisors or engineers and initial training would be completed before the hybrid system was installed. In addition to specific equipment operations, the training curriculum content would include courses in human relations, knowledge of the entire manufacturing process, basic mathematics and reading skills, and process control [45].

For the hybrid system designer, then a training program that meets all these "shoulds" would clearly allow for the greatest use of humans and the largest assumptions about their capabilities. Most training falls short, however [47]. Therefore, the designer may need to design into the system ways to stimulate the training and development needed such as through embedded training techniques or equipment parts that are logically sequenced to accommodate the expected logic sequence of the semitrained operator.

Personnel Policies

Personnel policies that change with the introduction of hybrid systems include pay, job security, and career progression. Operators in hybrid systems can no longer be paid based on traditional standards of individual work, job attendance, or production quantity. Rather, since coordinated activity is more important than individual activity in keeping the systems operational, group pay schemes are clearly needed [21]. Moreover, since unattended machines can create costly errors in production runs, the content of work is more important than

sheer worker presence. Thus, it is often found that workers are paid, based not on the number of hours worked, but on salary, derived either from competencies [20] or job grades [49]. Finally, by changing manufacturing priorities from solely quantity to include quality, and with the operator's work pace no longer under this control, piece rate or uptime incentive systems must often be replaced by profit bonuses [65], [74]. For the system designer, then the equipment must match the pay scheme. Questions the designer should ask include: How is competent performance with the machine to be measured? How much of performance is dependent on others? How closely tied to the organizational profits is the output of the manufacturing system? The designer must have answers to these questions to ensure the system is designed so that operators will be adequately motivated to fulfill their job responsibilities.

Job security is another personnel policy important to the success of hybrid system implementation [42]. Without job security, there is often a substantial resistance to the introduction of automated work environments. Such resistance may result in overall work inefficiency. Several options are available to the firm struggling to promise job security. These options include bringing subcontracted work back into the plant and long-range planning prior to implementation [49], [67].

A third personnel policy changing with hybrid systems is career progression [49]. Since job classifications are broader and autonomy greater, promotions across narrowly defined job classifications and informal supervisory control can no longer be used as the basis for career progression. Moreover, since increased training needs make high turnover more costly, there is an enhanced incentive for the organization to develop career ladders for operators. Options for career ladders include skill or task modules, multiple grades of operators, and operator-to-engineer, or operator-to-programmer paths [45]. To facilitate such progression, embedded training devices and multilayered maintenance requirements should be considered by managers of hybrid systems.

Organizational Climate

Resistance to hybrid production systems abounds in U.S. manufacturing firms today. A number of reasons account for this resistance. Cost-accounting procedures often fail to adequately consider the range of benefits provided by the technology so that payback periods seem too long or return-on-investment appears too low [40]. In many manufacturing firms, the technical and managerial staff lack sufficient knowledge of the new technology to suggest ways of adapting it to their own production system [18]. In addition, managers of manufacturing systems are rarely rewarded for the type of risk-taking that is necessitated by the introduction of hybrid systems [66]. Rarely are design engineers encouraged to design for manufacturability; thus, identifying well-defined families of parts which could be efficiently produced by the hybrid system becomes difficult [35]. Finally, hybrid systems often require interdepartmental coordination to develop common data bases, design for manufacturability standards, procedures for tool changing, maintenance, quality control,

inspections, and scheduling [24]. In general, most of today's manufacturing firms do not encourage such interdepartmental coordination.

Given the above reasons, it is clear that a series of changes within the organizational climate is a prerequisite when introducing hybrid systems. One such change is that management must encourage the innovation and a certain level of risk taking. This encouragement must be initiated at all levels within the organization and be consistent with the strategic vision of the company's future [71]. To ensure that operators accept the level of discretion in their jobs, the organizational climate must also become more participative in nature. That is, workers will be more accepting of these new job designs and technologies only if they have the ability to influence design and technical decisions [12].

In addition, for organization members to be more participative and discretionary, they must be well-informed about those aspects of the organization that influence their job performance [19]. In one organization, information about customer satisfaction and quarterly profits was routinely shared with the operators [55]. This form of external feedback becomes an important component of progressive improvement.

