CHAPTER 1

THE DISCIPLINE OF ERGONOMICS AND HUMAN FACTORS

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The purpose of science is mastery over nature.

F. Bacon (*Novum Organum, 1620*)

1 INTRODUCTION

Ergonomics (Gr. *ergon* + *nomos*), the study of work, was originally defined and proposed by the Polish scientist B. W. Jastrzebowski (1857a–d), as a scientific discipline with a very broad scope and a wide range of interests and applications, encompassing all aspects of human activity, including labor, 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: *useful work*, which brings improvements for the common good, and *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 spiritual forces. He lists the four main benefits of useful work as being exemplified by property, ability, perfection, and felicity.

The contemporary ergonomics discipline, introduced independently by Murrell in 1949 (Edholm and Murrell, 1973), was viewed at that time as an applied science, a technology, and sometimes both. British scientists founded the Ergonomics Research Society in 1949. According to Kuorinka (2000), the development of ergonomics internationally can be linked to a project initiated by the European Productivity Agency (EPA), a branch of the Organization for European Economic Cooperation, which established a Human Factors Section in 1955. Under the EPA project, in 1956 specialists from European countries visited the United States to observe human factors research. In 1957 the EPA organized a technical seminar, "Fitting the Job to the Worker," at the University of Leiden, The Netherlands, during which a set of proposals was presented to form an international association of work scientists. A Steering Committee consisting of H. S. Belding, G. C. E. Burger, S. Forssman, E. Grandjean, G. Lehman, B. Metz, K. U. Smith, and R. G. Stansfield, was charged with developing specific proposals for such an association. The committee decided to adopt the name International Ergonomics Association. At a meeting in Paris in 1958, it was decided to proceed with forming the new association. The Steering Committee designated itself the Committee for the International Association of Ergonomic Scientists and elected G. C. E. Burger as its first president,

K. U. Smith as treasurer, and E. Grandjean as secretary. The Committee for the International Association of Ergonomic Scientists met in Zurich in 1959 during a conference organized by EPA, and decided to retain the name International Ergonomics Association. On April 6, 1959, at a meeting in Oxford, England, Grandjean declared the founding of the International Ergonomics Association (IEA). The committee met again in Oxford later in 1959 and agreed on a set of bylaws for the IEA. These were formally approved by the IEA General Assembly at the first International Congress of Ergonomics, held in Stockholm in 1961.

Over the last 50 years, *ergonomics*, a term that is used here synonymously with *human factors* (denoted HFE), has been evolving as *a unique and independent discipline that focuses on the nature of human–artifact interactions, viewed from the unified perspective of the science, engineering, design, technology, and management of human-compatible systems, including a variety of natural and artificial products, processes, and living environments* (Karwowski, 2005). The various dimensions of the ergonomics discipline are shown in Figure 1.

The International Ergonomics Association (IEA, 2003) defines *ergonomics* (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*. Ergonomists contribute to the design and evaluation of tasks, jobs, products, environments, and systems to make them compatible with the needs, abilities, and limitations of people. Ergonomics discipline promotes a holistic, human-centered 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, 1999; Salvendy, 1997; Karwowski, 2001; Vicente, 2004; Stanton et al., 2004).

Traditionally, the domains of specialization within HFE cited most often are physical, cognitive, and organizational ergonomics. *Physical ergonomics* is concerned primarily with human anatomical, anthropometric, physiological, and biomechanical characteristics as they relate to physical activity (Chaffin and Anderson, 1993; Pheasant, 1986; Kroemer et al., 1994; Karwowski and Marras, 1999; NRC, 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 sociotechnical systems, including their organizational structures, policies, and processes (Reason, 1999; Holman et al., 2003; Nemeth,

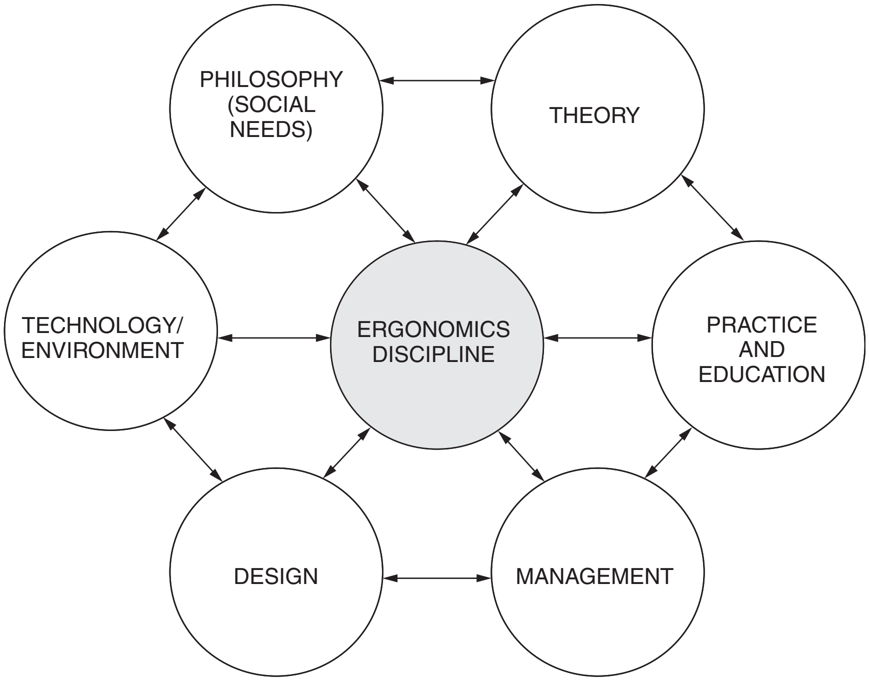


Figure 1 General dimensions of the HFE discipline. (After Karwowski, 2005.)

Table 1 Exemplary Domains of the Disciplines of Medicine, Psychology, and Ergonomics

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

Source: Karwowski (2005).

Table 2 Objectives of the HFE Discipline

- Basic operational objectives
  - Reduce errors
  - Increase safety
  - Improve system performance
- Objectives bearing on reliability, maintainability, 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

Source: Chapanis (1995).

2004). Examples of relevant topics include communication, crew resource management, design of working times, teamwork, participatory work design, community ergonomics, computer-supported cooperative work, new work paradigms, virtual organizations, telework, and quality management. The traditional domains noted above, together with new domains, are listed in Table 1.

According to the discussion above, the paramount objective of HFE is to understand interactions between people and everything that surrounds us, and based on such knowledge to optimize human well-being and overall system performance. Table 2 provides a summary of specific HFE objectives as discussed by Chapanis (1995). As pointed out by the National Academy of Engineering in the United States (NAE, 2004), in the future, ongoing developments in engineering will *expand toward tighter connections between technology and the human experience, including new products customized to the physical dimensions and capabilities of the user, and the ergonomic design of engineered products*.

2 HUMAN–TECHNOLOGY INTERACTIONS

Whereas 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 artifacts, as well as the artifacts themselves (NRC, 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 represents "design under constraints" of cost, reliability, safety, environmental impact, ease of use, available human and material resources, manufacturability, government regulations, laws, and politics (Wulf, 1988). 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 behavior, 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, 1997b). 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

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
34. Altitude, depth, and space
35. Other environmental issues

System Characteristics

36. General system features

Table 3 (*continued*)

Work Design and Organization

37. Total system design and evaluation
38. Hours of work
39. Job attitudes and job satisfaction
40. Job design
41. Payment systems
42. Selection and screening
43. Training
44. Supervision
45. Use of support
46. Technological and ergonomic change

Health and Safety

47. General health and safety
48. Etiology
49. Injuries and illnesses
50. Prevention

Social and Economic Impact of the System

51. Trade unions
52. Employment, job security, and job sharing
53. Productivity
54. Women and work
55. Organizational design
56. Education
57. Law
58. Privacy
59. Family and home life
60. Quality of working life
61. Political comment and ethical considerations

Methods and Techniques

62. Approaches and methods
63. Techniques
64. Measures

Source: EIAC (2004).

performance and product usability. The wide scope of issues addressed by the contemporary HFE discipline is presented in Table 3. Figure 2 illustrates the evolution of the scope of HFE with respect to the nature of human–system interactions. Originally, HFE focused on local human–machine interactions, whereas today, the primary focus is on broadly defined human–technology interactions. In this view the HFE can also be called the discipline of *technological ecology*. Tables 4 and 5 present the taxonomy of human- and technology-related components, respectively, which are of great importance to HFE discipline.

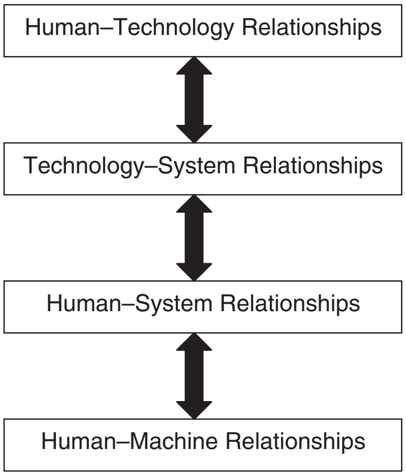


Figure 2 Expanded view of the human–technology relationships. (Modified from Meister, 1999.)

