ERGONOMICS, 1991, VOL. 34, NO. 6, 671–686

Complexity, fuzziness, and ergonomic incompatibility issues in the control of dynamic work environments

WALDEMAR KARWOWSKI

Center for Industrial Ergonomics, Department of Industrial Engineering, University of Louisville, Louisville, KY 40292, USA

Keywords: Ergonomic theory; Human–machine systems; Entropy; Fuzzy set theory.

This paper explores some of the basic methodological issues related to the foundations of *ergonomics* as a science. In the first part, the modelling efforts in ergonomics research are reviewed. Next, the issue of fuzziness inherent to all complex human-machine-environment systems is discussed. Finally, the concepts of ergonomic system and its entropy are presented, and the principle of ergonomic incompatibility is formulated. It is proposed that the aim of the *science of ergonomics* is to identify, determine, and reduce the undesirable system's entropy. In this view, it is postulated that the basic aim of *ergonomics* is realized through the unique investigative process exploring the ergonomic system's incompatibilities.

1. Introduction

In the beginning there was chaos. There was also uncertainty due to the seemingly complex and threatening environments around the first human beings. Since the Prehistoric Time, people have tried to cope with these dynamic environments while striving for survival. People were also having their first encounters with the primitive hand tools they designed, built, and used for their living. It was then when the practice of ergonomics began. Although much has changed since those times, today, as in the Prehistoric Time, the human-made objects (systems) are also inherently *incompatible* with the very human nature defined in the perceptual, cognitive, physical, or behavioural terms.

The true phenomenon continuously changing, however, is the nature of incompatibility relation between the human and the sophisticated man-made tools within the context of complex environments. The ergonomic incompatibility, inherent to any small- or large-scale work systems where complexity of human–machine interactions introduces the natural factors of imprecision and fuzziness, becomes then the essence of scientific investigation in ergonomics. The field of ergonomics faces the problems of dynamic work system complexity and related fuzziness which tend to increase the ever present incompatibility between the workers and the workplace.

Since Wojciech Jastrzebowski of Poland (1857) defined ergonomics by joining two Greek words, *ergon*=work, *nomos*=natural laws, researchers have been looking for the fundamental laws based on which this developing discipline could be classified as a science. Jastrzebowski's concept of the proposed science relied upon the manner of utilizing four distinct characteristics of an animated nature, i.e., motor (physical), sensory (aesthetic), mental (intellectual), and spiritual (moral). The 'science of labour', therefore, signified the science of work, play, thinking, and devotion. One of the main ideas of Jastrzebowski's work was the proposition that human vital forces deplete and decline due to their excessive or insufficient use.

Although ergonomics can be treated as a science or technology, most ergonomists are unanimous as to the goal of applied ergonomics, i.e., the fitting of the task to the person (Grandjean 1987). But opinions vary as to the essence of ergonomic investigation. From the methodological viewpoint, ergonomics as a science is still in its early stage of development. As pointed out by Wilson *et al.* (1987), 'most of the well-known textbooks in ergonomics have largely ignored methodology, or have raised only certain methodological issues . . . '. There are only a few books related to the methodological problems in ergonomics, and they are devoted mainly to the research techniques and measurements. The basis for understanding the unique foundations of the science of ergonomics has not yet been adequately developed. The above difficulties and other related problems, which are important for understanding of the science of ergonomics, should be addressed from the perspective of methodology of science (Karwowski *et al.* 1988).

2. Modelling efforts in ergonomics

Human factors (i.e., ergonomics) is concerned with 'the consideration of human characteristics, expectations, and behaviours in the design of the things people use in their work and everyday lives and of the environments in which they work and live' (McCormick 1970). The 'things' that are designed are complex human–machine systems. 'Design' implies choosing of values for the design variables so that the system objectives, in this case fitting the task to a person, are optimized (Evans and Karwowski 1986). Hence the use of mathematical models in the design process becomes apparent.

2.1. *Mathematical models in ergonomics*

A model is a representation of a 'real system'. The key feature of a mathematical model is the use of symbols, equations, and other mathematical statements to represent reality. Because of the abstract nature of mathematics, mathematical models can be applied to a much greater variety of situations than either iconic or analog models. These models can usually be classified as being either normative or descriptive, multiobjective or single objective, dynamic or static, and stochastic or deterministic in nature.

Pew and Baron (1983) distinguished two basic approaches to human performance modelling, i.e., (*a*) psychologically-based models (reliability models, network models, information processing models); and (*b*) control-theoretic models for continuous control and control models for signal detection and decision-making. Normative models of performance, such as signal detection theory, optimal control, or Bayesian decision-making, play a very important role in workload measurement by specifying precise dimensions of performance, and the dimensions along which performance under workload may depart from a model-defined optimal level (Wickens 1979). Johannsen (1979) defends the use of formal mathematical models (classical and optimal control theory) in systems where the human is an element of a closed loop, and where single channel behaviour is known to be probable time line analysis (queuing theory, supervisory theory).

According to Harre (1972) there are two major purposes of models in science: *logical*, used to enable one to make certain inferences which would not otherwise be possible to be made; and *epistemiological*, used to express and enable us to extend our knowledge of the world. Thus, models are helpful for explanation and theory formation, as well as simplification and concretization. Zimmermann (1980) classifies scientific models into three groups: *formal* models (purely axiomatic systems with fictitious hypotheses; *factual* models (conclusions from the models have a bearing on reality and they have to be verified by empirical evidence); and *prescriptive* models which postulate rules according to which people should behave. The quality of a model depends on its properties and the functions for which the model is designed (Zimmermann 1985). In general, good models must have three major properties: formal consistency (all conclusions follow from the hypothesis); usefulness; and efficiency (the model should fulfil the desired function at a minimum effort, time and cost).

