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VIEWPOINTS ON THEORETICAL GROUNDS OF ERGONOMICS

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ABSTRACT

The man-machine system is a subsystem of the production process system. The man-machine system may be divided into its subsystems in a variety of ways. From the ergonomic viewpoint it is useful to make this subdivision such that it contains the systems of matter, energy, and information. This division has the advantage that it discovers in a clear-cut manner all the different material, energetic, and information exchange processes through which the man-machine system communicates with its environment. It also makes it possible to construct a distinct total description of the structure of the man-machine system and of the hierarchy of this structure. The man-machine system always has its spatial characteristics and its dynamics in time. In the system analytical approach it is important to pay attention to the structural time of systems. Man has his biological rhythm which is highly complicated, ranging from fractions of a second to periods covering years. The mechanical component of the man-machine system also has its functional rhythm, regular optimum timing of maintenance, etc. The fitting together of these two different structural times that takes place in the man-machine system has remained on a relatively mechanical treatment in ergonomics. As human work in the machine system becomes increasingly preplanned, as the machine component in automation becomes "independent" and its inner dynamics complicated, the problems in working rhythm, pauses, and working time in general occupy a central position which cannot be neglected in machine design.

The man-machine system has its objective efficiency. This efficiency is usually considered in the light of a crude and biased input-output approach. The input and the output can be very accurately designed for the mechanical component but changes in the human component are often not considered. Although the estimation and increasing of this efficiency is a highly difficult and complicated task, it should be one of the core problems in ergonomics.

Along with the development of the productive forces, with the accumulation of objectified human work, and with the increase in productivity, man becomes increasingly alienated from the immediate nature and lives among and in interrelationships with the products of his own labour. Man's environment becomes increasingly inorganic and societal. In addition to interpersonal transactions and communication, man may be met also in the products of labour. Since the functionings of the technical environment are mostly mechanic and electronic, their "behaviour" is dictated in a major part by the material conditions of their own. At the same time, man comes into contact with the compounds, energies and information of increasing complexity which are in a certain sense alien to his biological being and his consciousness. The characteristics of the technicalisation of the living environment are usually – and also in their coarsest form – first reflected in the working environment. The interactions themselves and the problems connected with them are however similar in essence in all the goal-directed activities where man is involved with objectified labour.

A system approach is applied in this presentation to the man-machine system (MMS) in a way that the immediate working environment is also included in the system. Subsystems of matter, energy and information are dealt with, as well as their dynamics within the whole system.

The systems of matter, energy and information are factually in tight interrelationships; in theoretical treatment they may however be abstracted into three systems. From the viewpoint of ergonomics this classification has heuristic value in that it provides a possibility to consider factors, that have traditionally been included in ergonomics or industrial hygiene, as parts of one dynamic system. The subdivisions may in systems approach be made in several ways but not arbitrarily; thinking has to correspond to the properties of the objective reality[6]. In the following I have used the basic properties of matter as the basic classification and as the foundation of the analysis. After treatment of the notions of matter, energy and information, the MMS is considered in the framework of space and time. This "structural" level leads eventually to a functional treatment of the system. The aim has been construction of such an approach which would make it possible to include labour safety perspectives in the technical and economic planning of the production process.

STRUCTURE OF THE MAN-MACHINE SYSTEM

The system of matter

Matter may in the inorganic part of the MMS exist in solid, fluid, gaseous or plasmatic form. The functions of the machines which shape and dress the object of work have been developed through mechanical and physical solutions toward chemical procedures. The chemical form of matter provides extraordinary possibilities to utilize automation and continuous processes. Biological labour is today used mainly in the foodstuff and pharmaceutical industries. Ecological considerations favour an increasing utilization of the biological processes.

The worker's contact with chemical compounds takes place through his skin and lungs, his outer covering. Eighty per cent of the chemical compounds enter the worker's organism during work through air impurities. Although the air space of the working post is usually not considered in the MMS, it has its essential function in it. Without breathing the biological subsystem of the MMS cannot function. Although this is a triviality, as many other occupational safety and health aspects, the human requirements of the air space and air quality are once and again neglected in the designing of industrial settings. On the other hand, the metabolic processes of the worker generate chemical impurities which have to be removed from the working space and substituted with clean air. It is consequently rational to consider the air space in the MMS, that is, to include it in the system, not in its environment. Keeping the work-space air sufficiently clean requires usually certain technical solutions. These bear distinct importance not only for the health of the worker but also for the efficiency of his work and for his attentiveness in spite of the fact that those technical solutions – e.g., general ventilation – with which the work-space air quality is regulated, are in a certain extent loose from the machine system itself.