Table 5 Taxonomy of HFE Elements: Technology

- Technology elements
  - Components
  - Tools
  - Equipments
  - Systems
- Degree of automation
  - Mechanization
  - Computerization
  - Artificial intelligence
- System characteristics
  - Dimensions
  - Attributes
  - Variables
- Effects of technology on the human
  - Changes in human role
  - Changes in human behavior
- Organization–technology relationships
  - Definition of organization
  - Organizational variables

Source: Meister (1999).

According to Meister (1987), the traditional concept of a *human–machine system* is an organization of people and the machines they operate and maintain in order to perform assigned jobs that implement the purpose for which the system was developed. In this context, system is a *construct* whose characteristics are manifested in physical and behavioral phenomena (Meister, 1991). The system is critical to HFE theorizing because it describes the substance of the human–technology relationship. General system variables of interest to HFE discipline are shown in Table 6.

The human functioning in human–machine systems can be described in terms of perception, information processing, decision making, memory, attention, feedback, and human response processes. Furthermore, the human work taxonomy can be used to describe five distinct levels of human functioning, ranging from primarily physical tasks to cognitive tasks (Karwowski, 1992a). These basic but universal human activities are (1) tasks that produce force (primarily, muscular work), (2) tasks of continuously coordinating sensory-monitoring functions (e.g., assembling or tracking tasks), (3) tasks of converting information into motor actions (e.g., inspection tasks), (4) tasks of converting information into output information (e.g., required control tasks), and (5) tasks of producing information (primarily creative work) (Luczak et al., 1999). Any task in a human–machine system requires processing of information that is gathered based on perceived and interpreted relationships between system elements. The information processed may need to be stored by either a human or a machine for later use.

Table 4 Taxonomy of HFE Elements: The Human Factor

- Human elements
  - Physical/sensory
  - Cognitive
  - Motivational/emotional
- Human conceptualization
  - Stimulus–response orientation (limited)
  - Stimulus–conceptual–response orientation (major)
  - Stimulus–conceptual–motivational–response orientation (major)
- Effects of technology on the human
  - Performance effects
    - Goal accomplishment
    - Goal nonaccomplishment
    - Error/time discrepancies
    - Feeling effect
    - Technology acceptance
    - Technology indifference
    - Technology rejection
  - Demand effects
    - Resource mobilization
    - Stress/trauma
- Effects of the human on technology
  - Improvement in technology effectiveness
  - Absence of effect
  - Reduction in technological effectiveness
- Human–technological relationships
  - Controller relationship
  - Partnership relationship
  - Client relationship
- Human operations in technology
  - Equipment operation
  - Equipment maintenance
  - System management
  - Type/degree of human involvement
    - Direct (operation)
    - Indirect (recipient)
    - Extensive
    - Minimal
    - None

Source: Meister (1999).

Table 6 General System Variables

1. Requirements constraints imposed on the system
2. Resources required by the system
3. Nature of its internal components and processes
4. Functions and missions performed by the system
5. Nature, number, and specificity of goals
6. Structural and organizational characteristics of the system (e.g., its size, number of subsystems and units, communication channels, hierarchical levels, and amount of feedback)
7. Degree of automation
8. Nature of the environment in which the system functions
9. System attributes (e.g., complexity, sensitivity, flexibility, vulnerability, reliability, and determinancy)
10. Number and type of interdependencies (human–machine interactions) within the system and type of interaction (degree of dependency)
11. Nature of the system's terminal output(s) or mission effects

Source: Meister (1999).

The scope of HFE factors that need to be considered in the design, testing, and evaluation of any human–system interactions is shown in Table 7 in the form of an exemplary ergonomics checklist. It should be noted that such checklists also reflect practical application of the discipline. According to the Board of Certification in Professional Ergonomics (BCPE), a practitioner of ergonomics is a person who (1) has a mastery of a body of ergonomics knowledge, (2) has a command of the methodologies used by ergonomists in applying that knowledge to the design of a product, system, job, or environment, and (3) has applied his or her knowledge to the analysis, design testing, and evaluation of products, systems, and environments. The areas of current practice in the field can best be described by examining the focus of the Technical Groups of the Human Factors and Ergonomics Society, as illustrated in Table 8.

3 HFE AND ECOLOGICAL COMPATIBILITY

HFE discipline advocates *systematic use of knowledge concerning relevant human characteristics 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 (HFES), 2003]. Typically, such goals include improved (system) effectiveness, productivity, safety, ease of performance, and the

Table 7 Examples of Factors to Be Used in Ergonomics Checklists

I. Anthropometric, Biomechanical, and Physiological Factors

1. Are the differences in human body size accounted for by the design?
2. Have the right anthropometric tables been used for specific populations?
3. Are the body joints close to neutral positions?
4. Is the manual work performed close to the body?
5. Are any forward-bending or twisted trunk postures involved?
6. Are sudden movements and force exertion present?
7. Is there a variation in worker postures and movements?
8. Is the duration of any continuous muscular effort limited?
9. Are the breaks of sufficient length and spread over the duration of the task?
10. Is the energy consumption for each manual task limited?

II. Factors Related to Posture (Sitting and Standing)

1. Is sitting/standing alternated with standing/sitting and walking?
2. Is the work height dependent on the task?
3. Is the height of the worktable adjustable?
4. Are the height of the seat and backrest of the chair adjustable?
5. Is the number of chair adjustment possibilities limited?
6. Have good seating instructions been provided?
7. Is a footrest used where the work height is fixed?
8. Has work above the shoulder or with hands behind the body been avoided?
9. Are excessive reaches avoided?

Table 7 (*continued*)

10. Is there enough room for the legs and feet?
11. Is there a sloping work surface for reading tasks?
12. Have combined sit–stand workplaces been introduced?
13. Are handles of tools bent to allow for working with the straight wrists?

III. Factors Related to Manual Materials Handling (Lifting, Carrying, Pushing and Pulling Loads)

1. Have tasks involving manual displacement of loads been limited?
2. Have optimum lifting conditions been achieved?
3. Is anybody required to lift more than 23 kg?
4. Have lifting tasks been assessed using the NIOSH (Waters et al., 1993) method?
5. Are handgrips fitted to the loads to be lifted?
6. Is more than one person involved in lifting or carrying tasks?
7. Are there mechanical aids for lifting or carrying available and used?
8. Is the weight of the load carried limited according to recognized guidelines?
9. Is the load held as close to the body as possible?
10. Are pulling and pushing forces limited?
11. Are trolleys fitted with appropriate handles and handgrips?

IV. Factors Related to the Design of Tasks and Jobs

1. Does the job consist of more than one task?
2. Has a decision been made about allocating tasks between people and machines?
3. Do workers performing the tasks contribute to problem solving?
4. Are difficult and easy tasks performed interchangeably?
5. Can workers decide independently on how the tasks are carried out?
6. Are there sufficient possibilities for communication between workers?
7. Is sufficient information provided to control the tasks assigned?
8. Can the group take part in management decisions?
9. Are shift workers given enough opportunities to recover?

V. Factors Related to Information and Control Tasks

Information

I. Has an appropriate method of displaying information been selected?
2. Is the information presentation as simple as possible?
3. Has the potential confusion between characters been avoided?
4. Has the correct character/letter size been chosen?
5. Have texts with capital letters only been avoided?
6. Have familiar typefaces been chosen?
7. Is the text/background contrast good?
8. Are the diagrams easy to understand?
9. Have the pictograms been used properly?
10. Are sound signals reserved for warning purposes?

Control

1. Is the sense of touch used for feedback from controls?
2. Are differences between controls distinguishable by touch?
3. Is the location of controls consistent, and is sufficient spacing provided?
4. Have the requirements for control–display compatibility been considered?
5. Is the type of cursor control suitable for the intended task?
6. Is the direction of control movements consistent with human expectations?
7. Are the control objectives clear from the position of the controls?
8. Are controls within easy reach of female workers?

(*continued overleaf*)

Table 7 (*continued*)

9. Are labels or symbols identifying controls used properly?
10. Is the use of color in controls design limited?

Human–computer interaction

1. Is the human–computer dialogue suitable for the intended task?
2. Is the dialogue self-descriptive and easy to control by the user?
3. Does the dialogue conform to the expectations on the part of the user?
4. Is the dialogue error-tolerant and suitable for user learning?
5. Has command language been restricted to experienced users?
6. Have detailed menus been used for users with little knowledge and experience?
7. Is the type of help menu fitted to the level of the user's ability?
8. Has the QWERTY layout been selected for the keyboard?
9. Has a logical layout been chosen for the numerical keypad?
10. Is the number of function keys limited?
11. Have the limitations of speech in human–computer dialogue been considered?
12. Are touch screens used to facilitate operation by inexperienced users?