2.2. *Methodological challenges of ergonomics research*

Research on human–machine–environment systems poses an important methodological challenge (Topmiller 1981). This is due to the complexity of such systems, and a need for simultaneous consideration of a variety of interacting factors that affect several dimensions of both individual and group performance. Three general approaches used to study such systems can be distinguished, i.e.: (1) direct observations as a means of improving performance through modification; (2) the use of various analytical methods of modelling and fast-time computer simulation, especially in the conceptual design stages; and (3) the use of real-time simulation and manipulating various system parameters according to experimental design methods.

A review of the above approaches reveals two important methodological issues (Williges 1981). First, only a limited number of the existing variety of experimental design and analysis procedures have been used in complex system research involving human performance. Second, there is a lack of methodology for development of research techniques in the human factors area which would address complex system experimentation problems.

Research techniques applied in ergonomics about 30 years ago included the following: methods of direct observations (operator opinions, activity sampling techniques, process analysis, etc.; accident study methods (risk analysis, critical-incident technique; statistical methods; experimental methods (design of experiments); psychophysical methods (psychophysical scaling and measurement); and articulation testing methods (Chapanis 1959). Much progress has been made, as evidenced by comparison of these methods with the contemporary methods of human factors engineering, both in quantity and quality, in the development of new innovative techniques for the study of humans (Topmiller 1981). Yet, we are still at the beginning stage of building robust mathematical models for the analysis of complex human–machine systems. This is partially due to lack of appropriate design theory, as well as complexity of human behaviour at work.

Bernotat (1984) points out the non-existence of a human factors design theory, and cites as the main reasons for this situation the following: first, the human being is too complex a 'system' to be fully understood or describable in all his/her properties, limits, tolerances, and performance capabilities; second, no comprehensive mathematical tool has been available up to now to describe and integrate all the above mentioned measures and findings about human behaviour; and third, ergonomics is too young a science to have a real chance to develop the required theory. Chapanis (1959) argues that 'we do not have adequate methods for finding out all the things we need to know about people. Above all, we need novel and imaginative techniques for the study of man. This is an area in which behavioural scientists can learn much from the engineering and physical sciences.' This argument is still valid today.

Mathematical models in human factors suffer from the so-called 'measuring problem', which refers to descriptions of the varying task load, the social environment, the state of physical environment, measurement of human workload, design and measurement of the information flow, and status of the machine (Bernotat 1984). At present, only measurements of the state of physical environment and the status of the machine can be relatively easily performed. According to Sheridan and Ferrell (1981), 'engineering systems can be made compatible with human characteristics and limitations only by means of quantitative analysis and experiment, and only when the behaviour of both man and machine can be described in comparable terms'. Such comparable terms, applicable to the performance of both machines and human operators, are provided, for example, by three classes of models, i.e., information, control, and decision models.

Information processing models describe the probabilistic relationships between sets of inputs and outputs, and are based on the Shanon-Winer measure of information. Manual control models, based on control theory, treat the human operator as an integral part of a control loop in order to evaluate total human–machine performance. Such models are either linear or quasi-linear, and depending on the nature of the input to the human operator can be classified as compensatory, pursuit, review, or precognitive. Modelling of human decision behaviour is needed in order to facilitate the interface between the decision-maker and an engineering system, and to incorporate subjective knowledge, values and needs into the decision-making procedures.

One of the commonly used techniques for the design of engineering systems is simulation. According to Pritsker (1984), simulation is the representation of the dynamic behaviour of the system by moving it from state to state in accordance with well-defined operating rules. A key concept in the above definition is the idea of a system state. The system state is defined in terms of the numeric values assigned to the attributes (i.e., descriptors) of the entities (i.e., things) in the system. In some cases, these attributes can be viewed as output or performance variables of the system. In other cases the attributes can be viewed as being intermediate variables of the system.

The general classification scheme for simulation models/system concerns the types of attributes in the model/system. The model can be either discrete in nature, continuous in nature, or combined discrete/continuous, depending upon whether the attributes of the model are all discrete variables, all continuous variables, or variables which can change either continuously or discretely, respectively. Most of the simulation models built for manufacturing/production type purposes in general, and ergonomics, in particular, are discrete in nature (Evans and Karwowski 1986). Simulation modelling is sometimes used when no other modelling technique is appropriate. This can occur when the relationships between the input variables and the output variables are very complex, such as when these relationships cannot be written down in a functional form, or when there is a great deal of uncertainty in the output variable values for given input variable values.

3. Human factors: fuzzy factors

Although the usefulness of the mathematical language for modelling purposes in ergonomics is undisputed, there are limits of the possibility of using the classical mathematical language which is based on the dichotomous character of set theory to models in particular systems and phenomena (Zimmermann 1985). Such restriction applies especially to the human factors area due to vagueness of the natural language, and the fact that empirical research natural language cannot be substituted by formal languages. Furthermore, formal languages are rather simple and poor, and are useful only for specific purposes. Mathematics and logic, as research languages which are widely applied in natural sciences and engineering, are not very useful for modelling purposes in behavioural sciences and especially in human factors studies.

Ergonomics, defined operationally as an interdisciplinary study aimed at optimization of work systems with respect to physical and psychological characteristics of people, investigates complex and usually ill-defined (imprecise) relationships between workers, machines, and physical environments (Karwowski and Mital 1986). The main goal of such investigation is to identify and reduce the existing incompatibilities between human capacities and task requirements, and by doing so to make the workplace safe, healthy, and productive, as well as a comfortable and satisfying one. As observed by Oborne (1982), the human factors/ergonomics discipline arose as a response to the need to consider how the human operator manages to cope with his/her environment. From the very beginning, however, this objective has not been easy to fulfill for at least two main reasons. First, there is a natural imprecision and uncertainty inherent to complex human-centred systems; and second, there is a lack of research methodology which would allow one to account for, rather than disregard, the human- and system-based uncertainties in the analysis process.

Human-centred systems, which are the objects of ergonomics research, are very complex and, therefore, difficult to analyse. Furthermore, an ergonomist must deal effectively with at least three different types of uncertainty inherent to such systems; i.e., inaccuracy, randomness, and vagueness. Uncertainties due to inaccuracy are related to observations and measurements (representations), while those due to randomness (of events) are independent from observations and constitute an objective property of some real process (Bezdek 1981). Uncertainty due to vagueness (or fuzziness) has to do with the complexity of the system under investigation and the human thought and perception processes (Zadeh 1973). The last category of uncertainty is of utmost importance to human factors/ergonomics studies, and has to be taken into account more carefully (Karwowski and Mital 1986).