Finally, since hybrid systems rely on coordinated rather than individual activity, coordinated action must occur at all levels in the organization and not only at the operator level. This need for coordination in the managerial ranks has led to increased use of interdepartmental liaison devices such as task forces [15], CAD/CAM coordinators [45], plant operations committees [49], and matrix structures [45].

The hybrid system designer, therefore, must ensure that the system matches the organizational climate. If participation is not an important element of the organization in which the hybrid system is located, then the system may need to be designed to expect less worker discretion than ideally desired. Moreover, if there is little cooperation among the managerial ranks, cooperation can hardly be expected at lower levels. Thus, the manager of the hybrid system design could be at a crossroads: change the organizational climate or accept a less optimal hybrid system design. To ensure that the hybrid system matches the existing or desired organizational climate, the system designer must understand how specific technical features of the system being designed will impact the organization and its climate. Tools, such as the Human Infrastructure Impact Statement [45], [46] are currently being developed to aid designers in this capacity.

CONCLUSION

Broadly defined, hybrid systems are those that integrate capabilities of humans with computer-controlled machines for optimum system performance. Increased automation will involve more extensive use of software-controlled machines interacting with humans as supervisors, operators, system analysts, programmers, trouble shooters, maintenance, and technical managers.

Managers of high technology organization are increasingly making decisions which require engineering and technology based knowledge. This paper has raised several of the engineering issues as they concern the human component of

the hybrid systems. In raising these issues, this paper has identified several suggestions for the manager responsible for the design and management of human factors engineering of hybrid systems. These suggestions are summarized below.

The issue of reliability is an important design concern for hybrid systems to attain higher productivity and safe. Determining system reliability is more difficult for computerized systems due to a higher degree of complexity within the system hardware, software and human interactions. The need for higher system reliability has to be addressed as early as possible in the design of the system, particularly for software-dominant hybrid operations. A suggestion is for the managers to concentrate technical and managerial resources as early in the hybrid system development as possible. Design and operational retrofitting to increase productivity and safety in the later stages of system life cycle might prove untenable.

Productivity of a hybrid system is essentially composed of a synergy between machine production and human interfaces to optimize performance. Managers need to have a quantitative evaluation strategy for machine output versus the human cognitive workload requirements. Operators, faced with machine pacing and controlled supervision of computerized equipment, can be less vigilant, bored, or instantaneously overstressed. Efforts to design and provide an adaptive interface will be needed to adjust task loading and potential information-handling conflicts for system operators. For instance, today's hybrid robotic work cells are evolving into a cooperative problem-solving team. Physical tasks and activities are to be largely delegated to the robot while an intelligent human-robot interface would provide cognitive solutions safe and productive flexible work-cell operations.

This emphasis on cooperation should be extended beyond operator-machine interaction. Job responsibilities of categories of technical and support personnel need to reflect the requirements for an integrated and productive hybrid system. Operators should be more responsible for quality control and maintenance as well as production volume and schedule. This leads to higher degrees of job control discretion and autonomy for the operators which requires a broader and more flexible job classification.

These new job responsibilities require a different approach to selection, training, and retraining procedures. The selection criteria for operators of hybrid systems should emphasize cognitive and problem solving skills, human relations and team-playing skills, and ability to adjust to machine-pacing variables. The operator training should be a combination of in-house and external resources with emphasis on individual hands-on training for the entire manufacturing process.

With a shift in the importance of quality and reliability rather than quantity, new bases for hourly and salary pay are being established. Group pay schemes should be based on product quality, operator competence and profit bonuses. Job security and career progression are directly tied to the technical requirements of jobs within hybrid systems. Multiple job grades with intensive embedded training for promotion suggested as ways to increase the security and stability of these jobs.

The participative nature of many jobs with a hybrid system

operation requires that operators and engineers have the ability to influence decisions across different departments. This requires coordination of activities within all levels of the organization. Effective coordination is particularly important within the managerial ranks, where it is suggested that departmental liaisons, operations committees, and matrix organizational structures for activity coordination be utilized.

Clearly, an exhaustive description and elaboration of the complete hybridization process and its causal connections have not been developed in the present paper. For individual managers, many of the issues associated with the introduction of hybrid systems will be case-specific. The authors recognize that many facets remain to be fully identified, studied and applied when integrating new technology into current manufacturing environments. However, we have provided a framework in which such an attempt may be realized.

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