VI. Environmental Factors

Noise and vibration

1. Is the noise level at work below 80 dBA?
2. Is there an adequate separation between workers and source of noise?
3. Is the ceiling used for noise absorption?
4. Are acoustic screens used?
5. Are hearing conservation measures fitted to the user?
6. Is personal monitoring to noise/vibration used?
7. Are the sources of uncomfortable and damaging body vibration recognized?
8. Is the vibration problem being solved at the source?
9. Are machines regularly maintained?
10. Is the transmission of vibration prevented?

Illumination

1. Is the light intensity for normal activities in the range 200 to 800 lux?
2. Are large brightness differences in the visual field avoided?
3. Are the brightness differences between task area, close surroundings, and wider surroundings limited?
4. Is the information easily legible?
5. Is ambient lighting combined with localized lighting?
6. Are light sources properly screened?
7. Can light reflections, shadows, or flicker from the fluorescent tubes be prevented?

Climate

1. Are workers able to control the climate themselves?
2. Is the air temperature suited to the physical demands of the task?
3. Is the air prevented from becoming either too dry to too humid?
4. Are drafts prevented?
5. Are the materials/surfaces that have to be touched neither too cold nor too hot?
6. Are the physical demands of the task adjusted to the external climate?
7. Are undesirable hot and cold radiation prevented?
8. Is the time spent in hot or cold environments limited?
9. Is special clothing used when spending long periods in hot or cold environments?

Source: Based on Dul and Weerdmeester (1993).

Table 8 Subject Interests of Technical Groups of the Human Factors and Ergonomics Society

	Technical Group	Description/Areas of Concern
I.	Aerospace systems	Applications of human factors to the development, design, operation, and maintenance of human–machine systems in aviation and space environments (both civilian and military).
II.	Aging	Human factors applications appropriate to meeting the emerging needs of older people and special populations in a wide variety of life settings.
III.	Cognitive engineering and decision making	Research on human cognition and decision making and the application of this knowledge to the design of systems and training programs. Emphasis is on considerations of descriptive models, processes, and characteristics of human decision making, alone or in conjunction with other people or with intelligent systems; factors that affect decision making and cognition in naturalistic task settings; technologies for assisting, modifying, or supplementing human decision making; and training strategies for assisting or influencing decision making.
IV.	Communications	All aspects of human-to-human communication, with an emphasis on communication mediated by telecommunications technology, including multimedia and collaborative communications, information services, and interactive broadband applications. Design and evaluation of enabling technologies and infrastructure technologies in education, medicine, business productivity, and personal quality of life.
V.	Computer systems	Human factors aspects of (1) interactive computer systems, especially user-interface design issues; (2) the data-processing environment, including personnel selection, training, and procedures; and (3) software development.
VI.	Consumer products	Development of consumer products that are useful, usable, safe, and desirable. Application of the principles and methods of human factors, consumer research, and industrial design to ensure market success.
VII.	Education	Design of educational systems, environments, interfaces, and technologies, as well as human factors education. Improvement in educational design and addressing educational needs of those seeking to increase their knowledge and skills in the human factors/ergonomics field.
VIII.	Environmental design	Ergonomic and macroergonomic aspects of the constructed physical environment, including architectural and interior design aspects of home, office, and industrial settings. Promotion of the use of human factors principles in environmental design.
IX.	Forensics professional	Application of human factors knowledge and technique to ‘‘standards of care’’ and accountability established within legislative, regulatory, and judicial systems. Emphasis on providing a scientific basis to issues being interpreted by legal theory.
X.	Industrial ergonomics	Application of ergonomics data and principles for improving safety, productivity, and quality of work in industry. Concentration on service and manufacturing processes, operations, and environments.
XI.	Internet	Human factor aspects of user-interface design of Web content, Web-based applications, Web browsers, Webtops, Web-based user assistance, and Internet devices; behavioral and sociological phenomena associated with distributed network communication; human reliability in administration and maintenance of data networks; and accessibility of Web-based products.
XII.	Macroergonomics	Improving productivity and quality of work life and integrating psychosocial, cultural, and technological factors with human–machine performance interface factors in the design of jobs, workstations, organizations, and related management systems.
XIII.	Medical systems and functionally impaired populations	All aspects of the application of human factors principles and techniques toward the improvement of medical systems, medical devices, and the quality of life for functionally impaired user populations.
XIV.	Perception and performance	The relationship between vision and human performance, including (1) the nature, content, and quantification of visual information and the context in which it is displayed; (2) the physics and psychophysics of information display; (3) perceptual and cognitive representation and interpretation of displayed information; (4) workload assessment using visual tasks; and (5) actions and behaviors that are consequences of visually displayed information.
XV.	Safety	Research and applications concerning human factors in safety and injury control in all settings and attendant populations, including transportation, industry, military, office, public building, recreation, and home improvements.

(*continued overleaf*)

Table 8 (*continued*)

Technical Group		Description/Areas of Concern
XVI.	System development	Concerned with research and exchange of information for integrating human factors into the development of systems. Integration of human factors activities into system development processes in order to provide systems that meet user requirements.
XVII.	Surface transportation	Human factor aspects of mechanisms for conveying humans and resources: (1) passenger, commercial, and military vehicles, on- and off-road; (2) mass transit; maritime transportation; (3) rail transit, including vessel traffic services; (4) pedestrian and bicycle traffic; (5) and highway and infrastructure systems, including intelligent transportation systems.
XVIII.	Test and evaluation	A forum for test and evaluation practitioners and developers from all areas of human factors and ergonomics. Concerned with methodologies and techniques that have been developed in their respective areas.
XIX.	Training	Fosters information and interchange among people interested in the fields of training and training research.
XX.	Virtual environment	Human factors issues associated with human–virtual environment interaction, including (1) maximizing human performance efficiency in virtual environments; (2) ensuring health and safety; and (3) circumventing potential social problems through proactive assessment.

contribution to overall human well-being and quality of life. Although the term *compatibility* is a key word in the definition above, it has been used primarily in a narrow sense only, often in the context of the design of displays and controls, including studies of spatial (location) compatibility or the intention–response–stimulus compatibility related to the movement of controls (Wickens and Carswell, 1997). Karwowski and his co-workers (Karwowski et al., 1988; Karwowski, 1985, 1991) advocated the use of *compatibility* in a greater context of the ergonomics system. For example, Karwowski (1997) introduced the term *human-compatible systems* to focus on the need for comprehensive treatment of compatibility in the human factors discipline.

The *American Heritage Dictionary of the English Language* (Morris, 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, 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 psychophysiological responses of the human body (e.g., heart rate, electromyography, 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 profession (Karwowski, 1998). However, even though 20 years ago ergonomics was perceived by some (see, e.g., Howell, 1986) as a highly unpredictable area of human scientific endeavor, today HFE has positioned itself as a unique, *design-oriented* discipline, independent of engineering and medicine (Moray, 1994; Sanders and McCormick, 1993; Helander, 1997a; Karwowski, 1991, 2003).

Figure 3 illustrates the human-system 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 among a human operator (human capacities and limitations), technology (in terms of products, machines, devices, processes, and computer-based systems), and 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 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 system (enterprise) performance is affected by matching of the positive and negative outcomes of the complex compatibility relationships among the human operator, technology, and the environment. Positive outcomes include such measures as work productivity, performance times, product quality, and subjective psychological (desirable) behavioral outcomes such as job satisfaction, employee morale, human well-being, and commitment. The negative outcomes include both human and system-related errors, loss of productivity, low quality, accidents, injuries, physiological stresses, and subjective psychological (undesirable) behavioral outcomes such as job dissatisfaction, job/occupational stress, and discomfort.