3.1. *The concept of fuzziness*

Fuzziness relates to the specific kind of vagueness having to do with gradations in categories, i.e., degree of vagueness (Smithson 1982). Uncertainty measured by fuzziness refers to the gradation of membership of an element in some class (category). Although such uncertainty arises at all levels of cognitive processes (Hersh *et al.* 1976, Kramer 1983), people have the abilities to understand and utilize vague and imprecise concepts which are difficult to analyse within the framework of traditional scientific thinking. Therefore, awareness of vagueness and inexactness, implicit in human behaviour, should be the basis of any human factors/ergonomics studies. Furthermore, ergonomists should learn and apply the mathematical tools for dealing with vague and imprecise concepts.

According to Zadeh (1965), the theory of fuzzy sets represents an attempt for constructing a conceptual framework for a systematic treatment of vagueness and uncertainty due to fuzziness in both quantitative and qualitative ways. Such framework is much needed in the human factors/ergonomics area. As pointed out by Singleton (1982), 'most human characteristics have very complex contextual dependencies which are not readily expressible in tabulations of numbers or even in multivariate equations'. Yet, there is growing evidence that people comprehend vague concepts, such as concepts of a natural language, as if they were represented by fuzzy sets and could be manipulated according to the rules of fuzzy logic (Oden 1977, Brownell *et al.* 1978). Moreover, recent research in semantic memory and concept formation (McCloskey *et al.* 1978) indicates that natural categories are fuzzy sets with no clear boundaries separating category members from non-members. One can certainly understand the meaning of such concepts as 'excessive workload', 'low illumination', 'heavy weight', 'high level of stress', and 'tall man', to name a few commonly used descriptors of the human–environment relationship.

As noted by Singleton (1982), 'no one has yet developed a comprehensive set of crude and approximate, but simple and inexpensive, techniques finding solutions to ergonomics problems'. Fuzzy set theory, which allows interpretation and manipulation of imprecise (vague) information and recognition and evaluation of uncertainty due to fuzziness (in addition to randomness), may be the closest solution to the above stated need available to ergonomists today. Formal treatment of vagueness is an important and necessary step toward more realistic handling of imprecision and uncertainty due to human and behaviour through process at work.

The theory of fuzzy sets may prove successful in narrowing the gap between the world of the precise or 'hard' sciences and the world of the cognitive or 'soft' sciences. This can be achieved by providing a mathematical framework in which vague conceptual phenomena, where fuzzy descriptors, relations, and criteria are dominant, can be adequately studied and modelled (Zimmermann 1985).

3.2. *Conventional versus fuzzy set theory and logic*

In a conventional (classical) set theory, an element x either belongs or does not belong to a set X, and the characteristic (membership) function f_x can be represented as follows:

$$\begin{cases} 1 \text{ if } x \in X \text{ (truth value}=1\text{: true)} \\ 0 \text{ if } x \notin X \text{ (truth value}=0\text{: false)} \end{cases} \tag{1}$$

The concept of fuzzy set extends the range of membership values for f_x, and allows graded membership, usually defined on an interval [0, 1]. Consequently, an element may belong to a set with a certain degree of membership, not necessarily 0 or 1. The 'excluded middle' concept is then abandoned, and more flexibility is given in specifying the characteristic function.

In view of the above, the mathematical logic can also be modified. Interestingly, the classical logic was actually extended as early as 1930 by Polish mathematician Lukasiewicz, who proposed the infinite-valued logic. As stated by Giles (1981), 'Lukasiewicz logic is exactly appropriate for the formulation of the "fuzzy set theory" first described by Zadeh; indeed, it is not too much to claim that is related to fuzzy set theory exactly as classical logic is related to ordinary set theory'. Fuzzy logic and fuzzy reasoning are described by Baldwin (1981).

A fuzzy subset A of a universe of discourse U (Zadeh 1965) is defined by a membership function f_A: $U \rightarrow [0, 1]$ which associates with each element u of U a number $f_A(u)$ in the interval [0, 1], where $f_A(u)$ represents the grade of membership of u in A. Formally, A can be written as:

$$A = \{(u, f_A(u)), u \in U\} \tag{2}$$

The support of A is the set of points in U at which $f_A(u)$ is positive. An α-level set of A

is a non-fuzzy set denoted by A_α which contains all elements of U whose grade of membership in A is greater than or equal to α. A is called normal if there is x such that $f_A(x)=1$. To simplify the notation, a fuzzy subset A with discrete membership function can be expressed as follows:

$$A=f_1/u_1+f_2/u_2+f_3/u_3+\ldots+f_n/u_n \qquad (3)$$

where f_i, $i=1, 2, \ldots, n$, is the grade of membership of u in A, and $U=u_1+u_2+u_3\ldots+u_n$. For the given fuzzy subsets A and B one can perform several basic operations, for example, the union of two fuzzy subsets A and B, denoted $A\cup B$; can be defined as: $f_{A\cup B}=f_A\vee f_B$, while the intersection of two fuzzy subsets, denoted $A\cap B$; can be defined as: $f_{A\cap B}=f_A\wedge f_B$, where $\vee$ and $\wedge$ denote MAX and MIN operators, respectively.

The linguistic characterization, one of the most important concepts of fuzzy set theory, uses a linguistic variable with values which are not numbers but words (or sentences) of a natural (or artificial) language (Zadeh 1975). A linguistic value is interpreted as a label for a fuzzy restriction on the values of the base variable. The fuzzy restrictions on the values of the base variable are characterized by the compatibility functions. Each such function associates with each value of the base variable a number in the interval [0, 1] representing the compatibility with the fuzzy restriction. Typical values of the linguistic variables comprise of primary terms (like 'low' or 'average'), hedges: 'very' or 'more-or less'; fuzzy connectives: 'and', 'or', and the negation 'not'. The hedges, connectives and negation are used as modifiers of the operands (primary terms) in a context-dependent situation.

