1 Human resources and system design

1.1 Concepts

1.1.1 The human contribution

The human role as a system controller

The business of designing machines, processes and systems can be pursued more or less independently of the properties of people. Nevertheless people are always involved, the designer himself is a human being and his product will shape the behaviour of many workers and other users. More fundamentally, the design activity will be meaningless unless it is directed towards serving some human need. In spite of all this, the design process itself is often thought about and executed without any formal considerations about people. Inevitably the engineer, architect or other designer devotes most of his attention and expertise to devising mechanisms, buildings and so on which support some human activity more effectively than those currently available. The new machine or system must not be very different from the old one for a variety of reasons. The old one did its job, not perfectly but well enough to justify its existence. The new one is usually designed on the basis of copying the old one but removing as many as possible of the faults. There are other reasons such as commonality of components and, of course, shortage of imagination which lead to most design and development being a progressive iterative process. This happens to suit the human operators because most of their skills will transfer along the line of development of the machines and systems.

From the engineering point of view the hardware technology is central and the operators tag along supporting the activity of machines which are basically doing the work. In nineteenth century transport for example, the coach and horses was not a serious competitor for the steam-engined train, nor was the man with a spade as productive as the operator with a steam shovel. This was the earliest technology in which power was derived from sources other than animal muscles and the output was so obviously superior that men did not mind putting up with the inconvenience of machines which were uncomfortable or awkward to use. They even took pride in developing new skills which enabled them to use difficult machines which inexperienced people could not use. This attitude was reinforced by the second wave of technology which provided instrumentation, ways of sensing and recording data which gave more accurate and reliable data than that which can be detected directly by the human senses. At this stage the typical machine operator manipulated machine controls on the basis of data presented on instruments. The machine controls caused power to be applied and consequences to occur which resulted in changed readings on the instruments. The man was in the control loop (Hick and Bates, 1950). More recently, in the third wave of technology the man has been removed from the responsibility for continuous control (this is best done by computers working to a moderately flexible range of programs) but he remains as the monitor of the system performance and a selector of the appropriate program determined by the changing short-term objectives. He may keep the responsibility for setting-up and shutting-down the system or this also may be partially delegated to computers. This is the 'Supervisory Control' role (Sheridan and Johannsen, 1976). Information flow in these three phases of development of system control is shown in Fig. 1.1

Supervisory control is by no means universal, in fact it remains restricted to high technology systems such as aircraft, computer controlled machine tools, chemical plants and power stations. (Edwards and Lees, 1974). There are still many systems where the man is in the control loop, for example in vehicle driving and in most manufacturing production processes. There are many tasks where the operator is assisted only by hand-tools and simple powered machines, for example in craft-work and surgery. There are also plenty of tasks, although these are now perhaps more common in leisure than in paid work, where the man supplies the muscle power, for example the manual labourer and the active sportsman.

In general, the working man may function at any level from the senior partner in high technology operations to the provider of muscle power in physically demanding jobs. In all cases the ergonomic requirement is that the task as designed should make use of his abilities and be adaptive to his limitations.

The human contribution in high technology systems

All working systems, including those incorporating advanced technology of processes and process control, depend on skilled operators. There are social, economic and technical reasons for this.

Socially the public will not easily accept automatic systems. When seeking reassurance that a system is safe they study the people who are responsible for it. They have no means of assessing the reliability of automatic control systems but they can make some assessment of a skilled individual and without