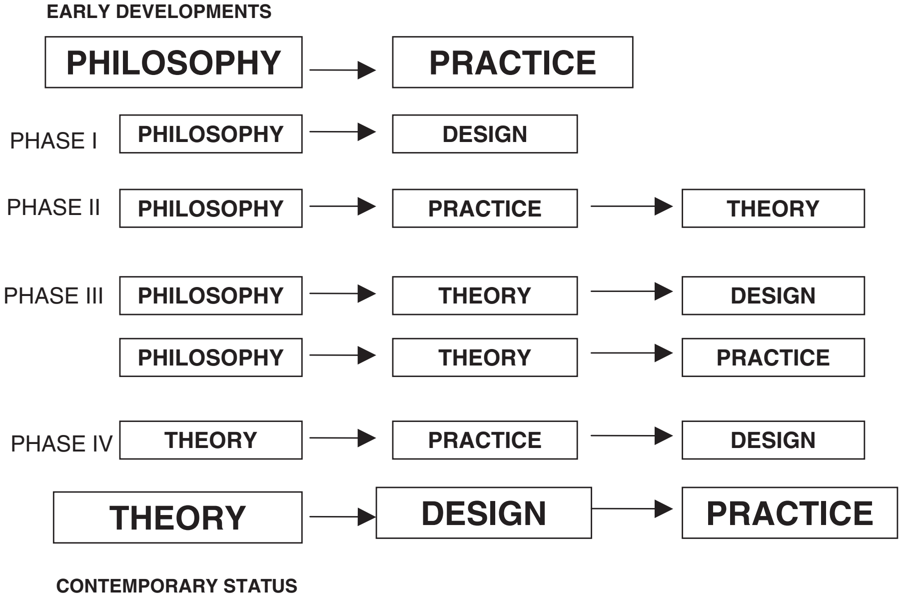


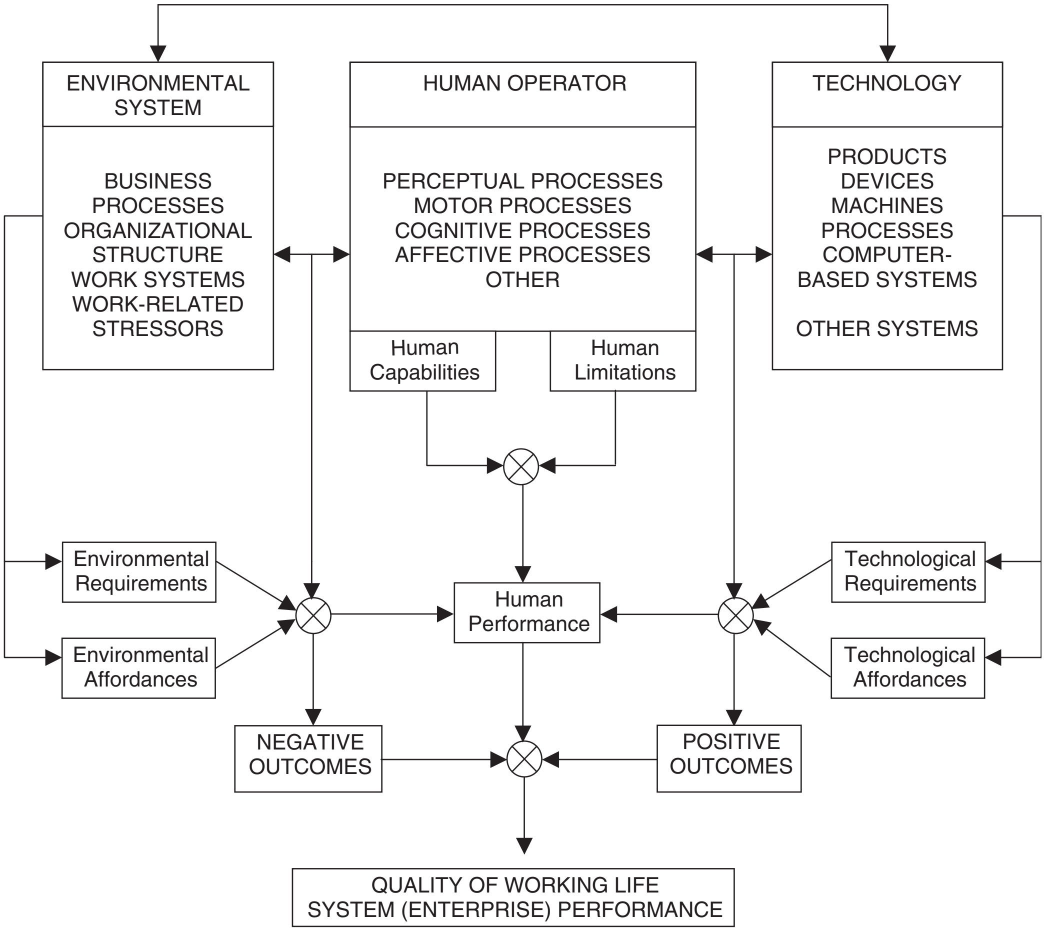
Figure 3 Evolution in development of the HFE discipline. (After Karwowski, 2005.)

4 DISTINGUISHING FEATURES OF THE CONTEMPORARY HFE DISCIPLINE AND PROFESSION

The main focus of the HFE discipline in the twenty-first century is on the design and management of systems that satisfy customer demands in terms of human compatibility requirements. Karwowski (2005) has discussed 10 characteristics of 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 in a manner similar to medicine, engineering, and psychology (see Table 1).
5. HFE deals with very complex phenomena that are not easily understood and cannot be simplified by making nondefendable assumptions about their nature.
6. Historically, HFE has been developing from the “philosophy of fit” toward practice. Today, HFE is developing a sound theoretical basis for design and practical applications (Figure 4).
7. HFE attempts to “by-step” the need for fundamental understanding of human–system interactions, without separation from a consideration of knowledge utility for practical applications, in the quest for immediate and useful solutions (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 socioeconomic development.
9. HFE has 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 the interactions between people and their environments. Also central to HFE interests is an understanding of how human–system interactions should be designed. On the other hand, HFE also falls under the category of applied research. Taxonomy of research efforts with respect 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 interpretation of these categories for HFE theory, design, and applications. Table 9 presents relevant specialties and subspecialties in HFE research as outlined by Meister (1999), who classified them into three main categories: (1) system/technology-oriented specialties,



Note: ⊗ – Matching of compatibility relationships

Figure 4 Human–system compatibility approach to ergonomics. (After Karwowski, 2005.)

		CONSIDERATIONS OF USE?	
		NO	**YES**
QUEST FOR FUNDAMENTAL UNDERSTANDING?	**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 HFE research. (After Karwowski, 2005.)

Table 9 Specialties and Subspecialties in HFE Research

System/Technology-Oriented Specialties

1. *Aerospace*: civilian and military aviation and outer-space activities.
2. *Automotive*: automobiles, buses, railroads, transportation functions (e.g., highway design, traffic signs, ships).
3. *Communication*: telephone, telegraph, radio, direct personnel communication in a technological context.
4. *Computers*: anything associated with the hardware and software of computers.
5. *Consumer products*: other than computers and automobiles, any commercial product sold to the general public (e.g., pens, watches, TV sets).
6. *Displays*: equipment used to present information to operators (e.g., HMO, HUD, meters, scales).
7. *Environmental factors/design*: the environment in which human–machine system functions are performed (e.g., offices, noise, lighting).
8. *Special environment*: this turns out to be underwater.

Process-Oriented Specialties

1. *Biomechanics*: human physical strength as it is manifested in such activities as lifting and pulling.
2. *Industrial ergonomics (IE)*: related primarily to manufacturing; processes and resultant problems (e.g., carpal tunnel syndrome).
3. *Methodology/measurement*: ways of answering HFE questions or solving HFE problems.
4. *Safety*: closely related to IE but with a major emphasis on analysis and prevention of accidents.
5. *System design/development*: processes of analyzing, creating, and developing systems.
6. *Training*: how personnel are taught to perform functions/tasks in a human–machine system.

Behaviorally Oriented Specialties

1. *Aging*: the effect of this process on technological performance.
2. *Human functions*: emphasizes perceptual-motor and cognitive functions. The latter differs from training in the sense that training also involves cognition but is the process of implementing cognitive capabilities. (The HFES specialty called *cognitive ergonomics/decision making* has been categorized.)
3. *Visual performance*: how people see; differs from displays in that the latter relate to equipment for seeing, whereas the former deals with the human capability and function of seeing.

Source: Adapted from Meister (1999).

(2) process-oriented specialties, and (3) behaviorally oriented specialties. In addition, Table 10 presents a list of contemporary HFE research methods that can be used to advance knowledge, discovery, and utilization through its practical applications.

5 PARADIGMS FOR THE 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 (modeling) is a foundation of the natural sciences, where progress is achieved by formulating hypotheses and following the modeling process systematically to verify and validate them. Design as the basis for engineering, where progress is achieved primarily by posing problems and systematically following the design process to construct systems that solve them.