3.3. *Fuzziness and ergonomics research*

Contemporary research techniques in the human factors/ergonomics area are based on the premise that if the uncertainty exists, one must restrict the model to eliminate, rather than incorporate, as much of it as possible. Such a premise is a consequence of adapting quantitative methods of analysis directly from physical sciences (Zadeh 1975). As pointed out by Lord Kelvin in the nineteenth century, '... a first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it'.

Traditional scientific thinking, based primarily on the Aristotelian logic is oriented towards exact, quantitative methods of analysis. Such methods (and corresponding models) equate uncertainty with randomness only and fail to recognize human- and system-based uncertainties due to vagueness. According to the principle of fuzzy incompatibility formulated by Zadeh (1973), at a high level of system complexity, the precision and significance (of the statements about the system's behaviour) become almost mutually exclusive characteristics. Therefore, an attempt to make precise and yet significant statements about the complex relationships between people, machines, and environments may be an illusive task, and the traditional modelling methods may not have much relevance here (Karwowski and Mital 1986).

A new methodology in the area of human factors/ergonomics is needed to account for imprecision and vagueness of such relationships. Zadeh (1974) points out that 'Although the conventional mathematical techniques have been and will continue to be applied to the analysis of humanistic systems, it is clear that the great complexity of such systems call for approaches that are significantly different in spirit as well as in substance from the traditional methods—methods which are highly effective when applied to mechanistic systems, but are far too precise in relation to systems in which human behaviour plays an important role'. Furthermore, as the author points out, 'in order to be able to make significant assertions about the behaviour of humanistic systems, it may be necessary to abandon the high standards of rigour and precision that we have become conditioned to expect of our mathematical analyses..., and become more tolerant of approaches which are approximate in nature'.

The above points of view were also shared by such philosophers of science as Schwartz and Popper. According to Schwartz (1962), 'an argument, which is only convincing if it is precise, loses all its force if the assumptions on which it is based are slightly changed, while an argument, which is convincing but imprecise, may well be stable under small perturbations of its underlying axioms'. Popper (1974) advocated that both precision and certainty are false ideals which are impossible to attain, and therefore often misleading if accepted as guides. According to the philosopher, 'The quest for precision is analogous to the quest for certainty, and both should be abandoned'. Zimmermann (1985) indicates that real situations are very often not crisp and deterministic, and they cannot be described precisely.

Most of the traditional human factors methodologies show an intense disregard for system complexities, and assume that the formal properties of mathematics (usually statistics) correspond to some existing relationship characteristic to the system under investigation (Zadeh 1974). For example, an uncertainty due to vagueness is often modelled (if not disregarded) as being of stochastic nature. One should notice that such treatment appears to defeat the purpose of any formal systems' analysis and modelling efforts. According to Karwowski and Mital (1986), regardless of the level of human work, at least three types of fuzziness are present and should be accounted for in the human–machine–environment systems, i.e.: (*a*) fuzziness stemming from our inability to acquire and process adequate amounts of information about the behaviour of a particular subsystem (or the whole system); (*b*) fuzziness due to vagueness of the relationships between people and their working environments, and complexity of the rules and underlying principles related to such systems, and finally; (*c*) fuzziness inherent in human thought processes and subjective perceptions of the outside world.

Uncertainty (looked upon in the context of mental workload) which causes unpredictability in one's stimulus and/or response, enters a work situation from several sources (Audley *et al.* 1979). These are varying parameters of the system structure external to the human operator, human-produced noise in observing the task stimuli, lack of good internal model of the external system, human-produced distortions in interpreting the externally stipulated criterion of performance, and human-produced motor noise. In view of the above, the theory of fuzzy sets offers a useful approach when the task demands are vague, with the main advantage being its ability to model imprecise task situations and, therefore, a potential to develop a framework for implementation of complex workload measures.

As suggested by Smithson (1982), the potential advantages for applications of a fuzzy approach in human sciences, and therefore, human factors are that, first, fuzziness, itself, may be a useful metaphor or model for human language and categorizing processes; and second, fuzzy mathematics may be able to augment conventional statistical techniques in the analysis of fuzzy data. The author reviewed several alternative methods for the analysis of fuzzy data (like measure of intercategory overlap, equivalence, etc.) and concluded that fuzzy methods are useful supplements for statistical techniques such as reliability analysis and regressions, and structurally oriented methods such as hierarchical clustering and multidimensional scaling. More theoretical and experimental research should be carried out to explore potential application for fuzzy set methods, especially in combination with other analytical techniques.

3.4. *Examples of early applications of fuzzy set theory in human factors research*

The theory of fuzzy sets has been successfully applied in the modelling of ill-defined systems in a variety of disciplines (cognitive psychology, information processing and control, decision-making sciences, biological and medical sciences, sociology and linguistics, image processing and pattern recognition, and artificial intelligence). At present, there are also many applications of fuzzy methodologies applications in human factors.

Terano *et al.* (1981) introduced a fuzzy set approach into fault-tree analysis, and studied the fuzziness of a human-reliability concept from the human–machine systems safety point of view. Kramer and Rohr (1982) developed a fuzzy model of driver behaviour based on simulated visual pattern processing in lane control. Saaty (1977) distinguished two types of fuzziness in lay perception (for example, perception of illumination intensity) and fuzziness in meaning, advocating that fuzziness is a basic quality of understanding. Hirsch *et al.* (1981) used a fuzzy dissimilitude relation to describe human vocal patterns. Simcox (1984) used the linguistic approach to devise a method for pragmatic communication in graphic displays. The proposed model involves determining a compatibility function that describes the degree of correspondence between an implied attribute of the display and the linguistic category that summarizes values of this attribute.