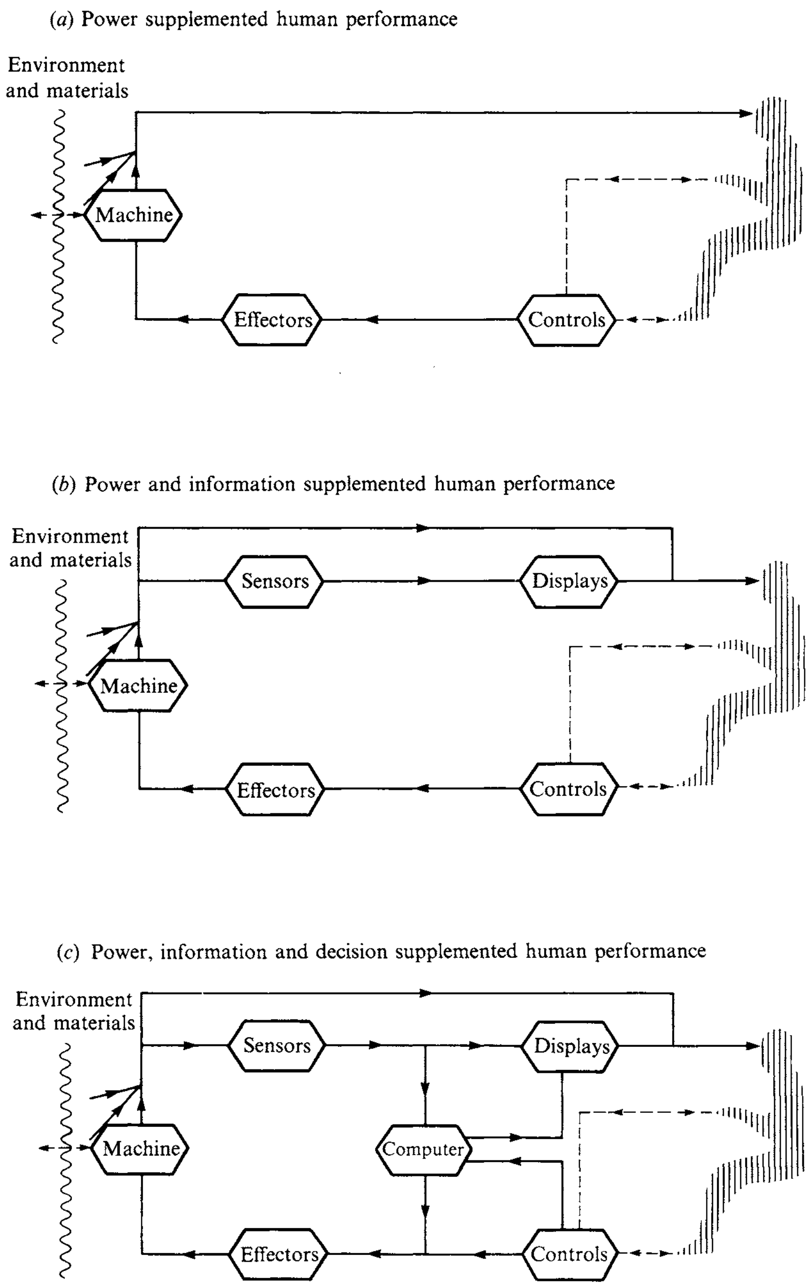

Fig. 1.1. The changing role of the human operator with technological development.

knowing very much about his working procedures they will trust his actions if he seems calm, competent and mature. The most direct example is the nervous airline passenger who is comforted by the belief that the middle-aged pilot he saw sitting on the flight deck is flying the aeroplane. Less directly but equally importantly, people living in the vicinity of a large plant would not take kindly to the idea that it was not under the control of human beings who are on the spot and are assumed to know exactly what is happening.

Economically it remains true that it is inordinately expensive to construct a system which must continue to be reliable without direct human intervention, for example under the sea or in space. Equally it is expensive to ensure that equipment will continue to function under rough handling conditions, for example the necessary 'ruggedising' of military equipment. A system can be designed much more economically if it can be assumed that skilled personnel are available to control and take care of it.

Technically the state of the art seems to be that systems are most efficient, reliable and safe when control is largely automatic but the human operator remains in a monitoring and supervisory role. That is, continuous dynamic dealing with minor perturbations is automatic and so also is the application of basic rules about safety; for example, the system or some part of it might be programmed to go through a step-change function such as a shut-down if certain parameters exceed prescribed limits. The role of the human operator in these circumstances is largely specified by operating instructions which are mandatory. Given this and this – he must do that. Characteristically his intervention in this way is a response to some other human requirement; for example, a maintenance man may wish to have a particular sub-system shut down for his attention or a user of the system product may wish to receive a different input to meet his purposes. Many of these interactions could be made automatic were it not for the basic need for a human presence for the social/economic reasons mentioned above and because the human operator has to act as the ultimate back-stop when things go badly wrong. Things go badly wrong when there has been some extreme untoward event such as a fire, an earthquake or a bomb, alternatively an unanticipated combination of faults may occur within the plant itself. In either case the human intervention must be a very high level one based on complex diagnosis and innovative design-type thinking about how best to cope so as to avoid a catastrophe. A catastrophe can happen when the system energy is no longer channelled as intended by the designers or because there is a release of toxic substances or both.