In view of the above, Karwowski (2005) discussed the following paradigms for HFE discipline: (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 (NRC, 2001). A definition of ergonomics discipline and profession adopted by IEA (2003) emphasizes fundamental questions and significant accomplishments, recognizing that the HFE field is constantly changing. A teaching paradigm for ergonomics should conform to established scientific

Table 10 Contemporary HFE Research Methods

Physical Methods

PLIBEL: method assigned for identification of ergonomic hazards Musculoskeletal discomfort surveys used at NIOSH
Dutch musculoskeletal questionnaire
Quick exposure checklist for the assessment of workplace risks for work-related musculoskeletal disorders
Rapid upper limb assessment
Rapid entire body assessment
Strain index
Posture checklist using personal digital assistant technology
Scaling experiences during work: perceived exertion and difficulty
Muscle fatigue assessment: functional job analysis technique
Psychophysical tables: lifting, lowering, pushing, pulling, and carrying
Lumbar motion monitor
Occupational repetitive action (OCRA) methods: OCRA index and OCRA checklist
Assessment of exposure to manual patient handling in hospital wards: MAPO (movement and assistance of hospital patients) index

Psychophysiological Methods

Electrodermal measurement
Electromyography
Estimating mental effort using heart rate and heart rate variability
Ambulatory methods and sleepiness
Assessing brain function and mental chronometry with event-related potentials
MEG and fMRI Magnetoencephalography and magnetic resonance imaging.
Ambulatory assessment of blood pressure to evaluate workload
Monitoring alertness by eyelid closure
Measurement of respiration in applied human factors and ergonomics research

Behavioral and Cognitive Methods

Observation
Heuristics
Applying interviews to usability assessment
Verbal protocol analysis
Repertory grid for product evaluation
Focus groups
Hierarchical task analysis
Allocation of functions
Critical decision method
Applied cognitive work analysis
Systematic human error reduction and prediction approach
Predictive human error analysis
Hierarchical task analysis
Mental workload
Multiple resource time sharing
Critical path analysis for multimodal activity
Situation awareness measurement and the situation awareness
keystroke level model
GOMS (Goals, operators, methods, and selection rules)
Link analysis
Global assessment technique

Team Methods

Team training
Distributed simulation training for teams
Synthetic task environments for teams
Event-based approach to training
Team building
Measuring team knowledge
Team communications analysis
Questionnaires for distributed assessment of team mutual awareness

Table 10 (*continued*)

Team decision requirement exercise: making team decision requirements explicit
Targeted acceptable responses to generated events or tasks
Behavioral observation scales
Team situation assessment training for adaptive coordination
Team task analysis
Team workload
Social network analysis
Environmental Methods
Thermal conditions measurement
Cold stress indices
Heat stress indices
Thermal comfort indices
Indoor air quality: chemical exposures
Indoor air quality: biological/particulate-phase contaminant
Exposure assessment methods
Olfactometry: human nose as a detection instrument
Context and foundation of lighting practice
Photometric characterization of the luminous environment
Evaluating office lighting
Rapid sound-quality assessment of background noise
Noise reaction indices and assessment
Noise and human behavior
Occupational vibration: a concise perspective
Habitability measurement in space vehicles and earth analogs
Macroergonomic Methods
Macroergonomic organizational questionnaire survey
Interview method
Focus groups
Laboratory experiment
Field study and field experiment
Participatory ergonomics
Cognitive walk-through method
Kansei engineering
HITOP analysis TM
TOP-Modeler C
CIMOP system C
Anthropotechnology
Systems analysis tool
Macroergonomic analysis of structure
Macroergonomic analysis and design

Source: Based on Stanton et al. (2004).

standards, emphasize the 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 this promise. Design of interactions with technological artifacts and work systems requires 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 users to understand the utility and limitations of technological artifacts. Ergonomics literacy prepares people to perform their roles in the workplace and outside the working environment. Ergonomically literate people can learn enough about how technological systems operate to protect themselves by making informed choices and making use of beneficial affordances of the artifacts and environment. People trained in ergonomics typically possess a high level of knowledge and skill related to one or more specific area of ergonomics application. Ergonomics literacy is a prerequisite to ergonomics competency. The following can be proposed as dimensions for ergonomics literacy (Figure 6):

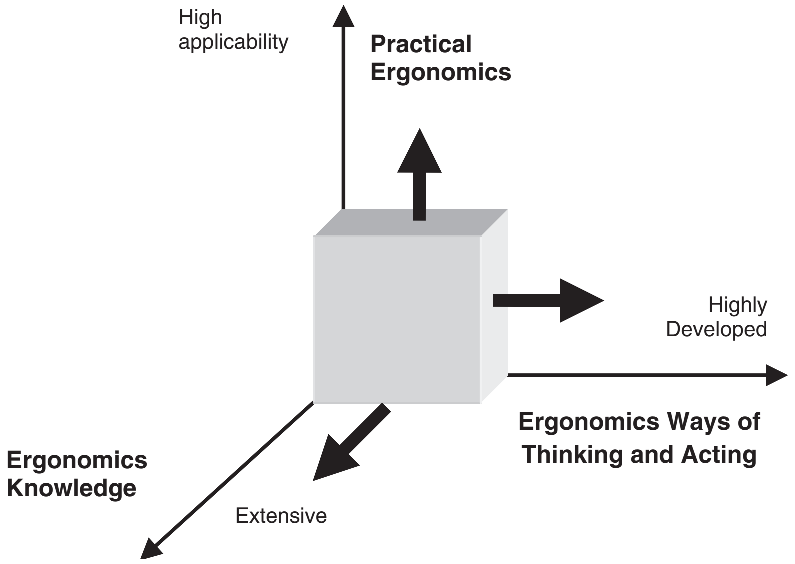


Figure 6 Desired goals for ergonomics literacy. (After Karwowski, 2005.)

1. *Ergonomics knowledge and skills.* A person has a basic knowledge of the philosophy of human-centered design and principles for accommodating human limitations.
2. *Ways of thinking and acting.* A person seeks information about benefits and risks of artifacts and systems (consumer products, services, etc.) and participates in decisions about purchasing and use and/or development of artifacts/ systems.
3. *Practical ergonomics capabilities.* A person can identify and solve simple task (job)-related design problems at work or home and can apply basic concepts of ergonomics to make informed judgments about usability of artifacts and the related risks and benefits of their use.

Finally, Table 11 presents a list of 10 standards for ergonomics literacy, which were proposed by Karwowski (2005) in parallel to a model of technological literacy reported by National Academy of Engineering (Pearson and Young, 2002). Eight of these standards are related to developing an understanding of the nature, scope, attributes, and the role of HFE discipline in modern society; two standards refer to the need for developing the abilities to apply the ergonomics design process and evaluate the impact of artifacts on human safety and well-being.

Table 11 Standards for Ergonomics Literacy: Ergonomics and Technology

An understanding of:

Standard 1: characteristics and scope of ergonomics
Standard 2: core concepts of ergonomics
Standard 3: 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: attributes of ergonomics design
Standard 8: role of ergonomics research, development, invention, and experimentation

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

Source: Karwowski (2005).

7 ERGONOMICS DESIGN

Ergonomics is a design-oriented discipline. However, as discussed by Karwowski (2003), ergonomists do not design systems; rather, HFE professionals design the interactions between artifact systems and humans. A fundamental problem involved in such a design is that typically there are multiple functional system–human compatibility requirements that must be satisfied at the same time. To address this issue, structured design methods for complex human–artifact 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 (Figure 7), or, more specifically, from the system–human compatibility needs to the relevant human–system interactions.

Suh (1990, 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"): (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 (2005) conceptualized the foregoing 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 human–system interactions and specific work system design solutions, and (4) processes domain, defined as management of compatibility (see Figure 9).

7.1 Axiomatic Design

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

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

where [**A**] is the design matrix that characterizes the product design. The design matrix [**A**] for three FRs and three DPs is

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

The following two design axioms, proposed by Suh (1990), are the basis for a formal methodology of design.

Axiom 1: Independence Axiom This 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).

Axiom 2: Information Axiom This 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 (FR_i) is defined in terms of the probability P_i of satisfying FR_i:

$$I_i = \log_2(1/P_i) = -\log_2 P_i \qquad \text{bits}$$

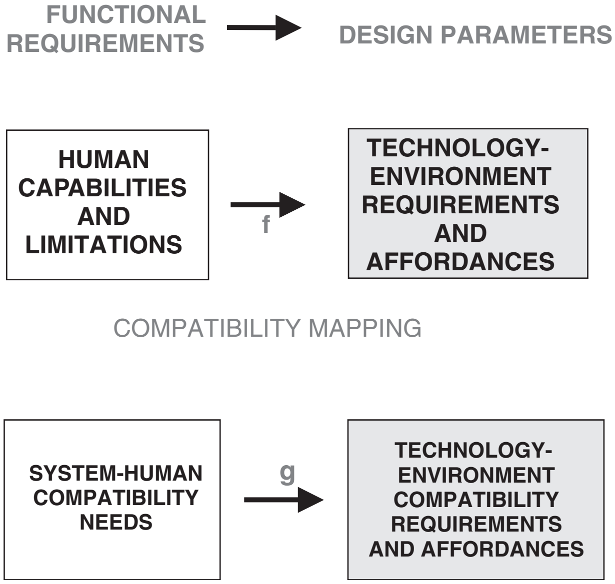


Figure 7 Ergonomics design process: compatibility mapping. (After Karwowski, 2005.)