Willaeys and Malvache (1979) investigated the perception of visual and vestibular information in a 'watch-and-decide' or industrial inspection (control) task. The imprecise nature of the human problem-solving procedures was related to the 'shaded' strategy of the operator's perception and to the 'hard-to-predict' environment of the human–machine environment. The labels of fuzzy sets used by the operator to describe different physical variables of the task were identified, and the fuzzy model of the process-control task was formulated. It was concluded that the fuzzy treatment of the operator's subjective information allowed the modelling of this complex system.

Benson (1982) developed an interactive computer graphics program for analytical tasks which are not well defined or utilize imprecise data. Colour scales were used to model subjectively defined categories under investigation. The use of a linguistic approach allowed the identification of membership for different categories of description of visual inspection. The perceptual properties of colour proved to be useful in selective focus attention and in distinguishing or disregarding variations between imprecisely defined categories.

Karwowski and others (1983, 1984, and 1984) developed a fuzzy set based model to assess the acceptability of stresses in manual lifting tasks. Measures of acceptability were expressed in terms of compatibility functions which described the degrees to which the combined effect of biomechanical and physiological stresses were acceptable to the human operator. The combined acceptabilities of a lifting task were similar to the subjective estimations of the overall task acceptability established by the subjects in a psychophysical experiment. Recently, Luczak and Ge (1989) applied fuzzy modelling to investigate the relations between physical weight and perceived load heaviness.

In the area of human decision-making, Hunt and Rouse (1984) proposed a fuzzy rule-based model of human problem-solving in the fault diagnosis tasks. The model was validated using a simulated fault diagnosis task (FAULT) for trouble-shooting in the functional network diagrams of six different automotive and aircraft systems. Onisawa (1988) developed several fuzzy concepts to improve the studies of human reliability issues. Recently, Karwowski *et al.* (1990) developed a framework fuzzy GOMS model for studying human–computer interaction on the text-editing task.

As early as 1959, before Zadeh (1965) published his first paper on fuzzy sets, Helmer and Rascher (1959) had indicated a need for the new reasoning procedures that would be tailored to the domain of the inexact sciences, i.e., sciences where reasoning is informal, terminology at times exhibits inherent vagueness, and reasoning may rely on reference to intuitively perceived facts. Clearly, inexact sciences, which do not make predictions with great precision, include human factors studies.

Fuzzy set theory, concerned with mathematical representation and manipulation of degree vagueness, is a powerful tool for the analysis of human work systems. Such systems are complex, their underlying structure and governing relations are not precisely known, its descriptions are generally linguistic in nature, and definitions of many variables and several concepts are vague. Human factors researchers must look into the enormous potential offered by fuzzy methods and fully explore their applications in the analysis of ergonomics systems.

4. Methodological basis of ergonomics

It is widely accepted today that ergonomics, although interdisciplinary in nature, is a separate scientific discipline, and ergonomists have a unique way of scientific thinking and practice (Singleton 1982). Some feel that ergonomics is essentially a science because of the object of investigation alone. Unfortunately, the methodological basis of ergonomics, which is critical to the evolution of ergonomics *as a science* (Kuhn 1974), has been largely ignored. This section of the paper explores some of the basic methodological issues related to the foundations of ergonomics as a science. In particular, the concepts of ergonomic system and its entropy are presented, and the principle of ergonomics incompatibility is formulated.

As discussed by Karwowski *et al.* (1991), the methodological foundations for the science of ergonomics, focus, among other issues, on the following questions. What is the object of the science of ergonomics? What is the ergonomic reality considered by ergonomics scientists? What is the structure of the investigative process in ergonomics? Some of the questions are addressed below.

4.1. *Ergonomic system*

An ergonomic system (ES), as a generalization of the concept of human–machine–environment system (HMES), consists of the human elements (H-subsystem), machine elements (M-subsystem), environmental elements (E-subsystem), and the ergonomic interactions (I-subsystem) as relations between these elements and time (T). The ergonomic system can then be described using the following notation:

$$ES = \{H, M, E, I, T\} \tag{4}$$

where:

$H = \{h_1, h_2, \ldots h_i\}$ = human elements
$M = \{m_1, m_2, \ldots m_j\}$ = machine elements
$E = \{e_1, e_2, \ldots e_u\}$ = environmental elements
$I = \{i_1, i_2, \ldots i_n\}$ = interactions, and
T = time.

Each interaction (i_j) reflects the existence or non-existence of the relationships between the relevant human (H) characteristics (such as physiological, biochemical or psychological), the ergonomic characteristics of a machine (M), and elements representing the environmental (physical and social) conditions (E). Each of the above elements can be simple or complex. For example, h_1 may represent simple reaction time, while h_3 may reflect a particular type of personality. Similarly, m_2 may relate to a certain type of switch control, while m_5 may represent the physical layout of all controls. Likewise, e_7 may denote dry bulb temperature, while e_{10} may represent the WGBT index (Karwowski *et al.* 1991).

4.2. *Entropy of the ergonomic system*

An ergonomic system can be characterized by the levels of its entropy. In general, an entropy is interpreted here as the dynamic deterioration of the state of *ideal* ergonomic interactions (zero level of the undesirable entropy) to an ultimate ergonomic inefficiency of the system. The total entropy of the ES is determined by the individual entropies of its human, machine, and environmental subsystems, and by the entropies of the interactions between their elements. The total entropy of an ergonomic system is dependent upon the number and structure of all the interactions characteristic for each state of the system. The entropy of each individual event depends upon the variety and complexity of all relevant interactions.

For each ES there exists a minimum level of entropy called the ergonomic entropy (EE) of the system. The EE is determined by (1) the entropy of the *ideal* human elements of the system, and (2) by the entropies of the *ideal* machine and environmental elements which are perfectly compatible with the human elements. The amount of entropy which is greater than the ergonomic entropy is called an undesirable entropy (UE) of the system.

An ergonomic system as described above has three basic properties (Karwowski *et al.* 1991). First, the total entropy (TE) of the system is a sum of the system's ergonomic entropy (EE) and its undesirable entropy (UE). Second, the ergonomic entropy (EE) of the (ES) is *non-reducible*. Third, the undesirable entropy (UE) of the ES is reducible, and therefore, should be an object of the ergonomic intervention.