The energy system

Similarly as man has during his biological development adjusted to a definable chemical composition of his air atmosphere, he has also adjusted to certain energy contents[4]. Since man's sensory modalities have been so developed that he receives the principal information he needs for his functioning through physical energies, these energies have an important role also in the information system. A certain natural variation exists in the energy atmosphere; it cannot however be great in order not to threaten man's health and the efficiency of his labour.

Also the mechanical component of the MMS is in an exchange of energy with the working environment. Save heat, it usually transmits (a) acoustic energy into the working environment to some extent; also (b) vibration through mechanical movement into those parts of the environment with which it is in an immediate material contact; eventually also (c) electromagnetic fields. In general, no systematic consideration has been given to the energy exchange between the system and the work environment in the planning of MMS's; instead, only those energetic events have been considered which immediately participate in the workout of the object of labour, or which are required in order to realize these events.

Thermal energy

Man's thermal regulation system is of central importance in the energy system. Man regulates his body temperature with external climatic conditions on one hand, and with his internal temperature on the other. Man is capable of adjusting "automatically" to certain changes in the climatic conditions by regulating the functioning of his organism. A long-lasting "abnormal" use of this regulation system however requires work; the strain of this work is subtracted from the general work efficiency and, further, leads to such mental reactions that affect the behaviour of the individual.

Disadvantageous climatic conditions cause, through reactions of the organism and through sensation, emotions and "alarm" the individual to correct his relationship with his environment by changing either his clothing or his environment. Man, however, has seldom this possibility when acting as a part of the MMS in the working process. Like in the chemical atmosphere, the climatic conditions – temperature, air velocity, relative humidity – may be regulated with ventilation which thus can be considered as a part of the MMS. Ventilation itself brings about a certain air movement in the work space.

Mechanical energy

Man does not act today as a mechanical power supply as he did earlier. The main energy needed in work is produced by the power system of the machine. Muscular output of human species is in the 1970's only about 1-2% of the inanimate energy consumption by humans. Since man transmits operative information to the machine mostly through mechanical energy, it follows that the work process in its present form contains certain mechanical work movements. Man participates in the energy systems of the MMS mainly through movements of the hands. It is important to note that hand movement is not – from the viewpoint of man – mere muscular activity but contains always informative and metabolic work in addition. Even when performing a simplest movement, man acts as a totality. Hand work includes, in addition to dynamic work, static work required by the maintenance of position. Hands being the part of the organism that immediately participates in the work process, man's working always requires, at least to some extent, also the movement of other organs. Even if work itself does not require it, man has to produce it at least for the sufficient functioning of his circulatory system and for the activation state of the CNS. There are also many tasks – especially in service work – where the main mechanical work is done with feet.

Acoustic energy

The vibration of the machine may be transmitted to the worker's hands or his whole body. Machine vibration also produces noise. Machine vibration is harmful not only to the human component of the MMS but also to the structure of the machine. Approximately 60 per cent of all the fractures of the metallic parts of the machines are fatigue fractures caused by vibration. Vibration is thus to be taken as waste energy considering the total system; its generation should be prevented and its dispersion blocked. Machine however usually has a considerably higher tolerance to vibration than man.

Vibration generates sound which is dispersed as waveform motion into the working environment. Since man utilizes sound as information carrier in speech, hearing has a central role in man's social interaction. A sufficiently long and intense exposure to sound causes permanent hearing impairment; depending on the nature of work and on the individual characteristics of the worker, even slight noise may strain him[5]. The acoustic information, as planned as a part of the MMS, is usually connected with warning signals; the worker obtains in many situations important information from the sounds of the running machine. The processing of such information may be part of his professional skill. In addition, noise may prevent hearing of sound signals that are significant to the work performance and thus render the latter difficult and promote work individuation, too[7]: "The aural feature of this work facilitates individuation. A high noise level is always present. The effect is, of course, to discourage communication and limit it to a few brief job-related remarks. It requires too much physical effort and time away from the machine for two operators to carry on a sustained conversation. Even if one were able to shout loudly enough, one runs risk of distracting another operator from her machine, since operators rely on the different sounds the machine makes at various points in the cycle as signals for making the changeover, as well as on sight."

It is therefore important that acoustic energy be treated as a part of the energy system of the MMS.

