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Ergonomics and human factors: the paradigms for science, engineering, design, technology and management of human-compatible systems[1]

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This paper provides a theoretical perspective on human factors and ergonomics (HFE), defined as a unique and independent discipline that focuses on the nature of human-artefact interactions, viewed from the unified perspective of the science, engineering, design, technology and management of human-compatible systems. Such systems include a variety of natural and artificial products, processes and living environments. The distinguishing features of the contemporary HFE discipline and profession are discussed and a concept of ergonomics literacy is proposed. An axiomatic approach to ergonomics design and a universal measure of system-human incompatibility are also introduced. It is concluded that the main focus of the HFE discipline in the 21st century will be the design and management of systems that satisfy human compatibility requirements.

Keywords: Ergonomics; Human factors; Human-compatible systems; Paradigms; Design; Management

1. Introduction

Over the last 50 years, ergonomics, a term that is used here synonymously with human factors (and denoted as HFE), has been evolving as a unique and independent discipline. Today, HFE is the discipline that focuses on the nature of human-artefact interactions, viewed from the unified perspective of the science, engineering, design, technology and management of human-compatible systems. Such systems include a variety of natural and

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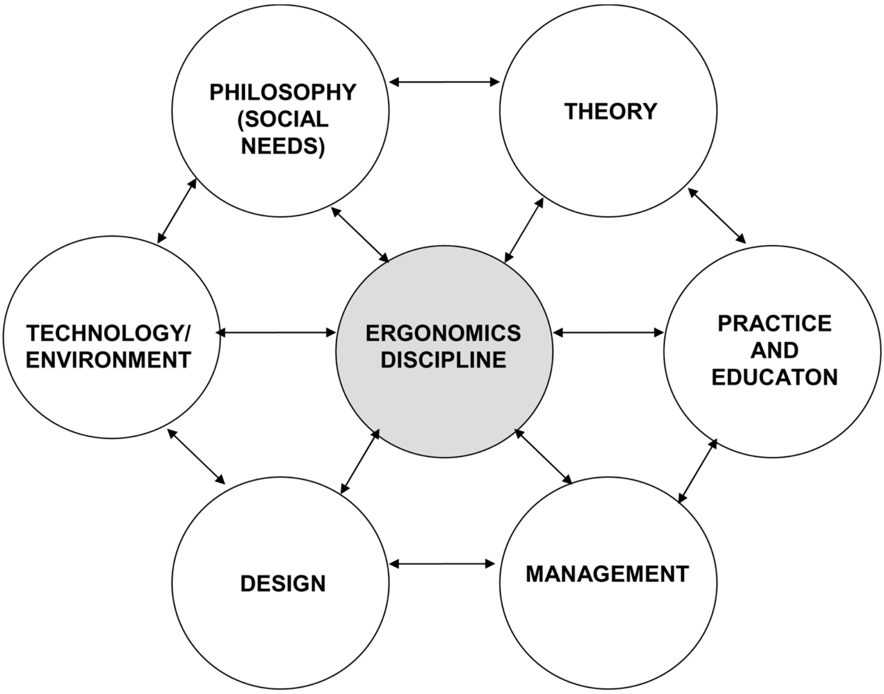


Figure 1. General dimensions of ergonomics discipline.

artificial products, processes and living environments. The various dimensions of the HFE discipline, defined in this manner, are shown in figure 1.

Historically, the philosophical framework for the unique discipline of ergonomics (ergon + nomos), or the study of work, was introduced by the Polish scientist W.B. Jastrzebowski (1857). Ergonomics was proposed as a scientific discipline with a very broad scope and a wide area of interests and applications, encompassing all aspects of human activity, including labour, entertainment, reasoning and dedication (Karwowski (1991, 2001). In his paper, published in the journal *Nature and Industry*, Jastrzebowski (1857) divided work into two main categories: the useful work, which brings improvement for the common good; and the harmful work, which brings deterioration (discreditable work). Useful work, which aims to improve things and people, is classified into physical, aesthetic, rational and moral work. According to Jastrzebowski, such work requires utilization of motor forces, sensory forces, forces of reason (thinking and reasoning) and the spiritual force. The four main benefits of useful work are exemplified through property, ability, perfection and felicity.

The contemporary ergonomics discipline, independently introduced by Murrell in 1949 (Edholm and Murrell 1974), was viewed at that time as an applied science, technology or both. The ergonomics discipline promotes a holistic, human-centred approach to work systems design that considers physical, cognitive, social, organizational, environmental and other relevant factors (Grandjean 1986, Wilson and Corlett 1990, Sanders and McCormick 1993, Chapanis 1996, 1999, Salvendy 1997, Karwowski 2001, Vicente 2004, Stanton *et al.* 2004). The International Ergonomics Association (2003) defined ergonomics (or human factors) as:

> ... the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance.

In the view of the International Ergonomics Association, ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people (IEA, 2003).

Traditionally, the most often cited domains of specialization within HFE are physical, cognitive and organizational ergonomics. Physical ergonomics is mainly concerned with human anatomical, anthropometric, physiological and biomechanical characteristics as they relate to physical activity (Chaffin and Anderson 1993, Kroemer *et al.* 1994, Pheasant 1996, Karwowski and Marras 1999, National Research Council 2001; Karwowski and Rodrick, 2001). Cognitive ergonomics focuses on mental processes, such as perception, memory, information processing, reasoning and motor response, as they affect interactions among humans and other elements of a system (Vicente 1999, Hollnagel 2003, Diaper and Stanton 2004). Organizational ergonomics (also known as macroergonomics) is concerned with the optimization of socio-technical systems, including their organizational structures, policies and processes (Karwowski *et al.* 1994b, Reason 1999, Hendrick 2000, Holman *et al.* 2003, Nemeth 2004). Examples of the relevant topics include communication, crew resource management, teamwork, participatory work design, community ergonomics, computer-supported cooperative work, virtual organizations and quality management. Exemplary domains of the HFE applications are listed in table 1.

According to the above discussion, the HFE discipline focuses on the understanding of interactions between people and systems, i.e. everything that surrounds people at work and outside of their working environment. Based on such knowledge, HFE aims to optimize human well-being and overall system performance. For example, table 2 provides a summary of selected HFE objectives applicable to systems engineering, as proposed by a past International Ergonomics Association (IEA) president, the late Al Chapanis (1996).

Table 1. Exemplary domains of the disciplines of medicine, psychology and ergonomics

Medicine	**Psychology**	**Ergonomics**
Cardiology	Applied psychology	Physical ergonomics
Dermatology	Child psychology	Cognitive ergonomics
Gastroenterology	Clinical psychology	Macroergonomics
Neurology	Cognitive psychology	Community ergonomics
Radiology	Community psychology	Rehabilitation ergonomics
Endocrinology	Counselling psychology	Participatory ergonomics
Pulmonology	Developmental psychology	Human-computer interaction
Gerontology	Experimental psychology	Neuroergonomics
Neuroscience	Educational psychology	Affective ergonomics
Nephrology	Environmental psychology	Ecological ergonomics
Oncology	Forensic psychology	Forensic ergonomics
Ophthalmology	Health psychology	Consumer ergonomics
Urology	Positive psychology	Human-system integration
Psychiatry	Organizational psychology	Ergonomics of aging
Internal medicine	Social psychology	Information ergonomics
Community medicine	Quantitative psychology	Knowledge ergonomics
Physical medicine	Social psychology	Nanoergonomics

Table 2. Objectives of human factors and ergonomics discipline*

Basic operational objectives
Reduce errors
Increase safety
Improve system performance
Objectives bearing on reliability, maintainability and availability and integrated logistic support
Increase reliability
Improve maintainability
Reduce personnel requirements
Reduce training requirements
Objectives affecting users and operators
Improve the working environment
Reduce fatigue and physical stress
Increase ease of use
Increase user acceptance
Increase aesthetic appearance
Other objectives
Reduce losses of time and equipment
Increase economy of production

*From Chapanis (1996).

2. Human-technology interactions

A recent report by the National Academy of Engineering (2004) in the USA states that in the near future, the ongoing developments in engineering will:

> ... expand toward tighter connections between technology and the human experience, including new products customized to the ... dimensions and capabilities of the user, and ergonomic design of engineered products.