One might think that one of the simple ways to reduce the entropy of a given interaction is to reduce the number of relevant machine elements to one. Unfortunately, such an approach could result in an increase, rather than decrease, of the system's entropy. This is because the reduction of certain elements of the given process causes an automatic introduction of other system's elements, i.e., human elements of high complexity, and may lead to an increase in the overall system's entropy. This simple example illustrates that manipulation of any one part of the ergonomic system results in often unforeseen changes in the number and/or structure of the other interactions, and, therefore, may change the system's entropy in an unpredictable manner.

4.3. *The purpose of ergonomics*

In view of the above discussion, the purpose of ergonomics as a science, is *to identify, select and structure all possible elements of H, M, and E subsystems so that the interactions between their elements occur in a state of minimum entropy* (i.e., ergonomic entropy of the system). Therefore, the primary objective of ergonomics is to reduce the level of undesirable entropy of an ergonomic system (Karwowski *et al.* 1991).

Ergonomic entropy constitutes an ideal lower limit of the total system's entropy, which seldom can be achieved practically. The ergonomic investigative process leads toward reducing the undesirable part of the total system's entropy. In practice, it would be very difficult to calculate an entropy of the ergonomic system. In fact, this could only be done by accepting a multitude of simplifying assumptions regarding the structure of ergonomic interactions, especially those related to the human elements. For example, an interaction which involves only two human elements, i.e., an eye and a hand, only seems simple. The process of signal perceptions, information processing, and movement construction are of multidimensional nature, and each dimension requires separate processing and movement construction reflected in the individual's level of training, movement abilities or personal characteristics. The complex subsystem of human elements and the relations between them is, then, the basis for a response to the simple stimulus (Karwowski *et al.* 1988).

4.4. *The principle of incompatibility*

The calculation of entropy of the real ergonomic system is also difficult, if not impossible, due to the investigator's inability to identify, recognize, and measure all relevant human elements and the related interactions. Therefore, ergonomics employs another way of describing and investigating an ergonomic system. Such an alternative approach is based on the concept of *natural incompatibility* between the human, machine, and environment subsystems. The above led us to the formulation of the main principle of the science of ergonomics, that is the *principle of ergonomic incompatibility* (Karwowski *et al.* 1988).

The natural incompatibility between human and machine/environmental subsystems is understood here in a common sense only. In order formally to utilize this concept in light of the scientific investigative process, and to explain the relationship between the system's entropy and incompatibility, we also introduce the concept of *ergonomic incompatibility* (EI).

Ergonomic incompatibility (EI) is the degradation (disintegration) of the ergonomic system reflected in the system's measurable inefficiency and associated with human losses. The following are the three main properties of the ergonomic incompatibility: (1) EI is identifiable and recognizable on the level of ergonomic interactions; (2) EI is measurable, based on the variables of the subsystem of H elements; (3) EI is related to undesirable entropy of an ergonomic system by way of homomorphism, i.e., the changes in EI exhibit the same pattern as changes in the UE; and (4) EI can be reduced by altering the interactions between the human, machine, or environment subsystems.

As proposed by Karwowski *et al.* (1988), the aim of the science of ergonomics is to identify, recognize, determine, and reduce the undesirable system's entropy. The object of ergonomic investigation is the ergonomic incompatibility. The basic aim of ergonomics is realized through the unique investigative process exploring the ergonomic system's incompatibilities.

5. The ergonomic system and the science of ergonomics

In summary, the ergonomic system is a construct developed for the purpose of scientific investigation of human work systems. The system contains the human, machine, and environmental elements and all the (ergonomic) interactions occurring between these elements in time. The total entropy of the ES is determined by the individual entropies of the human, machine and environmental components, and by the entropies of the interactions between them. Thus, the entropy attributable to the entire ES is due to the entropies derived from each of its interdependent elements. Such entropy is interpreted as the extent of deviation from the state of ideal ergonomic interactions (I) to the level of ultimate system inefficiency.

5.1. *Ergonomic entropy (EE) of the ergonomic system (ES)*

For each ES there exists a minimum level of entropy of the system called the ergonomic entropy (EE) of ES. Such EE is determined by (1) the entropy of the human elements of the system, in terms of deviations from the humans ideally suited by their sensory, mental and physical makeup for interaction with the remainder of the particular system; and (2) by the entropies due to machine and environmental elements which are not perfectly compatible with the human elements of the system.

5.2. *Undesirable entropy (UE)*

As discussed above, undesirable entropy (UE) of the ergonomic system is a portion of the total system's entropy which exceeds the level of EE. An ergonomic system as described above has three basic properties with respect to the system's uncertainty. First, the TE of the ergonomic system is the sum of the system's EE, and its UE. Second, the EE of the ES is non-reducible. Third, the UE of the ergonomic system is reducible, and constitutes the goal of ergonomic practice.

5.3. *The investigative process in ergonomics*

As proposed above, the following properties of ergonomic incompatibility suggest how such incompatibility can be identified, measured and reduced: (i) ergonomic incompatibility is identifiable and recognizable on the level of ergonomic interactions; (ii) ergonomic incompatibility is measurable based on the variables of the subsystem of H elements; (iii) ergonomic incompatibility can be reduced by altering some or all of the relevant interactions between the ergonomic system elements, i.e., the human, machine, or environmental subsystems, and (iv) EI is related to UE of an ES by way of homomorphism, i.e. the changes in EI of the ES exhibit the same pattern as changes in the UE.

From the operational point of view, the principle of ergonomic incompatibility is much more convenient to use than the ergonomic entropy. According to the second property, all measures of incompatibility can be based on the variables from the subsystem of human elements. The homomorphism property transforms the zero-level of undesirable entropy into the zero-level of ergonomic incompatibility, as well as the real (but unknown) level of the system's undesirable entropy into its estimated ergonomic incompatibility.