Other energies

The remaining energies include electromagnetic radiation and electromagnetic fields, pressure, electric current and electric charges, and static electricity. Lighting has a central role in the functioning of the MMS. The MMS has usually been planned for certain lighting conditions although the lighting equipment itself is usually added separately to the system.

According to the nature of work, recommendations can be given for general lighting. However, satisfactory lighting conditions are attained only by preplanning, as a part of the MMS. The lighting conditions cannot be considered separately from the size, colouring and shaping of the machines and other technical equipment.

With the exception of thermal radiation, all the electromagnetic radiation which is not used for lighting is unnecessary if not dangerous for man. The development of technology has introduced many highly dangerous radiations into the working process, for example, ionizing and microwave radiations. These man cannot sense; therefore the exposure is hard to be noted. On the other hand, exposure to radiation may have mutagenic effects. If ionizing radiation is used, man's immediate work process should be substituted with automated processes whenever possible.

The different forms of electric energy are usually connected with power transmission and control of the machine. Industrial electrification has made the insulation of man from the electric system of the MMS increasingly important. The use of plastics has also brought along an increased prevalence of static electric current. It is characteristic of the electric energy that it usually does not induce visible injuries save burns; the effects are either temporary or fatal. Chronic or psychological effects, however have not been investigated[2].

Information system

The information system may be considered in terms of its structure, or, in terms of what information is carried and processed. As referred earlier, the working environment bears an essential significance in the information system of the MMS. Except for the information mediated by the tactile sense, all the communication takes place through the working environment. The working environment thus adds necessarily its own entropy to the communication.

The effects of the working environment on the information system have not received a sufficient weight in the traditional MMS thinking where information exchange has been treated largely as empirical shaping and design of meters, dials and controls so that the operating errors be minimized. The information system however is usually not constant in the work site and thus it is not what it was originally planned. Except for the variation in the working environment, the effects of the functioning of the machine itself on the information system may also vary. It is indeed essential that the information system be planned with real situations in mind. Similarly, variation in the object of work and in the installation of the work equipment may alter the information system and introduce new requirements to it.

Focussing on the role of the working environment in the information system, the following conclusions seem central:

1. The information carriers in the information system are energies and matter. For the undisturbed functioning of man's sensory system, the matter and energy systems of the MMS have to be planned in such a manner that the information necessary both for man's work and for his vital functions is optimally achieved.
2. Man still transmits information to the machine almost exclusively by means of mechanical energy. The machine may change the information carrier, but the input of information must take place through mechanical motion.
3. Man has a limited capacity to receive and process information. His capacity is essentially dependent on the form as well as to which extent (as distributed to the different senses) a similar information content is given to him.
4. There are lags and entropies specific to the information exchange between man and machine. The machine processes information in a completely formal way, whereas man does it actively and in a goal--oriented way. This difference adds to a certain inconsistency present in the information system.
5. Man's consciousness is not a mere information system: it does not even in the MMS reduce to a part of the information subsystem of this larger system but rather stays social in nature. This has a bearance not only to man's well-being but also to the functional capacity of the MMS.
6. The uniqueness of each human organism always generates a certain variation in the MMS. Variability exists also within individuals; an individual produces background noise to the total system in the form of, e.g., tremor.

The foregoing applies especially to thê interactions between the information system and the working environment. Although man receives approximately

80% of his information in the work process through vision, the reception and processing of information has always a "wholeness" character in man[10].

Even when the lighting conditions are optimal, visual perception may be disturbed by unexpected sounds, vibration, etc. It is exactly the simultaneous use of several sensory modalities that guarantees the reliability of information exchange and the retention of the information. However, most of the questions pertaining to the information content and the social and psychological functions of information have been deliberately left outside the scope of this presentation.

Spatial characteristics of the man-machine system

The MMS always functions in a defined space and has its threedimensional spatial characteristics, which set up limiting conditions to the production space, to the layout plan of the production process, and to the dimensions of the working space. As the efficiency of the machine increases, the size of the machine usually becomes larger. On the other hand, with increasing amount of objectified labour, the measures of the productive fixed capital and its size requirements increase. The layout may be done according to the production line or in the form of a functional layout. The optimal space requirements can in both cases be rather accurately determined with systematic layout planning. In particular, the layout should meet the requirement that extensions can be realized in a meaningful way and that labour safety considerations are taken into account in the dimensioning of the space designed for the worker[12]. Different ergonomic recommendations and guidelines have been proposed for the spatial planning of the work space. They allow the MMS to be planned so that its spatial characteristics correspond to the dimensions and the movement paths of man. Attention can be given, for example, to the following factors: working in sitting or upright position, height of the working level, working region, reaching dimensions, watching distance, line of gaze, pedals, controls, etc.