While in the past ergonomics has been driven by technology (reactive design approach), in the future ergonomics should drive technology (proactive design approach). Technology can be defined as the entire system of people and organizations, knowledge, processes and devices that go into creating and operating technological artefacts, as well as the artefacts themselves (National Research Council 2001). Technology is a product and a process involving both science and engineering. Science aims to understand the 'why' and 'how' of nature (through a process of scientific inquiry that generates knowledge about the natural world). Engineering is the 'design under constraints' of cost, reliability, safety, environmental impact, ease of use, available human and material resources, manufacturability, government regulations, laws and politics (Wulf 1998). Engineering seeks to shape the natural world to meet human needs and wants: a body of knowledge of design and creation of human-made products and a process for solving problems.

Contemporary HFE discovers and applies information about human behaviour, abilities, limitations and other characteristics to the design of tools, machines, systems, tasks, jobs and environments for productive, safe, comfortable and effective human use (Sanders and McCormick 1993, Helander 1997). In this context, HFE deals with a broad scope of problems relevant to the design and evaluation of work systems, consumer products and working environments, in which human-machine interactions affect human performance and product usability. The wide scope of issues and problems addressed by the contemporary HFE discipline is presented in table 3. Figure 2 illustrates the evolution of the scope of HFE with regard to the nature of human-system interactions. Originally, HFE focused on local human-machine interactions, while today the main focus is on

Table 3. Classification Scheme for human factors/ergonomics*

1. General
HUMAN CHARACTERISTICS
2. Psychological aspects
3. Physiological and anatomical aspects
4. Group factors
5. Individual differences
6. Psychophysiological state variables
7. Task-related factors
INFORMATION PRESENTATION AND COMMUNICATION
8. Visual communication
9. Auditory and other communication modalities
10. Choice of communication media
11. Person – machine dialogue mode
12. System feedback
13. Error prevention and recovery
14. Design of documents and procedures
15. User control features
16. Language design
17. Database organization and data retrieval
18. Programming, debugging, editing and programming aids
19. Software performance and evaluation
20. Software design, maintenance and reliability
DISPLAY AND CONTROL DESIGN
21. Input devices and controls
22. Visual displays
23. Auditory displays
24. Other modality displays
25. Display and control characteristics
WORKPLACE AND EQUIPMENT DESIGN
26. General workplace design and buildings
27. Workstation design
28. Equipment design
ENVIRONMENT
29. Illumination
30. Noise
31. Vibration
32. Whole body movement
33. Climate
35. Altitude, depth and space
36. Other environmental issues
SYSTEM CHARACTERISTICS
37. General system features
WORK DESIGN AND ORGANIZATION
38. Total system design and evaluation
39. Hours of work
40. Job attitudes and job satisfaction
41. Job design
42. Payment systems

(*continued*)

Table 3. (continued)

43. Selection and screening
44. Training
45. Supervision
46. Use of support
47. Technological and ergonomic change
HEALTH AND SAFETY
48. General health and safety
49. Aetiology
50. Injuries and illnesses
51. Prevention
SOCIAL AND ECONOMIC IMPACT OF THE SYSTEM
52. Trade unions
53. Employment, job security and job sharing
54. Productivity
55. Women and work
56. Organizational design
57. Education
58. Law
59. Privacy
69. Family and home life
61. Quality of working life
62. Political comment and ethical considerations
METHODS AND TECHNIQUES
63. Approaches and methods
64. Techniques
65. Measures

*From Ergonomics Abstracts (2004).

broadly defined human-technology interactions. In this view, HFE can also be called the discipline of technological ecology.

Human factors and ergonomics and system-human compatibility

The HFE discipline advocates:

> . . . systematic use of the knowledge concerning relevant human characteristics in order to achieve compatibility in the design of interactive systems of people, machines, environments, and devices of all kinds to ensure specific goals . . .
>
> (Human Factors and Ergonomics Society 2004)

Typically, such goals include improved (system) effectiveness, productivity, safety, ease of performance and the contribution to overall human well-being and quality of life. Although the term compatibility is a key word in the above definition, it has been used in a narrow sense only, often in the context of the design of displays and controls, including the studies of spatial (location) compatibility or intention-response-stimulus compatibility related to movement of controls (Wickens and Carswell 1997). Karwowski and his co-workers (Karwowski *et al*. 1988, Karwowski 1991) advocated the use of compatibility in a greater context of the ergonomics system. For example, Karwowski (1997) introduced the term ‘human-compatible systems’ in order to focus on the need for comprehensive treatment of compatibility in the human factors discipline.

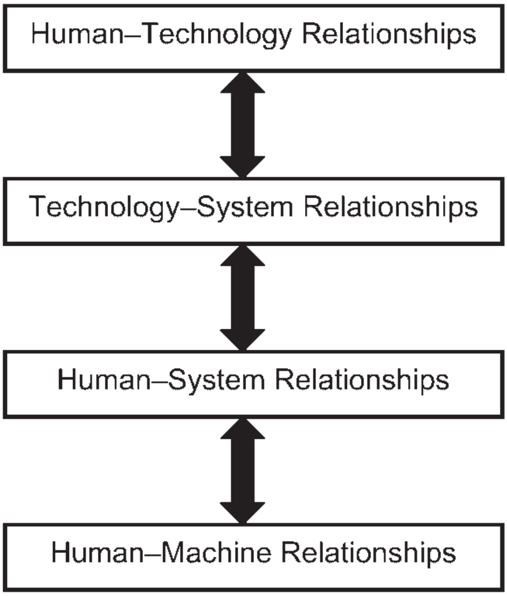


Figure 2. An expanded view of the human – technology relationships (modified after Meister 1999).

The American Heritage Dictionary Of English Language (1978) defines 'compatible' as: 1) capable of living or performing in harmonious, agreeable, or congenial combination with another or others; and 2) capable of orderly, efficient integration and operation with other elements in a system. From the beginning of contemporary ergonomics, the measurements of compatibility between the system and the human and evaluation of the results of ergonomics interventions were based on the measures that best suited specific purposes (Karwowski 2001). Such measures included the specific psycho-physiological responses of the human body (for example heart rate, electromyography (EMG), perceived human exertion, satisfaction, comfort or discomfort), as well as a number of indirect measures, such as the incidence of injury, economic losses or gains, system acceptance or operational effectiveness, quality or productivity. The lack of a universal matrix to quantify and measure human-system compatibility is an important obstacle in demonstrating the value of ergonomics science and the profession (Karwowski 1998). However, even though 20 years ago ergonomics was perceived by some (for example, see Howell 1986) as a highly unpredictable area of human scientific endeavour, today HFE has positioned itself as a unique, design-oriented discipline, independent of engineering and medicine (Sanders and McCormick 1987, Karwowski 1991, Moray 1995, Helander 1997).

Figure 3 illustrates the system-human compatibility approach to ergonomics in the context of quality of working life and system (an enterprise or business entity) performance. This approach reflects the nature of complex compatibility relationships between the human operator (human capacities and limitations), technology (in terms of products, machines, devices, processes and computer-based systems) and a broadly defined environment (business processes, organizational structure, the nature of work systems and the effects of work-related multiple stressors). The operator's performance is

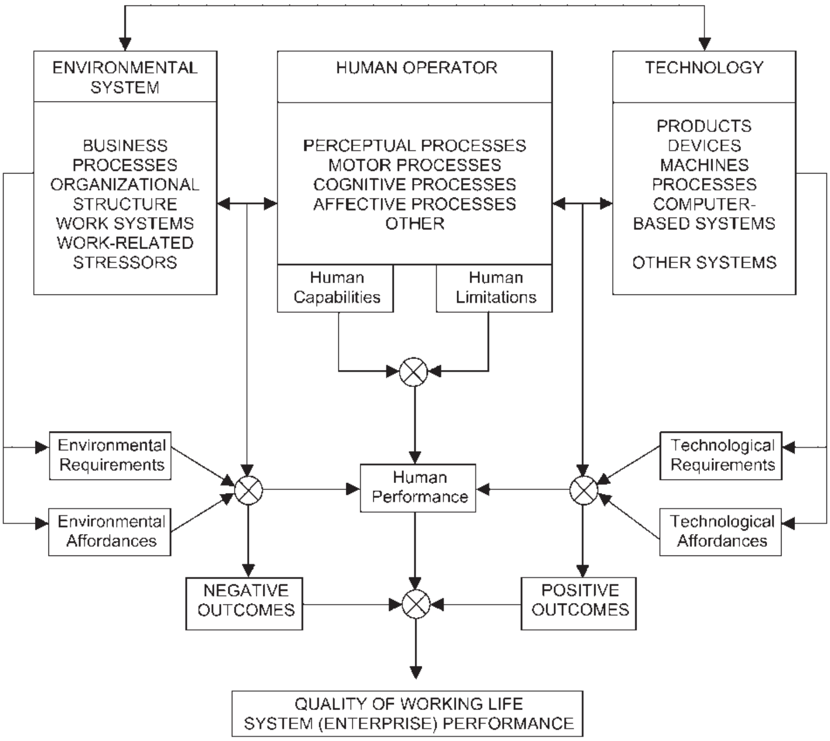


Figure 3. A human–system compatibility approach to ergonomics.
Note: ⊗ – Matching of compatibility relationships.