In the first stage of the investigative process in ergonomics, i.e., the stage of identification of ergonomic incompatibility, the current ergonomic knowledge is used to formulate problems regarding ergonomic incompatibility. The rules of ergonomic incompatibility are developed at the second (recognition) stage of the investigative process, i.e., recognition of ergonomic incompatibility. In the final stage of ergonomic investigation process, the practical principles for reduction (determination) of ergonomic incompatibility are prepared. These principles can then be applied on the factory floor by industrial engineering methods (Karwowski *et al.* 1991).

The complex interactions of the ergonomic system appear more frequently than simple interactions. An appropriate investigative process which finally elaborates the principles for minimizing the ergonomic incompatibility of the system starts with a good description of the above interactions, i.e., identification of the ergonomic incompatibility. The science of ergonomics should aim to formulate rules underlying such interactions, i.e., recognition of ergonomic incompatibility.

The degree of success in the above process, however, depends upon the efficiency of the whole investigative process, i.e., the scientific cognition. Therefore, if practical implementation of the ergonomic design data, i.e., the principles of reduction and of the ergonomic incompatibility, is based on the erroneous scientific process, the ergonomic incompatibility of the system may not necessarily decrease as the consequence of ergonomic intervention realized through 'fitting the task to the person' concept.

6. Conclusions

Since fuzziness plays an essential role in human cognition and performance, more research is needed to fully explore the potential of this concept in the area of human factors. It is believed that the theory of fuzzy sets and systems will allow one to account for natural vagueness, non-distributional subjectivity, and imprecision of human-centred systems which are too complex or too ill-defined to admit the use of conventional methods of analysis.

This paper offers some preliminary concepts and insights into methodological basis of the science of ergonomics. The proposed concept of ergonomic incompatibility allows to formulate the object of ergonomic investigation and define the aim of ergonomics as a science. In this view, the object of ergonomic investigation is the ergonomic incompatibility. The aim of the science of ergonomics is to identify, determine, and reduce the ergonomic incompatibility.

Acknowledgements

The author would like to acknowledge co-operation of Professor T. Marek and Dr C. Norworol from the Jagiellonian University at Krakow, Poland, in formulating the methodological basis for the science of ergonomics as presented in this paper. This work was supported in part by the Fulbright Scholarship at Tampere University of Technology, Finland, 1990.

References

AMSTERDAMSKI, S. 1975, *Betwen Experience and Metaphysics* (D. Reidel, Boston).

AUDLEY, R. J., ROUSE, W., SENDERS, T. and SHERIDAN, T. 1979, Final report of mathematical modelling group, in N. Moray (ed.), *Mental Workload: Its Theory and Measurement* (Plenum Press, New York), 269–285.

BALDWIN, J. F. 1981, Fuzzy logic and fuzzy reasoning, in E. Mamdani and B. Gaines (eds), *Fuzzy Reasoning and Its Applications* (Academic Press, London).

BENSON, W. H. 1982, Applications of fuzzy set theory to data display, in R. R. Yager (ed.), *Fuzzy Sets and Possibility Theory* (Pergamon Press, New York).

BERNOTAT, R. 1984, Generation of ergonomic data and their application to equipment design, in H. Schmidtke (ed.), *Ergonomic Data for Equipment Design* (Plenum Press, New York), 57–75.

BEZDEK, J. 1981, *Pattern Recognition with Fuzzy Objective Function Algorithms* (Plenum Press, New York).

BROWNELL, H. H. and CARAMAZZA, A. 1978, Categorizing with overlapping categories, *Memory and Cognition*, **6**, 481–490.

CHAPANIS, A. 1959, *Research Techniques in Human Engineering* (The John Hopkins Press, Baltimore).

EVANS, G. and KARWOWSKI, W. 1986, A perspective on mathematical modeling in human factors, in W. Karwowski and A. Mital (eds), *Applications of Fuzzy Set Theory in Human Factors* (Elsevier, Amsterdam), 3–28.

GILES, R. 1981, Lukasiewicz logic and fuzzy set theory, in E. H. Mamdani and B. R. Gaines (eds), *Fuzzy Reasoning and Its Applications* (Academic Press, London).

GRANDJEAN, E. 1988, *Fitting the Task to the Man* (Taylor & Francis, London).

HARRE, R. 1972, *The Philosophies of Science* (Oxford University Press, London).

HELMER, O. and RASCHER, N. 1959, *Management Science*, **6**, 25–52.

HERSH, M. M. and CARAMAZZA, A. 1976, A fuzzy set approach to modifiers and vagueness in natural language, *Journal of Experimental Psychology: General*, **105**, 254–276.

HIRSCH, G., LAMOTTE, M., MASS, M. T. and VIGNERON, M. T. 1981, Phonemic classification using a fuzzy dissimilitude relation, *Fuzzy Sets and Systems*, **5**, 267–276.

HUNT, R. M. and ROSE, W. B. 1984, A fuzzy rule-based model of human problem-solving. *IEEE Transactions on Systems, Man and Cybernetics*, **SMC-14**, 112–120.

JASTRZEBOWSKI, W. 1857, Rys Ergonomji, czyli Nauki o Pracy [in Polish], in *Ergonomia*, 1979, **2**, 13–29.

JOHANNSEN, G. 1979, Workload and workload measurement, in N. Moray (ed.), *Mental Workload: Its Theory and Measurement* (Plenum Press, New York), 3–11.

KARWOWSKI, W. 1983, A pilot study on the interaction between physiological, biomechanical, and the psychophysical stresses involved in manual lifting tasks, in K. Coombes (ed.), *Proceedings of the Ergonomics Society Conference* (Taylor & Francis, London), 95–100.

KARWOWSKI, W. and AYOUB, M. M. 1984, Fuzzy modelling of stresses in manual lifting tasks, *Ergonomics*, **27**, 641–649.

KARWOWSKI, W. and MITAL, A. 1986, *Applications of Fuzzy Set Theory in Human Factors* (Elsevier, Amsterdam).