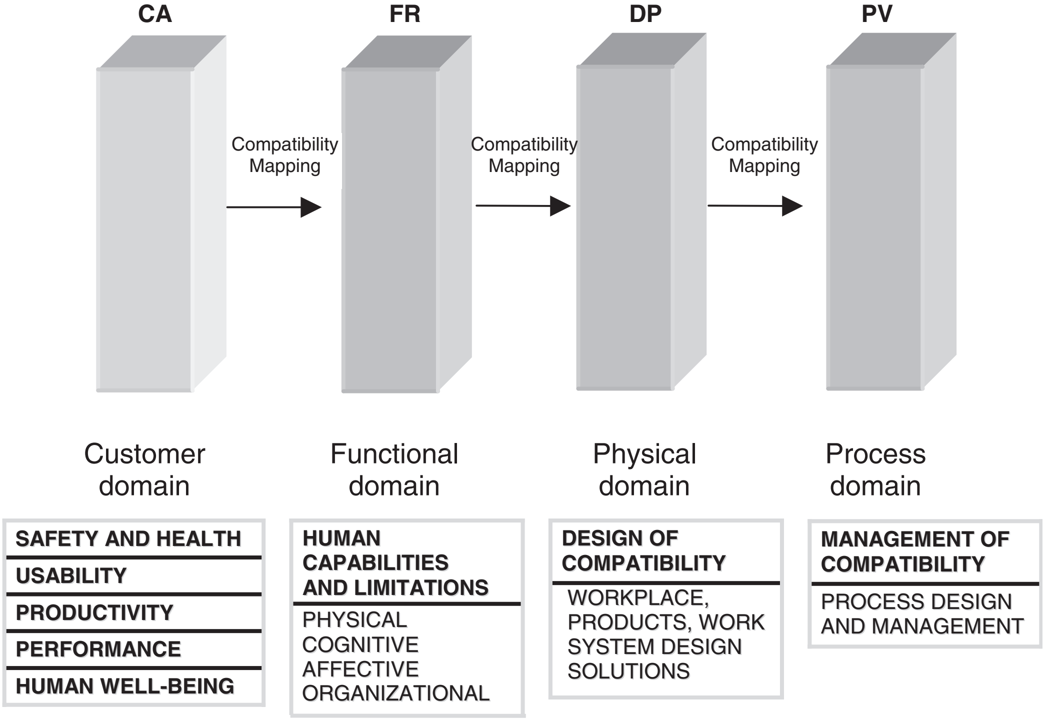


Figure 8 Four domains of axiomatic HFE design. (After Karwowski, 2005.)

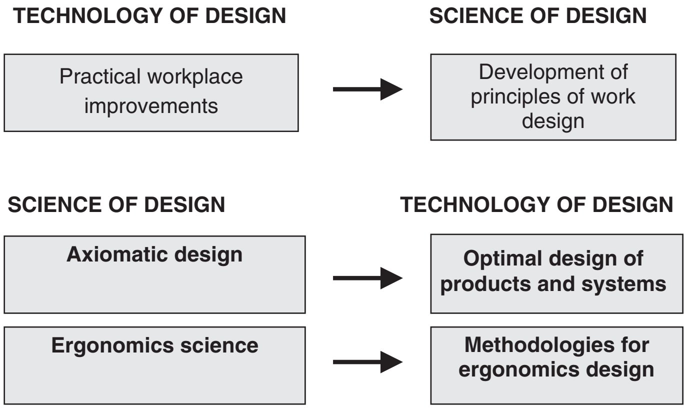


Figure 9 Axiomatic approach to ergonomics design. (After Karwowski, 2005.)

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

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

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

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

Axiom 1: Independence Axiom This 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: Human Incompatibility Axiom This 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.

As discussed by Karwowski (2001, 2003), in ergonomics design, axiom 2 can be interpreted as follows. The human incompatibility content of the design I_i for a given functional requirement (FR_i) is defined in terms of the compatibility C_i index satisfying FR_i:

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

where I denotes the incompatibility content of a design.

7.2 Theory of Axiomatic Design in Ergonomics

As discussed by Karwowski (1985, 1991, 1999, 2001, 2005), a need to remove the system–human incompatibility (or ergonomics entropy) plays the central role in ergonomics design. In view of this, the second axiomatic design axiom can be adopted for the purpose of ergonomics theory as follows.

The incompatibility content of the design I_i for a given functional compatibility requirement (FCR_i) is defined in terms of the compatibility C_i index that satisfies this FCR_i:

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

where I denotes the incompatibility content of a design, and the compatibility index $C_i (0 < C < 1)$ is defined depending on the specific design goals (i.e., the applicable or relevant ergonomics design criterion used for system design or evaluation).

To minimize 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 the 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 cases described above, the human–system incompatibility content can be assessed as discussed below.

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 is the maximum exposure (standard) for design parameter i and A_i is the actual value of a given design parameter i:

$$C_i = R_i/A_i$$

and hence

$$\begin{aligned} I_i &= -\log_2 C_i \\ &= -\log_2(R_i/A_i) = \log_2(A_i/R_i) \qquad \text{ints} \end{aligned}$$

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

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 is the actual value of a given design parameter i, and R_i is the desired reference or required (ideal) design parameter standard: i:

$$C_i = A_i/R_i$$

and hence

$$\begin{aligned} I_i &= -\log_2 C_i \\ &= -\log_2(A_i/R_i) = \log_2(R_i/A_i) \qquad \text{ints} \end{aligned}$$

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

As discussed by Karwowski (2004), the proposed units of measurement for system–human incompatibility (ints) are parallel and numerically identical to the measure of information (bits). The information content of the design in 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 spins, optimal number of choices, maximum number of hand repetitions per cycle time on a production line, minimum required decision time, and maximum heat load exposure per unit of time.

The general relationships between technology of design and science of design are illustrated in Figure 9. Furthermore, Figure 10 depicts such relationships for the HFE discipline. In the context of axiomatic design in ergonomics, the functional requirements are the human–system compatibility requirements,

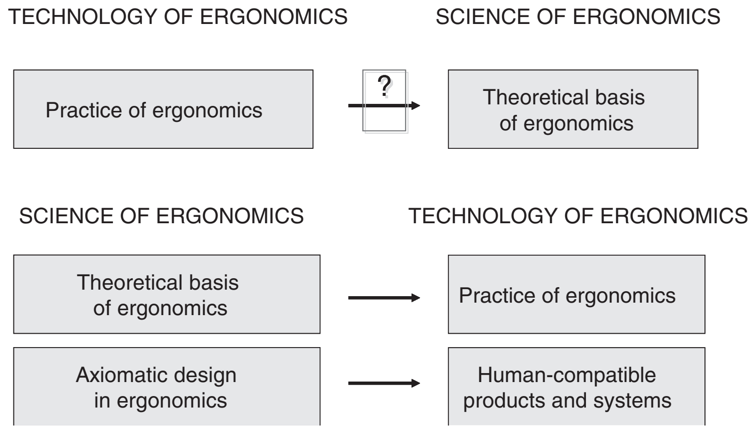


Figure 10 Science, technology, and design of human-compatible systems. (After Karwowski, 2005.)

while the design parameters are the human–system interactions. Therefore, ergonomics design can be defined as mapping from human–system compatibility requirements to 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.

7.3 Applications of Axiomatic Design

Helander (1995) was 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. Recently, Karwowski (2003) introduced the concept of system incompatibility measurements and the measure of incompatibility for ergonomics design and evaluation. Furthermore, Karwowski (2003) has also illustrated an application of the first design axiom adapted to the needs of ergonomics design, using an example of the design of the rear lighting system utilized to provide information about application of brakes in a passenger car. The rear lighting system is illustrated in Figure 11. 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 = provides early warning to maximize the lead response time(MLRT)| (information about the car in front that is applying brakes)

FR_2 = assures safe braking (ASB)

The traditional (old) design solution is based on two design parameters (DPs):

DP_1 = two rear brake lights on the sides (TRLS)

DP_2 = efficient braking mechanism (EBM)

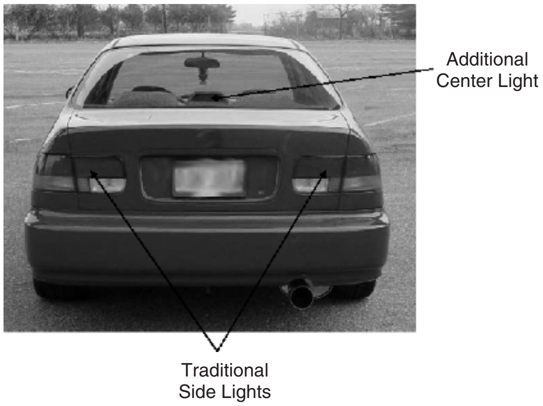


Figure 11 Redesigned rear light system of an automobile. (After Karwowski, 2005.)

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

$$\begin{Bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP}_1 \\ \mathrm{DP}_2 \end{Bmatrix}$$

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 slowdown. In other words, this rear lighting system does not provide early warning that would allow the driver to maximize his or her lead response time (MLRT) to braking.