an outcome of the compatibility matching between individual human characteristics (capacities and limitations) and the requirements and affordances of both the technology and environment. The quality of working life and the system (enterprise) performance is affected by matching of the positive and negative outcomes of the complex compatibility relationships between the human operator, technology and environment. Positive outcomes include such measures as work productivity, performance times, product quality and subjective psychological (desirable) behavioural outcomes, such as job satisfaction, employee morale, human well-being, commitment, etc.). The negative outcomes include both human and system-related errors, loss of productivity, low quality, accidents, injuries, physiological stresses and subjective psychological (undesirable) behavioural outcomes such as job dissatisfaction, job/occupational stress, discomfort, etc.

4. Distinguishing features of contemporary human factors and ergonomics discipline and profession

The main focus of the HFE discipline in the 21st century will be the design and management of systems that satisfy customer demands in terms of human compatibility requirements. It is possible to identify ten characteristics of the contemporary HFE discipline and profession. These distinguishing features are as follows:

1. HFE is very ambitious in its goals, but poorly funded compared to other contemporary disciplines.
2. HFE experiences continuing evolution of its fit philosophy, including diverse and ever-expanding human-centered design criteria (from safety to comfort, productivity, usability, or affective needs, such as job satisfaction or life happiness).
3. HFE has yet to establish its unique disciplinary identity and credibility among other sciences, engineering and technology.
4. HFE covers extremely diverse subject matters, similar to medicine, engineering, psychology (see table 1).
5. HFE deals with very complex phenomena that are not easily understood and cannot be simplified by making non-defendable assumptions about their nature.
6. Historically, HFE has been developing from the 'philosophy of fit' towards practice. Today, HFE is developing a sound theoretical basis for design and practical applications (see figure 4).
7. HFE attempts to 'by-step' the need for fundamental understanding of the human-system interactions without separation from the consideration of knowledge utility for practical applications, in the quest for the immediate and useful solutions (also see figure 5).
8. HFE enjoys limited recognition by decision-makers, the general public and politicians as to the value that it can bring to a global society at large, especially in the context of facilitating socio-economic development.
9. HFE has a relatively weak and limited professional educational base.
10. HFE is adversely affected by the ergonomics illiteracy of students and professionals in other disciplines, the mass media and the public at large.

Theoretical ergonomics is interested in the fundamental understanding of interactions between people and their environments. Central to HFE interests is also an under-

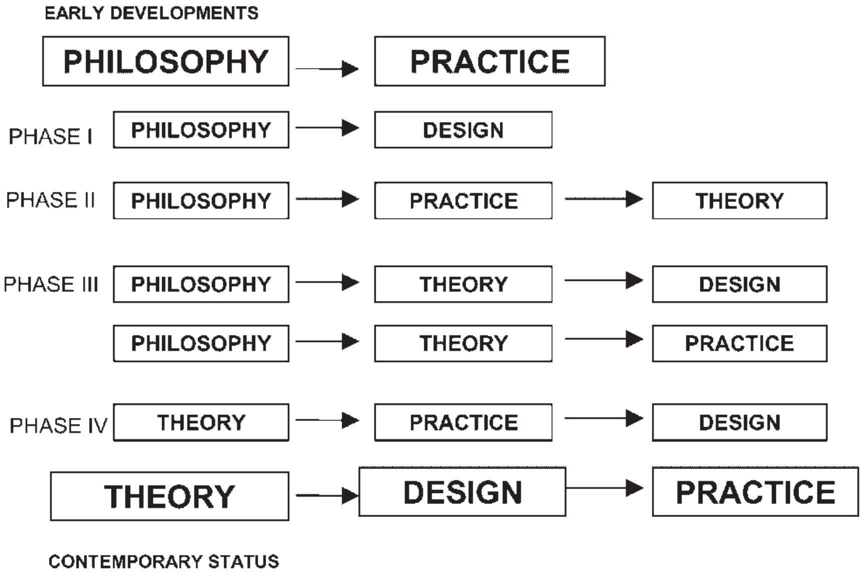
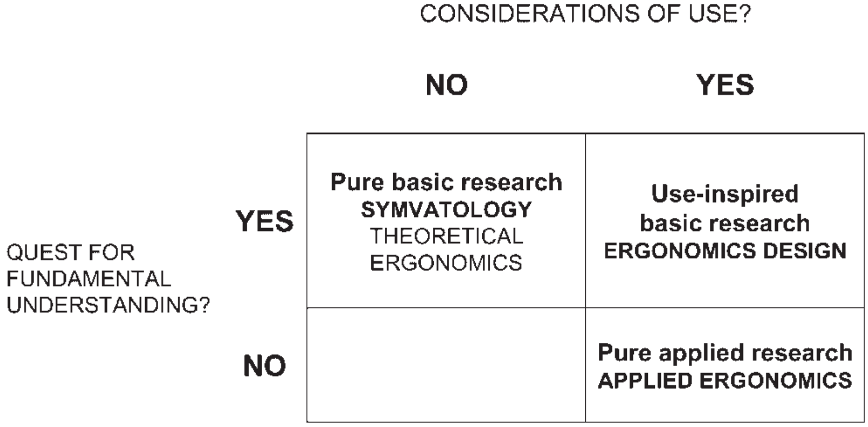


Figure 4. Evolution in the development of human factors and ergonomics discipline.



QUEST FOR FUNDAMENTAL UNDERSTANDING? / CONSIDERATIONS OF USE?	NO	YES
YES	**Pure basic research** **SYMVATOLOGY** THEORETICAL ERGONOMICS	**Use-inspired basic research** **ERGONOMICS DESIGN**
NO		**Pure applied research** **APPLIED ERGONOMICS**

Figure 5. Considerations of fundamental understanding and use in ergonomics research.

standing of how human-system interactions should be designed. On the other hand, HFE also falls under the category of applied research. A taxonomy of research efforts with regard to the quest for fundamental understanding and the consideration of use, originally proposed by Stokes (1997), allows for differentiation of main categories of research dimensions as follows: 1) pure basic research, 2) use-inspired basic research; and 3) pure applied research. Figure 5 illustrates the interpretation of these categories for HFE-related theory, design and applications.

5. Paradigms for ergonomics discipline

The paradigms for any scientific discipline include theory, abstraction and design (Pearson and Young 2002). Theory is a foundation of the mathematical sciences. Abstraction (modelling) is a foundation of the natural sciences, where progress is achieved by formulating hypotheses and systematically following the modelling process to verify and validate them. Design is the basis for engineering, where progress is achieved primarily by posing problems and systematically following the design process to construct systems that solve them.

Three main paradigms for the HFE discipline can be identified: 1) ergonomics theory; 2) ergonomics abstraction; and 3) ergonomics design. Ergonomics theory is concerned with the ability to identify, describe and evaluate human-system interactions. Ergonomics abstraction is concerned with the ability to use those interactions to make predictions that can be compared with the real world. Ergonomics design is concerned with the ability to implement knowledge about those interactions and use them to develop systems that satisfy customer needs and relevant human compatibility requirements.

Furthermore, the pillars for any scientific discipline include a definition, a teaching paradigm and an educational base (National Research Council 2002). A definition of the ergonomics discipline and profession adopted by the International Ergonomics Association (2000) emphasizes fundamental questions and significant accomplishments, recognizing that the HFE field is constantly changing. A teaching paradigm for ergonomics should conform to established scientific standards, emphasize development of competence in the field and integrate theory, experimentation, design and practice.