The worker in the MMS needs to move outside his specific work post at least to some extent. In the automated production, in spite of the control rooms, both the operators and the repair personnel move around the space of the whole production process. Thus, even if the streamlining of the materials and energies were completely programmed and took place within a closed system, the space requirements of the human component of the system could pose quite a complex planning task. The average incidence of accidents increases during different disturbances, during production interruptions, and during maintenance, repair and adjustment – partially for the very reason that the adjuster's work has been forgotten in making the spatial solutions.

The spatial characteristics of the work post also have social functions. To cite Mulcahy and Faulkner[7]: "The space of approximately nine square feet where the operator stands to run her machine is socially "safe" space for her. When she is obliged to leave it, she is then "out of place". It is away from the machines, in the aisles, that most conflict takes place, rather than directly behind the machines. Any intrusion into this "safe" space, especially by management, is unwelcome and is greeted with hostility, since it constitutes an invasion of the operator's territory and of the operator-machine dyad."

FUNCTIONS OF THE MAN-MACHINE SYSTEM

The load on man in the MMS can be divided into the external load (stress) formed by the external loading factors (factors of the matter, energy and information systems)[6], and the internal load (strain) which is a function of man's individual characteristics and also of his past life process[4].

The objective stress factors and the work process itself thus generate in man processes which lead to strain. It is strain that causes health effects. An equal stress causes in different individuals different strains; in spite of all its subjective characteristics, however, it always has its objective basis. The direct and indirect strain effects and particularly their transformation into disease depend largely on how well the worker can recover from the effects of the stress during or after work, that is, to what extent the strain is reversible or, for that matter, irreversible in a positive, progressive sense.

The work process and strain always form an entity, a dynamic system. Work always has its clear goal. It is for this reason that the MMS is considered from the systems analysis angle. Noise, for example, affects not only man's ears, not even merely his hearing sense but the individual as a totality. There are no separate hearing or respiratory systems except as abstractions: they are part of man's vital functions. It is thus not reasonable to argue whether there are interactions between the different factors in the working environment and the work process; the exploration should concentrate on what these interactions are and whether they are significant enough to be taken into account in labour protection practice.

The MMS always functions in time according to a certain rhythm which is a function of both the technical parameters of production and of the vital functions of man. Man's organism operates in a rhythm that has been formed during his developmental history. Work strain is thus a function of diurnal time, age and sex, and season[3]. Usually the rhythm of the machine does not coincide with that of the human component of the MMS. The functioning of the machine nevertheless dictates largely the way the work has to be done; human vital functions have in an increasing extent to adapt to the machine rhythm. According to Tsaregorodtsev[11]: "As long as the rhythms of psychophysiological and technological processes more or less corresponded, it was sufficient to have "spontaneous" biological tuning of the organism to changes in technological and production processes. Now that there is a certain disharmony, however, with the former often lagging behind the latter, special measures must be developed to eliminate the undesirable effects of such lack of rhythm. Psychology, physiology and ergonomics now have the task of developing measures that would guarantee the correct correlation between psycho-physiological and technological rhythms without harming the health of the worker".

The rhythm of human vital functions is, on the other hand, strongly affected by such environmental factors as lighting, noise, thermal conditions, etc.[3]. Man is not a nocturnal animal; night work is from the biological viewpoint always a situation that destroys the natural rhythm of the functions of the organism. Whether direct symptoms of health impairment are observed or not is immaterial; the potential risk always exists, and the strain on the organism increases.

Although the length of the working day, its partition into sequences, and other timing of the work process have to a certain extent been constrained by the man's biological rhythm, the adaptation of man to the time of the industrial system has its dysfunctions. Different systems have structural times of their own[1]. Man's functional time is not the same as that of the machine system; two systems with different internal "clocks" must therefore be fitted to each other in the MMS. The machines should be constructed, when possible, adjustable to the time use, rhythm and tempo selected by the worker. In the fixed-speed work the situation is reversed, although some level of fitting together may be attained with preadjustment of the machine speed and with proper timing of its different functions. The further the machine system becomes "independent" and self--sufficient, and the further its cybernetic control develops, the more it operates on the time structurally characteristic to its own system. Since the number of means of production increases at the same time, the economic factors lead to the situation where man has to adjust to the time of the machine system. The technical systems of the process industry have circulation times, regular optimum intervals of maintenance and repair, etc. of their own. The adjustment of these into man's biological rhythm, is usually possible with timing arrangements concerning the workers, although these possibilities have their limitations.