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

$$\text{DP1} = \text{a new rear lighting system (NRLS)}$$

$$\text{DP2} = \text{efficient braking mechanism (EBM)(the same as before)}$$

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

$$\begin{Bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP}_1 \\ \mathrm{DP}_2 \end{Bmatrix}$$

MLRT	X	0	**NRLS**
ASB	0	X	EBM

It should be noted that the original (traditional) rear lighting system (TRLS) can be classified as decoupled design. This old design ($\mathrm{DP}_{1,O}$) does not compensate for the lack of early warning that would make it possible to maximize the driver's lead response time (MLRT) whenever braking is needed, and therefore violates the second functional requirement (FR_2) for a safe braking requirement. The design matrix for new system (NRLS) is an uncoupled design that satisfies the independence of functional requirements (independence axiom). This uncoupled design ($\mathrm{DP}_{1,N}$) fulfills the requirement of maximizing lead response time (MLRT) whenever braking is needed and does not violate the FR_2 (safe braking requirement).

8 THEORETICAL ERGONOMICS: SYMVATOLOGY

It should be noted that the system–human interactions often represent complex phenomena with dynamic compatibility requirements. The are often nonlinear and can be unstable (chaotic) phenomena, modeling 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 the ergonomics science. The proposed subdiscipline is *symvatology*, the science of the artifact–human (system) compatibility. Symvatology aims to discover the laws of artifact–human compatibility, propose theories of artifact–human compatibility, and develop a quantitative matrix for measurement of such compatibility. Karwowski (2001) 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 artifacts (systems) and people. An *artifact system* is defined as a set of all artifacts (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 a human (or humans) with all the characteristics (physical, perceptual, cognitive, emotional, etc.) that are relevant to an interaction with the artifact system.

To optimize both the human and system well-being and performance, 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). The goal of quantifying artifact–human compatibility can be realized only if we understand its nature. Symvatology aims to observe, identify, describe, perform empirical investigations, and produce theoretical explanations of the natural phenomena of artifact–human compatibility. As such, symvatology should help to advance the progress of ergonomics discipline by providing methodology for design for compatibility, as well as design of compatibility between the artificial systems (technology) and humans. In the perspective described above, the goal of ergonomics should be to optimize both human and system well-being and their mutually dependent performance. As pointed out by Hancock (1997), it is not enough to assure the well-being of humans; one must also optimize the well-being of systems (i.e., artifact-based technology and nature) to make proper uses of life.

Due to the nature of the interactions, an artifact system is often a dynamic system with a high level of complexity, that exhibits nonlinear behavior. The *American Heritage Dictionary of the English Language* (1978) defines *complex* as consisting of interconnected or interwoven parts. Karwowski et al. (1988) and Karwowski and Jamaldin (1995) proposed representing an artifact–human system as a construct that contains a human subsystem, an artifact subsystem, an environmental subsystem, and a set of interactions occurring between the various elements of these subsystems over time. In the framework above, compatibility is a dynamic, natural phenomenon that is affected by the artifact–human system structure, its inherent complexity, and its entropy or the level of incompatibility between the system's elements. Since the structure of system interactions 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, denoted here as an ordered set [(complexity, compatibility)], is defined by four pairs: (high, high), (high, low), (low, high), (low, low). Under the best scenario (i.e., the most optimal state of system design), the artifact–human system exhibits high compatibility and low complexity levels. It should be noted that the transition from a high to a 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 artifact–human systems that improved (higher) system compatibility can be achieved only at the expense of increasing system complexity.

As discussed by Karwowski and Jamaldin (1995) lack of compatibility, or ergonomics incompatibility (EI), defined as degradation (disintegration) of an artifact–human system, is reflected in the system's measurable inefficiency and associated human losses. To express the innate relationship between the systems's complexity and compatibility, Karwowski et al. (1988, 1994a) proposed the *complexity–incompatibility principle*, which can be stated as follows: *As artifact–human system complexity increases, the incompatibility between system elements, as expressed through their ergonomic interactions at all system levels, also increases, leading to greater ergonomic (nonreducible) entropy of the system and decreasing the potential for effective ergonomic intervention.*

The foregoing principle was illustrated by Karwowski (1995) using as examples design of a chair (see Figure 12) and design of a computer display, two common problems in the area of human–computer interaction. In addition, Karwowski and Jamaldin (1996) discussed the complexity–compatibility paradigm in the context of organizational design. It should be noted that the principle reflects the natural phenomena that others in the field have described in terms of difficulties encountered when humans interact with consumer products and technology in general. For example, according to Norman (1989), the paradox of technology is that adding functionality to an artifact typically comes with the trade-off of increased complexity. These added complexities often lead to increased human difficulty and frustration when interacting with these artifacts. One reason for the above is that technology, which has more features, also has less feedback. Moreover, Norman noted that added complexity cannot be avoided when functions are added, and can be minimized only with good design, which follows natural mapping between system elements (i.e., control–display compatibility). Following Ashby's (1964) law of requisite variety, Karwowski and Jamaldin (1995) proposed a corresponding law, called the *law of requisite complexity*, which states that only design complexity can reduce system complexity. This means that only added complexity of the regulator, expressed by system compatibility requirements, can be used to reduce ergonomics system entropy (i.e., reduce overall artifact–human system incompatibility).

9 CONGRUENCE BETWEEN MANAGEMENT AND ERGONOMICS

Advanced technologies with which humans interact toady constitute complex systems that require a high level of integration from both the *design and management* perspectives. *Design integration*

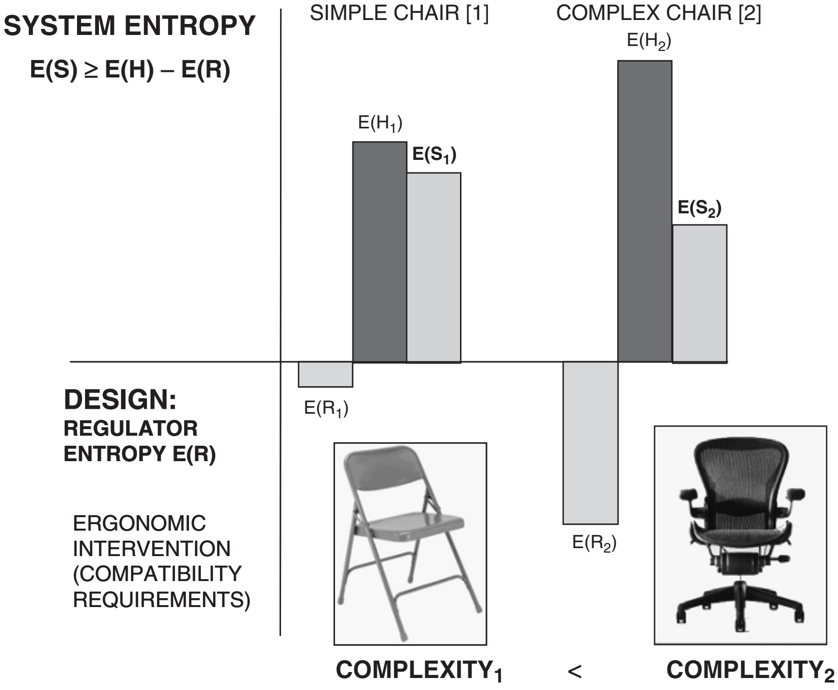


Figure 12 System entropy determination: example of chair design. (After Karwowski, 2002.)

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 interactions among various system elements across process and product quality, workplace and work system design, occupational safety and health programs, and corporate environmental protection polices.

Scientific management originated with the work of Frederick W. Taylor (1911), who studied, among other problems, *how jobs were designed* and how workers could be trained 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 and central to ergonomics are (1) *organizing*, (2) *human resource planning*, and (3) *effective and efficient achievement of organizational goals*. In the description of these elements, the original terms proposed by Griffin (2001) are applied to ensure precision of the concepts and terminology used. *Organizing* is deciding which method of organizational element grouping is best. *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.

It should be noted that 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. Job analysis as a systematic analysis of jobs within an organization allows determination of a person'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*: a systematic analysis of the workplaces in an organization. *Job analysis* consists of job description and 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 way*. Such factors include work stress in the context of individual worker behavior and human resource management in the context of safety and heath management. Work stress may be caused by the four categories of organizational and individual factors: (1) decision related to *task demands*; (2) *work environment demands*, including physical, perceptional, and cognitive task demands, as well as quality of the work environment (i.e., adjustment of tools and machines to human characteristics and capabilities); (3) *role demands* related to relations with supervisor and co-workers; and (4) *interpersonal demands*, which can cause conflict between workers (e.g., management style, group pressure). Human resource management includes the provision of safe work conditions and environment at each workstation, workplace, and in the entire organization.

It should also be noted that 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 an HFE subdiscipline often called *industrial ergonomics*. Industrial ergonomics investigates human–system relationships at the individual workplace (workstation) level or at the work system level, embracing 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.

Another important subdiscipline of HFE with respect to the central focus of management discipline is *macroergonomics*. According to Hendrick and Kleiner (2001), macroergonomics is concerned with the analysis, design, and evaluation of work systems. *Work* denotes any form of human effort or activity. *System* refers to *sociotechnical* systems, which range from a single person 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) organizational design (i.e., the work system's structure and processes used to accomplish desired functions).