Finally, an introductory course sequence in ergonomics should be based on the curriculum model and the disciplinary description.

6. Ergonomics competency and literacy

As pointed out by the National Academy of Engineering (Pearson and Young 2002), many consumer products and services promise to make people's lives easier, more enjoyable, more efficient or healthier, but very often do not deliver on these promises. Design of interactions with technological artefacts and work systems require involvement of ergonomically competent people – people with ergonomics proficiency in a certain area, although not generally in other areas of application, similar to medicine or engineering.

One of the critical issues in this context is the ability of the users to understand the utility and limitations of technological artefacts. Ergonomics literacy prepares individuals to perform their roles in the workplace and outside of the working environment. An ergonomically literate person has appropriate knowledge about how technological systems operate in order to make informed choices and make use of beneficial affordances of technological artefacts and related environments. People trained in ergonomics typically posses a high level of knowledge and skill related to one or more specific areas of ergonomics application. Ergonomics literacy is a prerequisite to ergonomics competency. The following can be proposed as a set of dimensions for ergonomics literacy (see figure 6):

1. Ergonomics knowledge and skills: an individual has the basic knowledge of the philosophy of human-centred design and principles for accommodating human limitations.

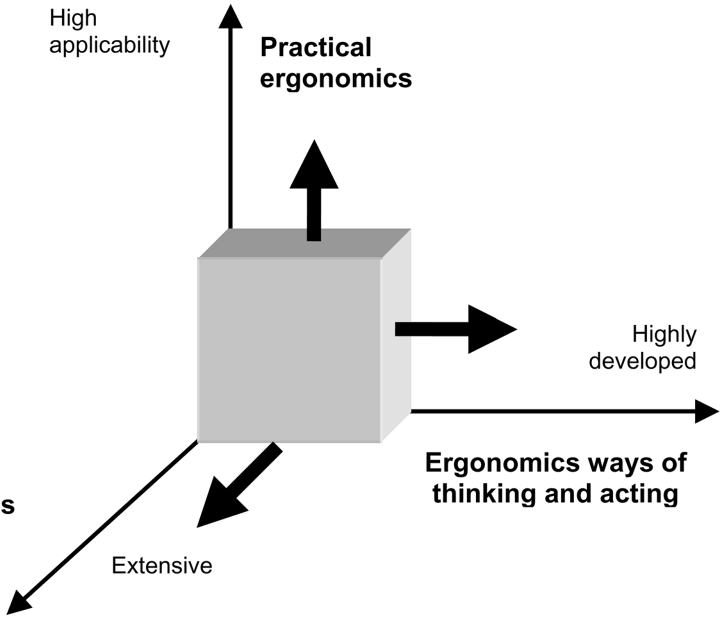


Figure 6. Desired goals for ergonomics literacy.

2. Ways of thinking and acting: an individual seeks information about benefits and risks of artefacts and systems (consumer products, services, etc.) and participates in decisions about purchasing and use and/or development of artefacts/systems.
3. Practical ergonomics capabilities: an individual can identify and solve simple task (job)-related design problems at work or home and can apply basic ergonomics concepts to make informed judgments about usability of artefacts and the related risks and benefits of their use.

Table 4 presents a list of ten standards for ergonomics literacy, in parallel to a model of technological literacy reported by the National Academy of Engineering (Pearson and Young 2002). Eight of these standards are related to developing an understanding of the nature, scope, attributes and role of the HFE discipline in modern society, while two of them refer to the need for developing the abilities to apply the ergonomics design process and evaluate the impact of artefacts on human safety and well-being.

7. Ergonomics design

Ergonomics is a design-oriented discipline. However, ergonomists do not design systems, but rather HFE professionals design the interactions between the artefact systems and humans. One of the fundamental problems involved in such a design is that, typically, there are multiple functional system-human compatibility requirements that must be satisfied at the same time. In order to address this issue, structured design methods for complex human-artefact systems are needed. In such a perspective, ergonomics design can be defined in general as mapping from the human capabilities and limitations to system (technology-environment) requirements and affordances (see figure 7) or, more specifically, from the system-human compatibility needs to the relevant compatibility requirements.

Suh (1989, 2001) proposed a framework for axiomatic design, which utilizes four different domains that reflect mapping between the identified needs ('what one wants to achieve') and the ways to achieve them ('how to satisfy the stated needs'). These

Table 4. Standards for ergonomics literacy: ergonomics and technology

Having an understanding of:
Standard 1: characteristics and scope of ergonomics
Standard 2: the core concepts of ergonomics
Standard 3: the connections between ergonomics and other fields of study and relationships among technology, environment, industry and society
Standard 4: cultural, social, economic and political effects of ergonomics
Standard 5: role of society in the development and use of technology
Standard 6: effects of technology on the environment
Standard 7: the attributes of ergonomics design
Standard 8: the role of ergonomics research, development, invention and experimentation
Having abilities to:
Standard 9: apply the ergonomics design process
Standard 10: assess the impact of products and systems on human health, well-being, system performance and safety

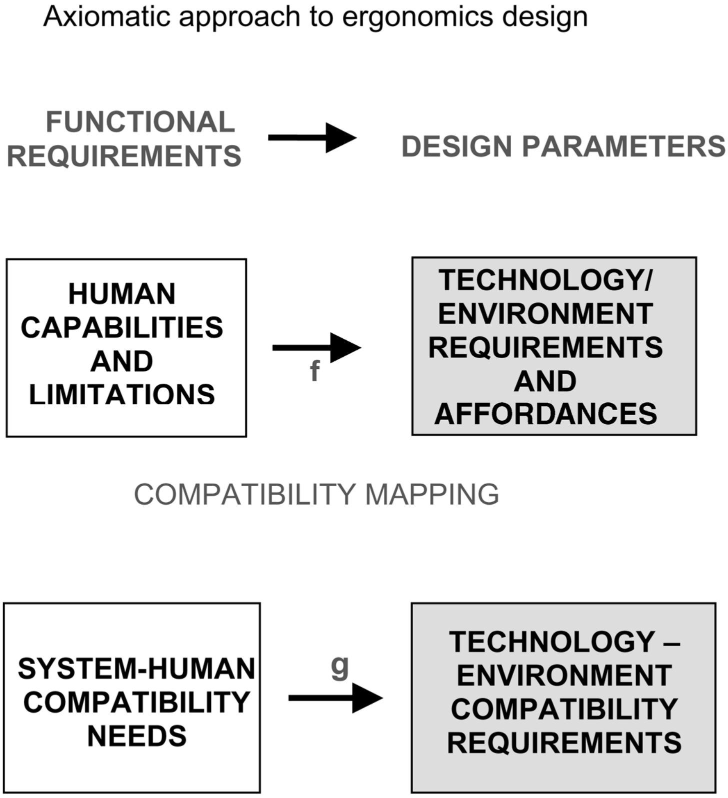


Figure 7. Ergonomics design process: compatibilty mapping.

domains include: 1) customer requirements (customer needs or desired attributes); 2) functional domain (functional requirements and constraints); 3) physical domain (physical design parameters); and 4) processes domain (processes and resources). Karwowski (2003) conceptualized the above domains for ergonomics design purposes as illustrated in figure 8, using the concept of compatibility requirements and compatibility mappings between the domains of: 1) HFE requirements (goals in terms of human needs and system performance); 2) functional requirements and constraints expressed in terms of human capabilities and limitations; 3) physical domain in terms of design of compatibility, expressed through the human-system interactions and specific work system design solutions; and 4) processes domain, defined as management of compatibility.