The demands on the operator stem from two kinds of task which are not compatible because they require very different levels of skill. On the one hand he must cope with routines where the demand is for precise obedience to established instructions and on the other hand he might suddenly be faced with a need to respond in a creative manner totally outside any instructions.

Superficially the solution would seem to be to have two kinds of operators, those who carry out the routines and others who are on call should unforeseen emergencies arise. There are two snags about this approach. Firstly there may not be time or it may not be physically possible to suddenly introduce a high level operator, for example we cannot put a different pilot on the flight deck when an aircraft gets into trouble. Secondly, the high level operator will not maintain his skill and familiarity with the system unless he operates regularly within it. His ability to intervene effectively must be a function of his 'hands on' experience supported of course by his conceptual knowledge of how the system functions.

This last proposition is based on experience of systems where the intervention requires complex manipulative activity, for example a surgeon dealing with an emergency during an operation or an aircraft pilot taking over manually. It is not so obviously true where the intervention takes the form essentially of a decision to initiate a single direct action such as closing a particular valve or starting up a stand-by pump. In these circumstances it is not clear whether or not the effectiveness of the intervention is quite so dependent on operating experience.

Taking for example the nuclear power plant control room, the question is whether the desk operators should be expected to cope with all emergencies which appear within the total information presentation or whether, for complex and dangerous situations, a more senior person such as the shift-charge engineer should be called upon to make the decisions. This policy issue must be cleared before the basic personnel decisions about selection and training of staff at the various levels can be made and before the information presentations can be designed.

The human contribution in low technology systems

The extreme case of man as a source of muscle power is dealt with in the previous book in this series – *The Body at Work*. Such working situations are now relatively rare in developed countries and the man is more usually employed in tasks where there is a considerable control element requiring extensive information processing. Such tasks range from the use of simple hand tools to tracking using complex powered machinery.

Human beings are needed for those tasks for a variety of reasons from their highly dexterous manipulative potential through to their ability to accept informal instructions. These reasons are given in detail in the discussion of man–machine function allocation (p. 35).

The demands on the human operator are difficult to quantify or even to describe because the process is essentially an interactive one. The skilled operator is working in harmony with his tools and machines. The concept of 'demand' is often not appropriate because it implies confrontation, the process is more aptly considered as one of cooperation and persuasion. The human operator is pursuing an objective, usually to make something or to go somewhere, and he achieves this with the assistance of the hardware at his disposal. This hardware, if it is well-designed, aids him in his progress toward his objective. There may be demands in the sense that there are always obstacles to be overcome but these stem from the nature and the variability of the situation he is in; that is, the materials he has to deal with or the environment he has to move through. The skilled operator will aim for efficient performance. Efficiency incorporates not only quantity and quality of achievement but also preservation of his own safety and health and that of others who might be involved as working partners, passengers or the general public in the neighbourhood.

Of course, if his tasks are badly designed they may well make unnecessary demands. These begin with bodily aspects of the operating posture required and the forces which must be exerted to operate controls. For a work-space which is used full-time very slight departures from the optimum may lead to problems in the long term, for example in strained ligaments, tendons and muscles. Posture is constrained not only by the physical dimensions of the work-space but also by the need to be in a position to see certain events and to feel others through control operations or machine movement. Other demands will arise if the information presented is inadequate in content, e.g. poor lighting may make it difficult to detect some relevant cues, or in structure, e.g. because of poor coding and presentation of information on dials, charts or screens. Correspondingly there may be output demands created by control operations which result in things happening too quickly or unexpectedly. The level of demand is to do not only with the tasks as they are done but also with the duration for which they must continue to be done. This applies particularly to routines and repetitive work where the main operator limitation is not capacity or skill but stamina.