In the planning and control of production, primarily the time required to finish a product is programmed and preplanned. If time-motion studies are used at the same time, the hand movements are at least in principle programmed with 0.036 second accuracy. Although the accuracy in real situations is considerably more modest, and although too accurate preplanning is not always even meaningful, the fact remains that the regulation of man's time use is continuously expanding. Since time use is of central importance in all the problems of production control, organization of production, work phase division, etc., it is feasible to evaluate to what extent the criteria of this planning are in concordance with existing psycho-physical knowledge of man's biological rhythm, of the work movements and of the time factors connected with perceptual tasks and sensomotor control of machines. Another matter of significance are the interrelationships between the distributions in time of performance capacity, fatigue, and setting of breaks.

Analysis of these factors would render it possible to set norms for absolute limits of the time functions of normal human performance, for example, how fast movements are absolutely outside normal human capacity, how break timing affects these limits, what are normal time minima of reception and processing of information. It would at least in principle be possible, based on this knowledge, to construct rough rules-of-thumb for the norm setting for work time, ranging from fractions of a second to days, as the basis for the preplanning of the timing of the production, and also as a basis for the evaluation of the feasibility of the present practices of production management.

DISCUSSION

The productivity of the MMS is usually treated in ergonomics either with mere output, or with input/output parameters as the criteria. This approach is easily misleading since it often neglects the facts that man is not just a part of the MMS but belongs to many other systems, and that factors outside work time exert a strong influence on the productivity of the MMS. Thus, particularly when there is a sufficient pool of cheap labour, the MMS is planned in the manner that the "wearing down" of man in this system is too fast for the reproduction of his capacities during or after work. The strain becomes easily exponential: the increase in output of the MMS causes a manifold increase in strain. The limit is quickly reached above which man's irreproducible reserves are used, or, at least such states are generated in the organism that the restoration of the "normal" state would take a long time. A narrow technical definition of the input/output ratio can in this situation lead to estimates of efficiency and productivity which give a biased picture of the real productivity of the system. The adoption of the time-motion studies leads often to fast working tempo and one-sided movements which cause the efficiency of the system to shift off of its optimum, although the productivity would superfluously seem to increase. From the production management point of view such "productivity" may turn profitable, but for the national economy it means direct "ravaging use" of the labour force. The worker is not in the position – not least because of his lacking economic possibilities to cover the increased costs of reproduction of his labour power – to recover from the work strains; the effects thus become irreversible. Similarly, fast monotonous work occupies such a large proportion of CNS work into keeping the alertness and vigilance at the required level that the share of this work, as related to the work factually directed to the shaping of the object of work, becomes significant. If a great deal of the worker's work is needed for "forcing" himself to the work performance, it becomes waste work and unnecessary use of energy, at least when compared to the kind of work that runs "naturally" due to its phasing, variability, motivation and interest. The efficiency decreases; the situation is in the long run not improved with artificial stimulants or drugs[9]. Also the stress of off-optimal thermal conditions, poor lighting, noise, etc. lowers the efficiency of the MMS. This has been shown and can be demonstrated with simple experiments. For example, the error rate increases exponentially when the temperature increases above the optimal region for the human thermal regulating system[9].

The work performance of the human component of the MMS reduces during the day shift after a peak at about 10 a.m. The form and slope of the decrease is strongly dependent on how the work breaks are arranged. It has been observed that the MMS is often loaded to such an extent that it is not meaningful even within the narrow interpretation of the efficiency[8]. Fatigue increases reaction times and error rates, as well as variation in the work performances. An optimum can thus be found beyond which the gain from the increased speed is compensated by a decrease in quality and by an increase of faulty products. Since the error rate is also dependent on the length of the working day, this optimum decreases during the day and is thus not constant. Even if the working tempo is speeded with the motivational incentive of piece-rate pay, the variation due to fatigue cannot be eliminated. Man is probably able to regulate this variation to some extent with his will power; the strain however increases still steeper, and, at least the potential for errors increases. This is extremely dangerous from the viewpoint of work safety. It is obvious that the highest productivity is in the long run reached on the condition that the MMS be loaded according to the real optimum of its efficiency. Overspeeding causes damage to both machine and man, although man has some capacity to restore his labour power and to prevent the damages from becoming irreversible. This efficiency can be altered by rearranging the total system, its components and their interrelationships; the existence of this efficiency is however and objective fact that cannot be circumvented and that must necessarily be taken into account in the planning of the MMS.

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