CHAPTER 13

Human Factors Engineering Methods and Tools

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13.1 INTRODUCTION

In popular culture, human factors engineering (HFE) has become synonymous with the terms *ergonomic* and *user friendly*. Even popular radio show hosts have a sense of these terms (Magliozzi and Magliozzi, 2000). But what do they really mean? How does one make something ergonomic and user friendly?

Ergonomics is the study of the principles of work. Taken literally, this definition is not too helpful, but we get a sense that how people use technology to accomplish work is important. The definition for HFE adopted by the U.S. Army manpower, personnel, and integration (MANPRINT) program provides a bit more insight. (Available on line at http://www.manprint,army.mil/manprint/index.htm) The definition is "the integration of human characteristics into system definition, design, development, and evaluation to optimize human–machine performance under operational conditions." From this definition we get the sense that we need to consider the physical and mental limits, biases, behaviors, health, and safety of the people who will be using technology when we decide how that technology (which can range from simple hand tools to a complex multimodal interface in a manufacturing plant control room) should be designed and what roles humans and machines should play. Some of these limits may seem obvious, such as body size or ability to lift, but others are more esoteric, such as those relating to human information processing. Some other definitions of HFE have included phrases such as "designing for human use" and an "approach that fits systems (or machines, jobs, processes) to people and not vice versa" (Wilson and Corlett, 1995).

The key to realizing this user-centered approach begins with seeing the design of new technology from the point of view of the full range of people who will ultimately use it—the target audience. Norman (1988) has written a very accessible and popular book on design that helps the reader recognize poor application of technology resulting from a lack

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of user-centered design. He proposes a set of design principles to use in evaluating a design and illustrates each with examples to which everyone can relate. Once we have developed the ability to view design from a user perspective, we realize that HFE applies to almost everything that humans create (machines, jobs, or processes), including consumer products, computer interfaces and websites, maintenance equipment and tasks, workstations, manufacturing assembly lines, buildings, vehicles, weapons systems, and medical devices. Given this wide range of application, what methods do we use to conduct an HFE program?

13.2 HUMAN FACTORS ENGINEERING METHODS

Over the past 80 or so years, many useful methods and techniques have been developed to accomplish user-centered design. These methods encompass research, design, and evaluation. It is impossible to describe all of them within the confines of this chapter [e.g., Wilson and Corlett (1995) lists more than 50 subcategories], but some of the basics will be highlighted. For more comprehensive information readers should refer to texts devoted solely to HFE topics and methods such as Karworski (2001), U.S. Department of Defense (DoD, 1999a), Wickens et al. (1997), Wilson and Corlett (1995), Weimer (1995), Sanders and McCormick (1993), and Salvendy (1987). On-line descriptions are also available. For example, see Nomos Management AB for usability methods at http://www.nomos.se/about/methods.shtml.

Based on methodical groupings from comprehensive texts on ergonomics methods, we propose a basic list of HFE methods. These methods encompass research, design, and evaluation:

- Time-and-motion analysis;
- Link analysis and operational sequence diagrams (OSDs);
- Task analysis, function allocation, and workload analysis;
- Accident and incident analyses;
- Anthropometric and biomechanical analyses; and
- Field study, survey, and usability analysis.

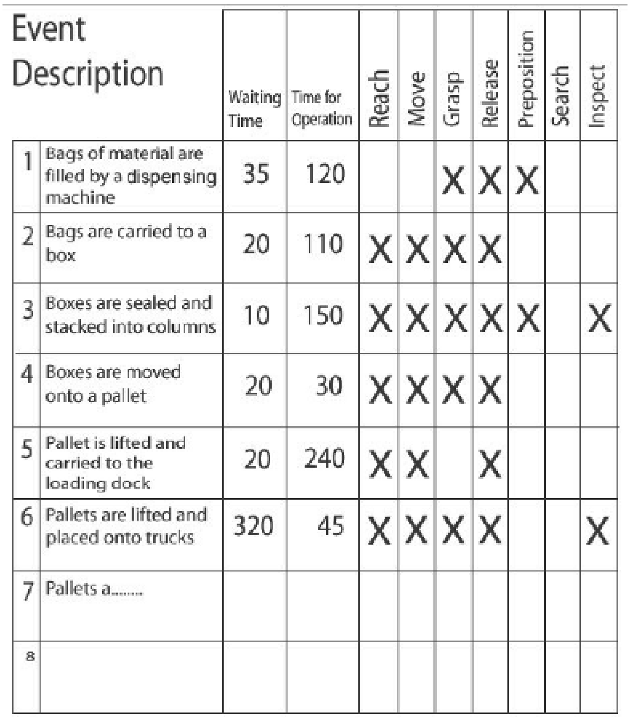
All of the methods involve developing an understanding of how the system you are designing will be used, by whom (the target audience), under what conditions, and what actions they will have to take. Each of the core methods provides different data and perspectives about the system, and the results of one method may serve as input to another. For example, time-and-motion analysis data are often used in both task and link analyses. Because of this, multiple methods are often used as part of an effective human engineering program.