7.1. Axiomatic design: design axioms

Axiomatic design process (Suh 2001) is described by the mapping process from functional requirements (FRs) to design parameters (DPs). The relationship between the two vectors, FRs and DPs, is as follows:

$$\{FR\} = [A]\{DP\}$$

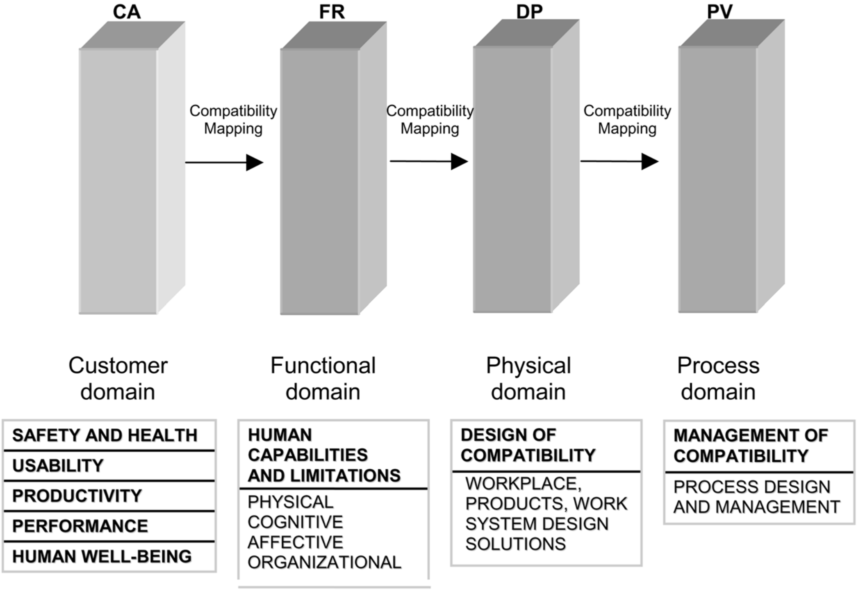


Figure 8. Four domains of design in ergonomics. CA = customer domain; FR = functional requirement; DP = design parameter; PV = process domain

where [A] is the design matrix that characterizes the product design. The design matrix [A] for three functional domains (FRs) and three physical domains (DPs) is shown below:

$$[\mathrm{A}] = \begin{bmatrix} \mathrm{A}_{11} & \mathrm{A}_{12} & \mathrm{A}_{13} \\ \mathrm{A}_{21} & \mathrm{A}_{22} & \mathrm{A}_{23} \\ \mathrm{A}_{31} & \mathrm{A}_{32} & \mathrm{A}_{33} \end{bmatrix}$$

The following two design axioms, proposed by Suh (2001), are the basis for a formal design methodology:

1. The independence axiom stipulates a need for independence of the FRs, which are defined as the minimum set of independent requirements that characterize the design goals (defined by DPs).

2. The information axiom stipulates minimizing the information content of the design. Among those designs that satisfy the independence axiom, the design that has the smallest information content is the best design.

According to the second design axiom, the information content of the design should be minimized. The information content I_i for a given functional requirement ($\mathrm{FR_i}$) is defined in terms of the probability P_i of satisfying $\mathrm{FR_i}$:

$$I_i = \log_2(1/P_i) = -\log_2 P_i[bits]$$

The information content will be additive when there are many functional requirements that must be satisfied simultaneously. In the general case of m number of FRs, the information content for the entire system I_{sys} :

$$I_{sys} = -\log_2 P_{\{m\}}$$

where $P_{\{m\}}$ is the joint probability that all m FRs are satisfied.

According to Suh (2001), in order to satisfy the information axiom one must assure that the system range (sr) (i.e. actual variation of the FR of the system) lies inside the specified (desired) design range (dr) associated with the FR (see figure 9). For a design with one FR, the probability P of achieving the FR (given by the area A_{cr}), which in the case of this uniform probability density function (pdf) is:

$$P = A_{cr} = \int_{sr^l}^{dr^u} p_s(FR)dFR = \frac{dr^u - sr^l}{|sr|} = \frac{|cr|}{|sr|}$$

where A_{cr} is the area of the system pdf over the common area; (dr) is the design range; |cr| is the common range; |sr| is the system range and sr^1 is the lower bound of the system range.

$$I = \log_2 \frac{|sr|}{|cr|}$$

In view of the above discussion, the information content of design with one FR is:

$$\text{I} = \log_2|\text{system range}|/|\text{common range}|$$

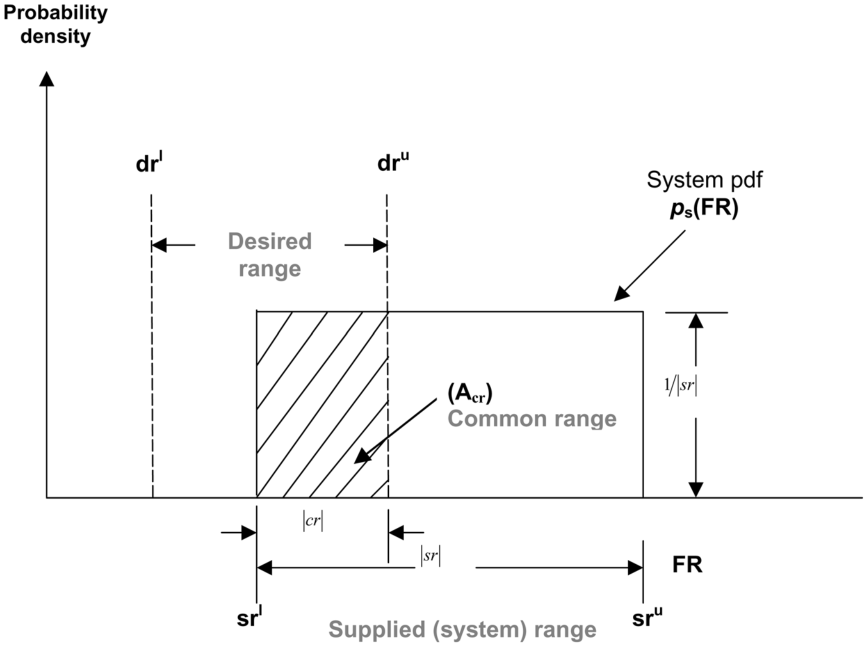


Figure 9. Ilustration of the desired (system) range, supplied (system) range and common range in axiomatic design (after Suh 1989). pdf = probability density function; FR = functional requirment.

For many FRs, information content for the design can be defined as follows:

$$I_{sys} = \sum_{i=1}^{m} I_i = -\sum_{i=1}^{m} \log_2 P_i$$

7.2. Applications of axiomatic design to ergonomics

The above axioms can be adapted for ergonomics design purposes as follows:

Axiom 1: The independence axiom stipulates a need for independence of the functional compatibility requirements (FCRs), which are defined as the minimum set of independent compatibility requirements that characterize the design goals (defined by ergonomics design parameters: EDPs).
Axiom 2: The system-human incompatibility axiom stipulates a need to minimize the incompatibility content of the design. Among those designs that satisfy the independence axiom, the design that has the smallest incompatibility content is the best design.

Helander (1994, 1995) was the first to provide a conceptualization of the second design axiom in ergonomics by considering selection of a chair based on the information content of specific chair design parameters. Kolich (2002) proposed to apply the axiomatic design to the evaluation of automobile seat comfort.

It should be noted that in the context of ergonomics design, the probability (p) of achieving FR, i.e. probability of satisfying human users with regard to a particular FR, can be calculated using a criterion of accommodating the desired range of a specific design variable (Helander 1995). In such a case, the information content for the design can be defined as follows:

$$\mathrm{I} = \log_2 |\text{desired (system) range}| / |\text{common range}|$$

The above model can be extended by introducing the concept of the compatibility index and formulating a measure of ergonomics (system) incompatibility. In ergonomics design, the information axiom can be interpreted as follows. The human incompatibility content of the design I_i for a given functional requirement ($\mathrm{FR_i}$) was defined in terms of the compatibility C_i index that satisfies a given $\mathrm{FR_i}$:

$$I_i = \log_2(1/C_i) = -\log_2 C_i \text{ [ints]}$$

The unit of such a measure of system-human incompatibility is an [int]. It should be noted that the compatibility index C_i $[0 < \mathrm{C} < 1]$ can be defined depending on the specific (ergonomics) design goals, i.e. the applicable or relevant ergonomics design criterion(a) used for system design or evaluation.

7.3. General framework for application of the information axiom in ergonomics

As discussed by Karwowski *et al.* (1988), Karwowski (1985, 1991, 1999, 2001) and Karwowski and Jamaldin (1995), a need to remove the system-human incompatibility (or ergonomics entropy) plays the central role in ergonomics design. In view of such discussion, the second axiomatic design axiom can be adopted for the purpose of ergonomics theory as follows. As pointed out above, the measure of system-human incompatibility, i.e. the incompatibility content of the design I_i for a given functional compatibility requirement (FCR_i) can be defined in terms of the compatibility C_i index that satisfies this FCR_i:

$$I_i = \log_2(1/C_i) = -\log_2 C_i \text{ [ints]}$$

In general, to minimize the system-human incompatibility one can either: 1) minimize exposure to the negative (undesirable) influence of a given design parameter on the system-human compatibility; or 2) maximize positive influence of the desirable design parameter (adaptability) on system-human compatibility. The first design scenario, i.e. a need to minimize exposure to the negative (undesirable) influence of a given design parameter (A_i), typically occurs when A_i exceeds some maximum exposure value of R_i, for example, when the compressive force on the human spine (lumbosacral joint) due to manual lifting of loads exceeds the accepted (maximum) reference value. It should be noted that if $A_i < R_i$, then C can be set to 1 and the related incompatibility due to considered design variable will be zero.