In principle, repetitive work is best left to automatic machines but the flexibility of human performance is often needed because slight changes are required either to modify the product or to cope with different materials. Batch production work is often of this kind and in general it is by no means as unchanging or boring as it might appear to the casual visitor to the factory. In all the clothing trades for example there are continuous changes in sizes, materials, colours, styles and so on which provide the appropriate variety for the customers and incidentally for the producer. Work design must take account of the needs of the consumer as well as those of the worker.

Ergonomics and other aspects of technology

The technical specialist who represents the people point of view implicit in the approach just described is the ergonomist. In the previous book in this series the relationship of ergonomics to other aspects or kinds of technology was discussed in detail. The unique feature of ergomonics is its emphasis on the characteristics of human operators and their relevance to the design of work.

The role of the ergonomist is essentially an advisory one. In the case of high technology design he must provide a service for the engineers and scientists who carry the technical design responsibility. This service may simply be as a source of information or the ergonomist can have more power in that the design decisions involving people have to be approved by him. This is usually restricted to obvious cases of man–machine interaction such as the design of displays, controls and work-spaces. In the case of low technology design again he has an advisory role but with a general emphasis on awareness of the kinds and ranges of people who are being catered for. For systems which are already operating the ergonomist is likely to cooperate with occupational health and safety specialists and to play a part in the consideration of accidents and occupational diseases which might arise from unnecessarily stressful work situations (p. 294).

It will be appreciated that for most kinds of work and most working organisations it is not feasible to employ specialist ergonomists. In such cases those who have responsibilities for work design need to have some awareness of the principles of ergonomics.

The philosophy of work

Ergonomics is sometimes confused by questions such as, who is the ergonomist servicing – the employer or the worker? or, to whom is he ultimately responsible – the state, the employer, the producer or the consumer? Fortunately it is possible to dispose of these issues without taking up any particular political position. Ergonomics seems to flourish equally well in capitalist and socialist/communist systems, ergonomics activity can be sponsored with equal validity by employers organisations and by workers organisations.

This is because, as already mentioned, ergonomics is about efficient use of people. There can be no good reason to object to this when it is recognised that efficiency incorporates personal factors such as safety, health and quality of working life as well as system factors such as productivity and quality of work. There is rarely any conflict in that good ergonomics is in line with the objectives of the worker, the employer and the consumer or customer. There are sometimes larger issues of whether what the system does is acceptable or not, for example in weapon systems, and the ergonomist as a citizen will have his own opinion on these matters but the ergonomist as an ergonomist is confined to questions of efficiency.

There is an underlying necessary ethic which is best summarised as the social contract. An individual is a member of a community from which he obtains considerable benefits, in return he develops special skills which he applies for the benefit of the community. The application of special skills in this way is called work. The ergonomist has to believe that work is a good thing and that to conduct it efficiently is always better than to conduct it inefficiently.

1.1.2 The design of systems

The system concept

A system is a set of interacting parts which has meaning as a whole because it is possible to define a purpose – a reason why the parts are seen to be related to the whole and a justification for the concept of the whole (Singleton, 1974). Thus, systems theory is essentially teleological – explanations are in terms of consequences rather than causes. The parts may themselves be complex and may be conceived as having their own subsidiary purposes in confluence with the system purpose, these are sub-systems. The system in turn is part of a larger complex – the parent system. Thus, systems are hierarchical and at each level the unit is considered as a functional rather than a physical entity.

The systems approach is often a convenient way of looking at human behaviour either internally – this is man as a set of sub-systems or in terms of the man interacting with mechanisms – man–machine systems, or man interacting with organisations – socio-technical systems. The enormous flexibility of the systems approach has its penalties in potential confusion due to the highly variable relationship between functional and physical entities. Sometimes this relationship is fairly close; for example, in the nervous system, the endocrine system, the digestive system and so on, and sometimes it remains almost entirely unknown, for example, the perceptual system and the decision-making system. These last two are obviously each related to the nervous system and to the brain but not necessarily to a particular part of the brain and taken together they overlap in such obscure ways that they are best regarded as sub-systems in different domains, one can talk in terms of one or the other but not both simultaneously.