KARWOWSKI, W., AYOUB, M. M., ALLEY, L. R. and SMITH, T. L. 1984, Fuzzy approach in psychophysical modeling of human operator manual lifting system, *Fuzzy Sets and Systems*, **14**, 65–76.

KARWOWSKI, W., KOSIBA, E., BENABDALLAH, S. and SALVENDY, G. 1990, A framework for development of fuzzy GOMS model for human-computer interaction, *International Journal of Human-Computer Interaction*, **2**, 287–305.

KARWOWSKI, W., MAREK, T. and NOWOROL, C. 1988, Theoretical basis of the science of ergonomics, in *Proceedings of the 10th Congress of the International Ergonomics Assdociation*, Sydney, Australia (Taylor & Francis, London), 756–758.

KARWOWSKI, W., MAREK, T. and NOWOROL, C. 1991, *Principia Ergonomica* (Elsevier, Amsterdam) (in preparation).

KRAMER, U. 1983, Uncertainty and similarity: cognitive aspects of man-machine interactions, in *Proceedings of the Third European Annual Conference on Human Decision-Making and Manual Control*, Roskilde, Denmark, 313.

KRAMER, U. and ROHR, R. 1982, A model of driver behavior, in G. Johannsen and J. E. Rijnsdorp (eds), *Analysis, Design, and Evaluations of Man-Machine Systems* (Pergamon Press, Oxford), 31–35.

KUHN, S. 1974, *The Structure of Scientific Revolutions*, 2nd Edition (The University of Chicago Press, Chicago).

LUCZAK, H. and LE, S. 1989, Fuzzy modelling of relations between physical weight and perceived heaviness: the effect of size-weight illusion in industrial liftig tasks, *Ergonomics*, **32**, 823–838.

McCORMICK, E. J. 1970, *Human Factors Engineering* (McGraw Hill, New York).

McCLOSKEY, M. E. and GLUCKSBERG, S. 1978, Natural categories: well-defined or fuzzy sets?, *Memory and Cognition*, **6**, 462–472.

OBORNE, D. T. 1982, *Ergonomics at Work* (John Wiley, New York).

ODEN, G. C. 1977, Human perception and performance, *Journal of Experimental Psychology*, **3**, 565–575.

ONISAWA, T. 1988, An approach to human reliability in man–machine systems using error possibility, *Fuzzy Sets and Systems*, **27**, 87–103.

PEW, R. W. and BARON, S. 1983, Perspectives on human performance modeling, *Automatica*, **19**, 663–676.

POPPER, K. 1974, The Logic of Scientific Discovery, in P. A. Schilpp (ed.), *The Philosophy of Karl Popper* (LaSalle, Illinois).

PRITSKER, A. A. B. 1984, *Introduction to Simulation and SLAM* (Systems Publishing Corporation, West Lafayette, IN).

SAATY, S. L. 1977, Exploring the interface between hierarchies, multiple objectives, and fuzzy sets, *Fuzzy Sets and Systems*, **1**, 57–68.

SCHWARTZ, J. 1962, The Pernicious Influence of Mathematics in Science, in E. Nagel, P. Suppes and A. Tarski (eds), *Logic, Methodology and Philosophy of Science* (Stanford University Press, Stanford, CA).

SHERIDAN, T. B. and FERRELL, W. R. 1981, *Man–Machine Systems: Information, Control, and Decisions Models of Human Performance* (The MIT Press, Cambridge, MA).

SIMCOX, W. A. 1984, A method for pragmatic communication in graphic displays, *Human Factors*, **26**, 483–487.

SMITHSON, M. 1982, Applications of fuzzy set concepts to behavioural sciences, *Mathematical Social Sciences*, **2**, 257–274.

SINGLETON, W. T. 1982, *The Body at Work: Biological Ergonomics* (Cambridge University Press, Cambridge).

TERANO, T., MURAYAMA, Y. and AKIJAMA, N. 1983, Human reliability and safety evaluation of man–machine systems, *Automatica*, **19**, 719–722.

TOPMILLER, D. A. 1981, Methods, past approaches, current trends and future requirements, in J. Moraal and K. F. Kraiss (eds), *Manned Systems Design: Methods, Equipment and Applications* (Plenum Press, New York), 3–21.

WICKENS, C. D. 1979, Measures of workload, stress and secondary tasks, in N. Moray (ed.), *Mental Workload: Its Theory and Measurement* (Plenum Press, New York), 79–99.

WILLIGES, R. C. 1981, Development and Use of research methodologies for complex system/simulation experimentation, in J. Moraal and K. F. Kraiss (eds), *Manned Systems Design: Methods, Equipment and Applications* (Plenum Press, New York), 59–87.

WILLAEYS, D. and MALVACHE, N. 1979, Contributions of the fuzzy set theory to man–machine systems, in M. M. Gupta, R. K. Ragade, and R. R. Yager (eds), *Advances on Fuzzy Set Theory and Applications* (North Holland, Amsterdam).

WILSON, J. R., CORLETT, E. N. and MANENICA, I. (eds) 1987, *Proceedings of the Second International Occupational Ergonomics Symposium*, Zadar, Yugoslavia (Taylor & Francis, London).

ZADEH, L. A. 1965, Fuzzy sets, *Information and Control*, **8**, 338–353.

ZADEH, L. A. 1973, Outline of a new approach to the analysis of complex systems and decision processes, *IEEE Transactions on Systems, Man and Cybernetics*, **SMC-3**, 28–44.

ZADEH, L. A. 1974, Numerical versus linguistic variables, *Newspaper of the Circuits and Systems Society*, **7**, 3–4.

ZADEH, L. A. 1975, The concept of linguistic variable and its application to approximate reasoning, *Information Sciences*, **8**, 199–249 and 301–357, and **9**, 43–80.

ZIMMERMANN, H. J. 1980, Testability and meaning of mathematical models in social sciences, *Mathematical Modelling*, **1**, 123–139.

ZIMMERMANN, H. J. 1985, *Fuzzy Set Theory and Its Applications* (Kluwer-Nijhoff Publishing, Boston).