The second design scenario, i.e. a need to maximize positive influence (adaptability) of the desirable feature (design parameter A_i) on system human compatibility), typically occurs when A_i is less than or below some desired or required value of R_i, (i.e. minimum reference value). For example, when the range of chair height adjustability is less than the recommended (reference) range of adjustability to accommodate 90% of the mixed (male/female) population. It should be noted that if $A_i > R_i$, then C can be set to 1 and the related incompatibility due to considered design variable will be zero. In both of the above described cases, the human-system incompatibility content can be assessed as discussed below.

7.3.1. Ergonomics design criterion: minimize exposure when $A_i > R_i$, The compatibility index C_i is defined by the ratio: R_i,/A_i where R_i = maximum exposure (standard) for design parameter *i* and A_i = actual value of a given design parameter *i*:

$$C_i = R_i/A_i$$

and hence:

$$I_i = -\log_2 C_i = -\log_2(R_{i\cdot}/A_i) = \log_2(A_i/R_i) \text{ [ints]}$$

Note that if $A_i < R_i$, then C can be set to 1 and incompatibility content I_i is zero.

7.3.2. Ergonomics design criterion: maximize adaptability when $A_i < R_i$, The compatibility index C_i is defined by the ratio: A_i /R_i, where A_i = actual value of a given design parameter *i* and R_i = desired reference or required (ideal) design parameter standard: *i*:

$$C_i = A_i/R_i$$

and hence:

$$I_i = -\log_2 C_i = -\log_2(A_i/R_i) = \log_2(R_i/A_i) \text{ [ints]}$$

Note that if $A_i > R_i$, then C can be set to 1 and incompatibility content I_i is zero.

As discussed by Karwowski (2005), the proposed units of measurement for the system-human incompatibility [ints] are parallel and numerically identical to the measure of information [bits]. The information content of the design is expressed in terms of the (ergonomics) incompatibility of design parameters with the optimal, ideal, or desired reference values, expressed in terms of ergonomics design parameters, such as range of table height or chair height adjustability, maximum acceptable load of lift, maximum compression on the spine, optimal number of choices, maximum number of hand repetitions per cycle time on a production line, minimum required decision time, maximum heat load exposure per unit of time, etc.

The general relationships between technology of design and science of design are illustrated in figure 10. Furthermore, figure 11 depicts such relationships for the HFE discipline. In the context of axiomatic design in ergonomics, the FRs are the human-system compatibility requirements, while the DPs are the human-system interactions. Therefore, ergonomics design can be defined as mapping from the human-system compatibility requirements to the human-system interactions. More generally, HFE can be defined as the science of design, testing, evaluation and management of human system interactions according to the human-system compatibility requirements.

7.4. Axiomatic design in ergonomics: applications

It is possible to illustrate an application of the first design axiom adapted to the needs of ergonomics design, using an example of the rear light system utilized to provide information about application of brakes in a passenger car. In this highway safety-related example, the FRs of the rear lighting (braking display) system were defined in terms of FRs and DPs as follows:

FR_1 = Provide early warning to maximize the lead response time (MLRT) (information about the car in front that is applying brakes).
FR_2 = Assure safe braking (ASB).

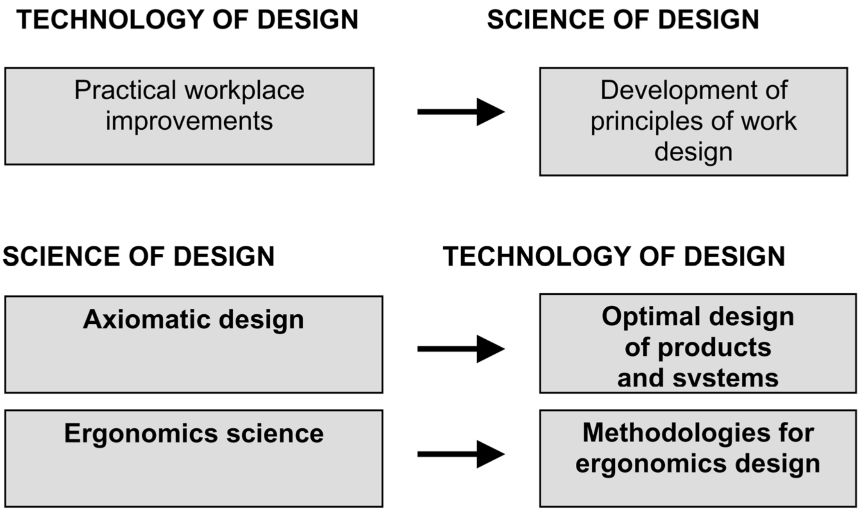


Figure 10. Aximatic approach to ergonomics design.

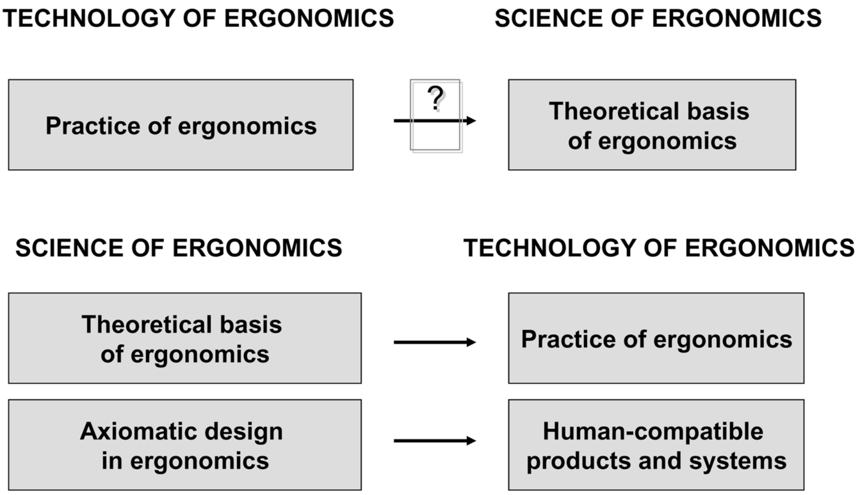


Figure 11. Science, technology and design in ergonomics.

The traditional (old) design solution is based on two DPs:
DP1 = Two rear brake lights on the sides.
DP2 = Efficient braking mechanism (EBM).

The design matrix of the traditional rear lighting system (TRLS) is as follows:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

MLRT	X	0	TRLS
ASB	X	X	EBM

This rear lighting warning system (old solution) can be classified as a decoupled design and is not an optimal design. The reason for such classification is that even with the efficient braking mechanism, one cannot compensate for the lack of time in the driver's response to braking of the car in front due to a sudden traffic slow-down. In other words, this rear lighting system does not provide early warning that would allow the driver to maximize his/her lead response time to braking.

The solution that was implemented about two decades ago utilizes a new concept for the rear lighting of the braking system. The new design is based on the addition of the third braking light, positioned in the centre (see figure 12) and at a height that allows this light to be seen through the windshields of the car proceeding the car immediately in front. This new design solution has two DPs:

DP1 = A new rear lighting system (NRLS).
DP2 = EBM (the same as before).