Systems theory is a useful way of identifying complex entities, particularly those which have a functional unity and of talking about relationships but it remains at some level of abstraction from reality. For example, to solve any design problem there has at some stage to be a switch from systems thinking to thinking in terms of physical entities because these are the things that can be created, precisely located and manipulated in the real world. Nevertheless, there are enormous dividends in being able to discuss functions independently of physical mechanisms and to explain relationships without being restricted to established and readily observable physical connections or separations.

For example, thinking of a power station as a way of translating energy from fuel into electric power enables the designer to consider various options. Should the fuel be of a fossil type such as coal or oil or should it be the radioactive elements in a nuclear reaction? When the heat has appeared how best should it be taken away – by pressurised water, by steam, by liquid sodium or by carbon dioxide? This heat has to be turned into mechanical energy, currently always by a steam turbine and the mechanical energy in a rotating shaft is then translated by a generator into electricity. The losses in this transfer of energy from one form to another can be calculated and the flow through the various sub-systems can be traced. The initial consideration of the power station as an energy processing system aids design discussions about the relative advantages and limitations of various mechanisms and their performance in practice. As the system operates it has to be controlled. The control of the flow of energy is partly through automatic servomechanisms and partly through human operations. The design problem of which does what is also best thought about initially in system terms. Distinct from the flow of energy the designer is, at this stage, thinking about the flow of information. Energy and information are processed by systems and sub-systems. In these terms, the human operator is a particular sub-system. Mechanical devices and human operators are not comparable physically beyond the mundane level of size but they are comparable as different sub-systems whose performance can be described and assessed in terms of the common metrics of energy and information. Hence the importance of systems concepts to ergonomics. If the human operator is to control functions within other sub-systems he must receive information about the system state through a man–machine interface. This interface takes its physical form in the control room. The control room is part of the communications channel between the human operators and the mechanisms and its design, as a man–machine interface, is one of the key ergonomics problems in power stations.

Office organisations also can be considered as systems. There will be certain physical mechanisms such as telephones, typewriters and computers but the flow of energy is trivial and the interest centres entirely on the flow of information. Consider, for example, a travel office. There is a vast amount of information available either in printed form or through computer networks.The objectives are to help members of the public to find their way through this information store and to transmit their orders for particular journeys or holidays to the providers of those services. The manager or designer of the office has to consider the various sub-systems he requires; one for dealing with enquiries, one for handling money, one for receiving new information, one for confirming orders and so on. The interface between the public and the information store is a counter manned by people. The counter assistants are parts of the interface. Information is exchanged verbally and through written documentation. In this kind of office the variety of requests for service is probably such that it would be necessary to provide a set of categories of the main kinds of activities or functions. It would then be possible to devise the appropriate system for presenting the required information. It is a very different situation from a power station control room but nevertheless the same principles of starting by the analysis of the required information apply.

The power station, the travel office and all other man-made systems have in common the employment of people so that sub-systems are required which are associated with personnel functions. It is necessary to attract and select staff, to train them, to provide them with various services and with potentiality for advancement as their skills increase with experience. The design of tasks is the common ground between personnel activities such as training and engineering activities such as workplace design.

Consideration of people in system terms provides the possibility of generalisations which apply across great varieties of physical and intellectual activities. The resulting knowledge is the content of ergonomics. Fig. 1.2 shows the outline of the systems design process in a way which emphasises the parallel roles of the engineer and the ergonomist concerned respectively with the design of the hardware and the personnel sub-systems and their common design problems of allocation of function and interface design.

The design of high technology systems

The insertion of an adequate Human Factors approach into a comprehensive design process is not easy, partly for the reason mentioned already that it has not habitually been regarded as necessary and partly because it cuts across all other decision-making. The Human Factors specialist can rightly be accused of wanting to have a finger in every pie because, as he sees it, behavioural considerations do affect every design decision. If ergonomics was confined to, say, the determination of the physical dimensions of the workspace then it would be more readily accepted by traditional designers, but the