The unique technology of human factors/ergonomics is the *human–system interface technology*. Human–system interface technology can be classified into five subparts, each with a related design focus (Hendrick, 1997; Hendrick and Kleiner, 2001):

1. *Human–machine* interface technology: hardware ergonomics
2. *Human–environment* interface technology: environmental ergonomics
3. *Human–software* interface technology: cognitive ergonomics
4. *Human–job* interface technology: work design ergonomics
5. *Human–organization* interface technology: macroergonomics

In this context, as discussed by Hendrick and Kleiner (2001), the HFE discipline discovers knowledge of human performance capabilities, limitations, and other human characteristics in order to develop human–system interface (HSI) technology, which includes interface design principles, methods, and guidelines. Finally, the HFE profession applies HSI technology to the design, analysis, test and evaluation, standardization, and control of systems.

10 INTERNATIONAL ERGONOMICS ASSOCIATION

Over the past 20 years, ergonomics as a scientific discipline and as a profession has grown rapidly by expanding the scope and breadth of theoretical inquiries, methodological basis, and practical applications (Meister 1997, 1999; Chapanis, 1999; Stanton and Young, 1999; Kuorinka, 2000; Karwowski, 2001; IEA, 2003). As a profession, the field of ergonomics has seen the development of formal organizational structures (i.e., national and cross-national ergonomics societies and networks) in support of HFE professionals internationally. As of 2004, the International Ergonomics Association (www.iea.cc), a federation of 42 ergonomics and human factors societies around the world, accounted for over 14,000 HFE members worldwide (see Table 12). The main goals of the IEA are to elaborate and advance the science and practice of ergonomics at the international level and to improve the quality of life by expanding the scope

Table 12 Membership by Federated Societies

Federated society	Name	Initials	Members
Australia	Ergonomics Society of Australia	ESA	536
Austria	Österreichische Arbeitsgemeinschaft für Ergonomie	OAE	32
Belgium	Belgian Ergonomics Society	BES	176
Brazil	Brazilian Ergonomics Society	ABERGO	140
Canada	Association of Canadian Ergonomists	ACE	545
Chile	Sociedad Chileana de Ergonomia	SOCHERGO	30
China	Chinese Ergonomics Society	ChES	450
Colombia	Sociedad Colombiana de Ergonomia	SCE	30
Croatia	Croatian Ergonomics Society	CrES	40
Czech Republic	Czech Ergonomics Society	CzES	33
Francophone Society	Societé d'Ergonomie Langue Française	SELF	680
Germany	Gesellschaft für Arbeitswissenschaft	GfA	578
Greece	Hellenic Ergonomics Society	HES	34
Hong Kong	Hong Kong Ergonomics Society	HKES	33
Hungary	Hungarian Ergonomics Society	MES	70
India	Indian Society of Ergonomics	ISE	53
Iran	Iranian Ergonomics Society	IES	30
Ireland	Irish Ergonomics Society	IrES	35
Israel	Israeli Ergonomics Society	IES	38
Italy	Societá Italiana di Ergonomia	SIA	191
Japan	Japan Ergonomics Society	JES	2,155
Mexico	Sociedad de Ergonomistas de Mexico	SEM	30
Netherlands	Nederlandse Vereniging Voor Ergonomie	NVVE	444
New Zealand	New Zealand Ergonomics Society	NZES	115
Nordic countries	Nordic Ergonomics Society	NES	1,510
Poland	Polish Ergonomics Society	PES	373
Portugal	Associação Portuguesa de Ergonomia	APERGO	101
Russia	Inter-Regional Ergonomics Association	IREA	207
Slovakia	Slovak Ergonomics Association	SEA	27
South Africa	Ergonomics Society of South Africa	ESSA	60
South Korea	Ergonomics Society of Korea	ESK	520
Southeast Asia	Southeast Asian Ergonomics Society	SEAES	64
Spain	Association Espanola de Ergonomia	AEE	151
Switzerland	Swiss Society for Ergonomics	SSE	128
Taiwan	Ergonomics Society of Taiwan	EST	98
Turkey	Turkish Ergonomics Society	TES	50
Ukraine	All-Ukrainian Ergonomics Association	AUEA	107
United Kingdom	Ergonomics Society	ES	1,024
United States	Human Factors and Ergonomics Society	HFES	3,655
Yugoslavia	Ergonomics Society of F. R. of Yugoslavia	ESFRY	50
Affiliated society	Human Ergology Society (Japan)	HES(J)	222
Total			14,845

Source: IEA, http://www.iea.cc/newsletter/nov2003.cfm.

of ergonomics applications and contributions to global society (Table 13).

Past and current IEA activities focus on the development of programs and guidelines to facilitate the discipline and profession of ergonomics worldwide. Examples of such activities include:

- International directory of ergonomics programs
- Core competencies in ergonomics
- Criteria for IEA endorsement of certifying bodies in professional ergonomics
- Guidelines for the process of endorsing a certification body in professional ergonomics
- Guidelines on standards for accreditation of ergonomics education programs at the tertiary (university) level
- Ergonomics quality in design (EQUID) program

More information about these programs can be found on the IEA Web site: www.ie.cc. In addition to the above, the IEA endorses scientific journals in the field. A list of the core HFE journals is shown in Table 14. A complete classification of the core and related HFE journals was proposed by Dul and Karwowski (2004).

IEA has also developed several actions for stimulating development of HFE in industrially developing countries (IDCs). Such actions include the following elements:

- Cooperating with international agencies such as the ILO (International Labour Organisation), WHO (World Health Organisation), and professional scientific associations with which the IEA has signed formal agreements
- Working with major publishers of ergonomics journals and texts to extend their access to federated societies, with particular focus on developing countries
- Development of support programs for developing countries to promote ergonomics and extend ergonomics training programs
- Promotion of workshops and training programs in developing countries through educational kits and visiting ergonomists
- Extending regional ergonomics networks of countries to countries with no ergonomics programs in their region
- Support to non-IEA member countries in applying for affiliation to IEA in conjunction with the IEA Development Committee

Table 13 IEA Technical Committees

Aging	Human–Computer Interaction
Agriculture	Human Reliability
Auditory Ergonomics	Musculoskeletal Disorders
Building and Architecture	Organizational Design and Management
Building and Construction	Process Control
Consumer Products	Psychophysiology in Ergonomics
Cost-Effective Ergonomics	Quality Management
Ergonomics for Children and Educational Environments	Rehabilitation Ergonomics
Hospital Ergonomics	Safety and Health
Human Aspects of Advanced Manufacturing	Standards

Table 14 Core HFE Journals

Official IEA journal	Ergonomics[a]
IEA-endorsed journals	Applied Ergonomics[a]
	Ergonomia: An International Journal of Ergonomics and Human Factors
	Human Factors and Ergonomics in Manufacturing[a]
	International Journal of Industrial Ergonomics[a]
	International Journal of Human–Computer Interaction[a]
	International Journal of Occupational Safety and Ergonomics
	Theoretical Issues in Ergonomics Science
Other core journals	Human Factors[a]
	Le Travail Human[a]
Non-ISI journals	Asian Journal of Ergonomics
	Japanese Journal of Ergonomics
	Occupational Ergonomics
	Tijdschrift voor Ergonomie
	Zeitschrift für Arbeitswissenschaft
	Zentralblatt für Arbeirsmedizin, Arbeitsschurz und Ergonomie

Source: Based on Dul and Karwowski (2004).

[a] ISI-ranked journal.

11 FUTURE CHALLENGES

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 subfield of neuroergonomics focuses on the neural control and brain manifestations of the perceptual, physical, cognitive, emotional, etc. interrelationships in human work activities (Parasuraman, 2003). As the *science of brain and work environment, neuroergonomics* aims to explore the premise of design of work to match the neural capacities and limitations of people. The potential benefits of this emerging branch of HFE are improvements in medical therapies and applications of more sophisticated workplace design principles. The near future will also see development of an entirely new HFE domain that could be called *nanoergonomics*. The idea of building machines at the molecular scale, once fulfilled, will affect every facet of our lives: medicine, health care, computer, information, communication, environment, economy, and many more (Henry T. Yang, Chancellor, University of California–Santa Barbara). Nanoergonomics will address issues of humans interacting with devices and machines of extremely small dimensions, and in general with nanotechnology.

Developments in technology and the socioeconomic dilemmas of the twenty-first century pose significant challenges for the discipline and profession of HFE. According to the report "Major Predictions for Science and Technology in the Twenty-First *Century*, published by the Japan Ministry of Education, Science and Technology (MITI, 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)
- Revolution in medicine (cell and organ regeneration, nanorobotics 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-forms on Earth)
- Cleanup of the negative effects of the twentieth century on the environment (organisms for environmental cleaning, regeneration of the ozone)
- Communication (nonverbal communication technology, new three-dimensional projections systems)
- Politics (computerized democracy)
- Transport and travel (natural sources of clean energy, automated transport systems, revolution 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 issues listed above will also affect future directions in development of the science, engineering, design, technology, and management of human-compatible systems.

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