The formal design classification of the new solution is uncoupled design. The design matrix for this new design is as follows:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

MLRT	X	0	NRLS
ASB	0	X	EBM

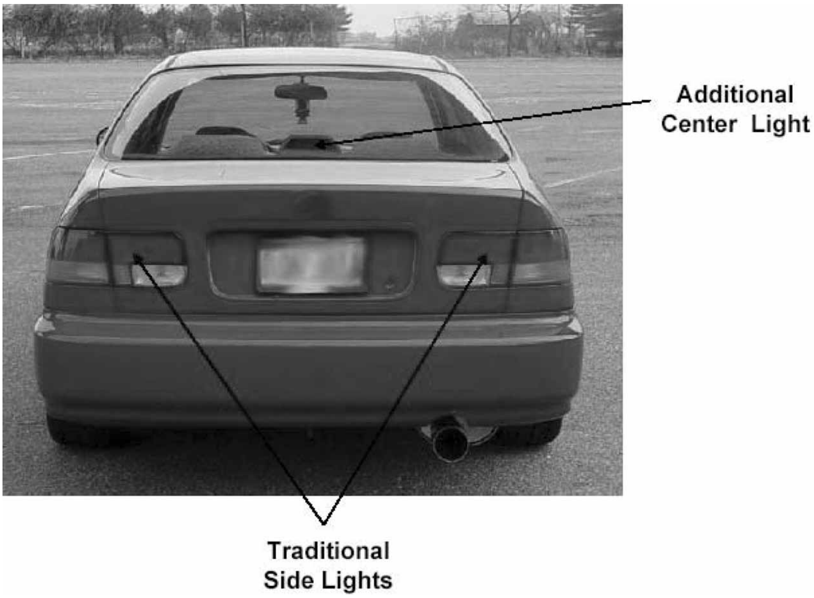


Figure 12. Illustration of the redesigned rear light system of an automobile.

The original TRLS can be classified as a decoupled design. This old design ($DP_{1,O}$) does not compensate for the lack of early warning that would allow drivers to maximize lead response time whenever braking is needed and, therefore, violates the second functional requirement (FR_2) of safe braking requirement. The design matrix for new system (NRLS) is an uncoupled design that satisfies the independence of FRs (independence axiom). This uncoupled design ($DP_{1,N}$) fulfils the requirement of maximizing lead response time whenever braking is needed and does not violate the FR_2 (safe braking requirement).

8. Theoretical ergonomics: symvatology

The system-human interactions often represent complex phenomena with dynamic compatibility requirements. These are often non-linear and can be unstable (chaotic) phenomena, modelling of which requires a specialized approach. Karwowski (2001) indicated a need for symvatology, as a corroborative science to ergonomics that can help in developing solid foundations for ergonomics science. The proposed sub-discipline is called symvatology, or the science of the human–human (system) compatibility. Symvatology aims to discover laws of the human–human compatibility, propose theories of the human–human compatibility and develop a quantitative matrix for measurement of such compatibility. Karwowski (2000) coined the term symvatology, by joining two Greek words: *symvatotis* (compatibility) and *logos* (logic, or reasoning about). Symvatology is the systematic study (which includes theory, analysis, design, implementation and application) of interaction processes that define, transform and control compatibility relationships between artefacts (systems) and people. An artefact system is defined as a set of all artefacts (meaning objects made by human work), as well as natural elements of the environment and their interactions occurring in time and space afforded by nature. A human system is defined as the human (or humans) with all the characteristics (physical, perceptual, cognitive, emotional, etc.), which are relevant to an interaction with the artefact system.

To optimize both the human and system well-being and performance, the system–human compatibility should be considered at all levels, including the physical, perceptual, cognitive, emotional, social, organizational, managerial, environmental and political. This requires a way to measure the inputs and outputs that characterize the set of system–human interactions (Karwowski 1991, Karwowski and Jamaldin, 1995). The goal of quantifying the human–human compatibility can only be realized if its nature is understood. Symvatology aims to observe, identify, describe, perform empirical investigations and produce theoretical explanations of the natural phenomena of the human–human compatibility. As such, symvatology should help to advance the progress of the ergonomics discipline by providing a methodology for design for compatibility, as well as a design of compatibility between the artificial systems (technology) and the humans. In the above perspective, the goal of ergonomics should be to optimize both the human and system well-being and their mutually dependent performance. As pointed out by Hancock (1997), it is not enough to ensure the well-being of the human, as one must also optimize the well-being of a system (i.e. the based-based technology and nature) to make the proper uses of life.

Due to the nature of the interactions, an artefact system is often a dynamic system with a high level of complexity and it exhibits non-linear behaviour. The American Heritage Dictionary of English Language (1978) defines ‘complex’ as consisting of interconnected or interwoven parts. Karwowski *et al.* (1988, 1995), proposed to represent the human-human system (S) as a construct, which contains the human subsystem (H), an artefact subsystem (A), an environmental subsystem (E) and a set of interactions (I) occurring between different elements of these subsystems over time (t). In the above framework, compatibility is a dynamic, natural phenomenon that is affected by the human–human system structure, its inherent complexity and its entropy or level of incompatibility between the system’s elements. Since the structure of system interactions (I) determines the complexity and related compatibility relationships in a given system, compatibility should be considered in relation to the system’s complexity.

The system space (see figure 13), denoted here as an ordered set (complexity, compatibility), was defined by the four pairs as follows: (high, high); (high, low); (low, high); (low, low). Under the best scenario, i.e. under the most optimal state of system design, the human–human system exhibits high compatibility and low complexity levels. It should be noted that the transition from the high to the low level of system complexity does not necessarily lead to an improved (higher) level of system compatibility. Also, it is often the case in most of the human–human systems that improved (higher) system compatibility can be achieved only at the expense of increasing the system’s complexity.

As discussed by Karwowski *et al.* (1988), the lack of compatibility, or ergonomics incompatibility, defined as degradation (disintegration) of the human–human system, is reflected in the system’s measurable inefficiency and associated human losses. In order to express the innate relationship between the system’s complexity and compatibility, Karwowski *et al.* (1988, 1994) proposed the Complexity-Incompatibility Principle, which can be stated as follows:

> As the (artefact-human) system complexity increases, the incompatibility between the system elements, as expressed through their ergonomic interactions at all system levels, also increases, leading to greater ergonomic (non-reducible) entropy of the system and decreasing the potential for effective ergonomic intervention.

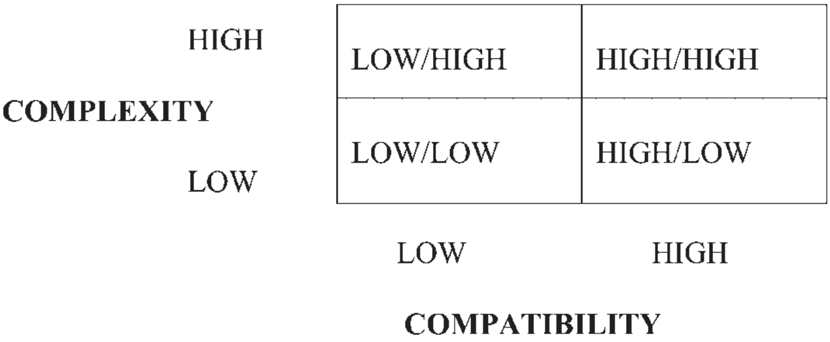


Figure 13. Complexity – compatibility paradigm in human factors and ergonomics research.

The above principle was illustrated by Karwowski (1995), using examples of chair design (see figure 14) and computer display design, which represent two common problems in the area of human – computer interaction. In addition, Karwowski (1996) discussed the complexity-compatibility paradigm in the context of organizational design. It should be noted that the above principle reflects the natural phenomena that others in the field have described in terms of difficulties encountered in human interactions with consumer products and technology in general. For example, according to Norman (1988), the paradox of technology is that added functionality to an artefact typically comes with the trade-off of increased complexity. These added complexities often lead to increased human difficulty and frustration when interacting with these artefacts. One of the reasons for the above is that technology that has more features may also provide less feedback. As noted by Norman (1988), the added complexity cannot be avoided when functions are added and can only be minimized with good design that follows natural mapping between the system elements (i.e. the control-display compatibility). Following Ashby's (1964) law of requisite variety, Karwowski (1995) proposed the corresponding law, called the 'law of requisite (ergonomics) complexity', which states that only (ergonomics) design complexity can reduce system complexity. The above means that only added complexity of the regulator (R = re/design), expressed by the system compatibility requirements, can be used to reduce the ergonomics system entropy, i.e. reduce the overall human – human system incompatibility.

9. Congruence between management and ergonomics

Advanced technologies, with which humans interact today, constitute complex systems that require a high level of integration from both the design and management perspectives (Karwowski *et al.* 1994b). Design integration typically focuses on the interactions between hardware (computer-based technology), organization (organizational structure), information system and people (human skills, training and expertise). Management integration refers to the interactions between various system elements across process and product quality, workplace and work system design, occupational safety and health programmes and corporate environmental protection polices.

Scientific management originated with the work by Frederick W. Taylor (1911), who studied, among other problems, *how jobs were designed* and how workers could be trained

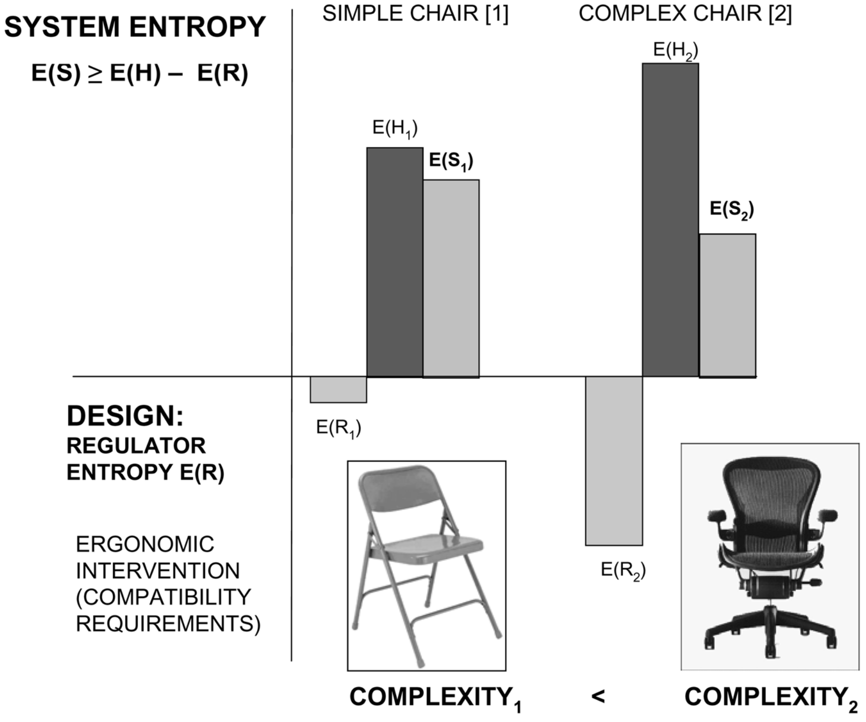


Figure 14. System entropy determination: example of a chair design (after Karwowski 2002)

to perform these jobs. The natural congruence between contemporary management and HFE can be described in the context of the respective definitions of these two disciplines. Management is defined today as a set of activities, including: 1) planning and decision-making; 2) organizing; 3) leading; and 4) controlling; directed at an organization's resources (human, financial, physical and information) with the aim of achieving organizational goals in an efficient and effective manner (Griffin 2001). The main elements of the management definition presented above, which are central to ergonomics, are the following: 1) organizing; 2) human resource planning; and 3) achieving effective and efficient of organizational goals. In the description of these elements, the original terms proposed by Griffin (2001) are applied in order to ensure precision of the used concepts and terminology. Organizing is deciding which way is the best for grouping organizational elements. Job design is the basic building block of organization structure. Job design focuses on identification and determination of the tasks and activities, for which the particular worker is responsible.

The basic ideas of management (i.e. planning and decision-making, organizing, leading and controlling) are also essential to HFE. Specifically, common to management and ergonomics are the issues of job design and job analysis. Job design is widely considered to be the first building block of an organizational structure. Systematic analysis of jobs within an organization provides for determination of an individual's work-related responsibilities. Human resource planning is an integral part of human resource management. The starting point for this business function is a job analysis, that is, a systematic analysis of workplaces in the organization. Job analysis consists of two parts:

1) job description; and 2) job specification. Job description should include description of task demands and work environment conditions, such as work tools, materials and machines needed to perform specific tasks. Job specification determines abilities, skills and other worker characteristics necessary for effective and efficient task performance in particular jobs.

The discipline of management also considers important human factors that play a role in achieving organizational goals in an effective and efficient manner. Such factors include: 1) work stress, in the context of individual worker behaviour; and 2) human resource management, in the context of safety and heath management. The work stress may be caused by the four categories of organizational and individual factors: 1) decisions related to task demands; 2) work environment demands including physical, perceptual and cognitive task demands; 3) role demands related to the relations with supervisor and co-workers; and 4) interpersonal demands, which can cause conflict between workers, e.g. management style, group pressure, etc. Human resource management includes provision of safe work conditions and environments at each workstation and workplace in the entire organization.

The elements of management discipline described above, such as job design, human resource planning (job analysis and job specification), work stress management and safety and health management, are essential components of the HFE sub-discipline, often called industrial ergonomics. Industrial ergonomics, which investigates the human – system relationships at the individual workplace (workstation) level or at the work system level, embraces knowledge that is also of central interest to management. From this point of view, industrial ergonomics in congruence with management is focusing on organization and management at the workplace level (work system level), through the design and assessment (testing and evaluation) of job tasks, tools, machines and work environments, in order to adapt these to the capabilities and needs of workers.

An established sub-discipline of HFE with regard to the central focus of management discipline is macroergonomics (Hendrick 1998). Macroergonomics is concerned with analysis, design and evaluation of work systems. Work denotes any form of human effort or activity. System refers to socio-technical systems, which range from a single individual to a complex multinational organization. A work system consists of people interacting with some form of: 1) job design (work modules, tasks, knowledge and skill requirements); 2) hardware (machines or tools) and/or software; (3) internal environment (physical parameters and psychosocial factors); (4) external environment (political, cultural and economic factors); and (5) an organizational design (i.e. the work system's structure and processes used to accomplishe desired functions). In this context, the unique technology of human factors/ergonomics (HF/E) is the human-system interface technology (Hendrick & Kleiner 2001).

10. Future challenges: neuro- and nanoergonomics

Contemporary HFE discipline exhibits rapidly expanding application areas, continuing improvements in research methodologies and increased contributions to fundamental knowledge as well as important applications to the needs of the society at large. For example, the sub-field of neuroergonomics focuses on the neural control and brain manifestations of the perceptual-physical-cognitive-emotional- etc., interrelationships in human work activities (Parasuraman 2003, Karwowski *et al.* 2003). As the science of brain and work environment, neuroergonomics aims to explore the premise of designing work to match the neural capacities and limitations of people. The potential benefits of this emerging branch of HFE are improvements of medical therapies and applications of more sophisticated workplace design principles. The near future will also see development of the entirely new HFE domain that can be called nanoergonomics. 'The idea of building machines at molecular scale, once fulfilled, will impact every facet of our lives, such as medicine, health care, computers, information, communication, environment, economy and many more.' (Henry T. Yang, Chancellor, University of California Santa Barbara). Nanoergonomics will address the issues of human interaction with devices and machines of extremely small dimensions and in general with nanotechnology.

Developments in technology and the socio-economic dilemmas of the 21st century pose significant challenges for the HFE discipline and profession. According to the report on '*Major predictions for science and technology in the 21st Century*' published by the Japan Ministry of Education, Science and Technology (2001), the following issues will affect the future of our civilization:

- Developments in genetics (DNA, human evolution, creation of an artificial life, extensive outer space exploration, living outside Earth).
- Developments in cognitive sciences (human cognitive processes through artificial systems).
- Revolutions in medicine (cell and organ regeneration, nano-robotics for diagnostics and therapy, super-prostheses, artificial photosynthesis of foods).
- Elimination of starvation and malnutrition (artificial photosynthesis of foods, safe genetic foods manipulation).
- Full recycling of resources and reusable energy (biomass and nanotechnology).
- Changes in human habitat (outer space cities, 100% underground industrial manufacturing, separation of human habitat from natural environments, protection of diversity of life form on Earth).
- Clean-up of the negative effects of the 21st century on the environment (organisms for environmental cleaning, regeneration of the ozone).
- Communication (non-verbal communication technology, new 3D projections systems).
- Politics (computerized democracy).
- Transport and travel (natural sources of clean energy, automated transport systems, revolutions in supersonic small aircraft and supersonic travel, underwater ocean travel).
- Safety and control over one's life (prevention of crime by brain intervention, human error avoidance technology, control of the forces of nature, intelligent systems for safety in all forms of transport).

The above issues will also affect the future directions in developments of the HFE discipline across science, engineering, design, technology and management of human-compatible systems.

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