13.2.1 Time-and-Motion Analysis

Time-and-motion analysis is one of the oldest methods in human and industrial engineering. Time-and-motion analysis involves observing a person using a system (or its predecessor) and recording the duration of each action performed. In an era of assembly line production and job specialization, engineers focused on improving the efficiency of job performance believed that any job could be performed more efficiently if unnecessary time and motions were eliminated. The first step in attacking this waste is to identify unnecessary motions (e.g., hand movements, back tracking, etc.) and the time required to perform them. Slack time and high-risk points for repetitive-motion injuries can also be identified. Choke points can be highlighted and the line rebalanced to eliminate them. Time-and-motion analyses may be carried out with the participant in the actual work setting (preferred) or a simplified representation of it. The recorder may be physically present with the participant or observations may be made from a time-stamped video recording. Care must be taken to clearly define start and stop points for each motion.

Time-and-motion analysis data are often used as input to other human engineering analysis methods. Data from multiple repetitions of the task are usually collected and often analyzed, simply by computing means and examining those means to identify key performance factors. If enough data are collected, the data can be described in terms of various sampling distributions (e.g., normal distribution with a mean *X* and a standard deviation SD). Figure 13.1 shows time-and-motion analysis data from a low-resolution study about loading bags of material in a chemical plant. We can see that event 6 has the greatest waiting time and event 5 takes the most time to accomplish. Further examination of these events should improve the loading time.

A weakness of many time-and-motion data collection efforts is the lack of control or assessment of the motivation of the participant performing the task. Human behavior,



Event Description		Waiting Time	Time for Operation	Reach	Move	Grasp	Release	Preposition	Search	Inspect
1	Bags of material are filled by a dispensing machine	35	120			X	X	X		
2	Bags are carried to a box	20	110	X	X	X	X			
3	Boxes are sealed and stacked into columns	10	150	X	X	X	X	X		X
4	Boxes are moved onto a pallet	20	30	X	X	X	X			
5	Pallet is lifted and carried to the loading dock	20	240	X	X		X			
6	Pallets are lifted and placed onto trucks	320	45	X	X	X	X			X
7	Pallets a........									
8										

Figure 13.1 Time-and-motion analysis data-loading bags of material in a chemical plant.

Task Number	Task Action	Action Type	Modality Type	Elapsed Time	Beginning Criteria	Ending Criteria	Compare Standard to Recorded	Comments	Suggested Solutions
1	Load Printer Paper	P R L	V P F M	30	Paper is available, operator is trained, written material in native language, 9th grade reading level proficiency	Reloaded paper cassette, ready to print.	Standard is set at 20 seconds, task recorded at 30 seconds	Standard was exceeded due to difficulty removing cassette tray	Quick release lock to enhance removal task
2	Load Printer Ink Cartridge	P R L	V P F M A	42	Cartridges are available, operator is trained in cartridge replace, written instructions in native language, 9th grade reading level	Installed ink cartridges. Tone sounds upon completion.	Standard set at 30 seconds, task recorded at 42 seconds	Errors were experienced in placing the cartridge properly. Task repetition was the result.	Increase training required for operators
3	etc...								

Action Key
P= Prepare
R= Read
L= Load
S= Search

Modality Key
V= Visual
P= Psychomotor
F= Fine Motor
M= Manual
A= Audible
S= Speech

Figure 13.2 Time studies and product usability.

including the speed, efficiency, and activity to perform tasks, is variable and dependent on motivation. These variables must be carefully assessed and controlled during a time-and-motion study.

Figure 13.2 demonstrates the use of time studies on product usability. In this case, the manufacturer of an office computer printer can identify the wasted efforts printer users are finding with the reloading of paper and ink cartridges. Extra time and steps can create a level of dissatisfaction and negative brand recognition. The study also provides data for factors such as the reading levels demanded by support material, labels, and product legends as well as the product training requirements. Niebel (1993) is a good source for detailed information on time-and-motion analysis.

13.2.2 Link Analysis and OSDs

Link analysis and OSDs are also focused on efficiency and are used to help identify the optimal placement of workspace infrastructure. Both use links and data from time-and-motion studies. A link may represent any relationship between a person and machine, between one person and another, or between one machine and another. Links can be characterized as

- Communication (visual, auditory, touch),
- Frequency (how often a person looks at something, movement from one place to another),

- Sequence of use (order of use or movement),
- Control (person to equipment), and
- Movement (eyes, hands, feet, whole-body location).

Once links have been identified and data collected, analysis is often facilitated through graphic representations. Graphical link data representation types are

- Link tables—summarize "importance of relationship" and "reason for proximity" per component pair;
- Adjacency layout diagrams—used to represent the frequency or importance of links (e.g., movements, functional connection, etc.);
- Spatial OSDs—describe the actual sequence of use; and
- Combination—provides elements of adjacency and spatial sequential use.

The diagrams are usually drawn in one plane (two dimensional) (see Fig. 13.3), but three-dimensional representations are possible. The diagrams are analyzed to try to arrange components according to sequence of use (place components in order of temporal use) or frequency of use (place most frequently used components in most convenient location). If links represent sequence or frequency, then this analysis primarily involves minimizing the distance between the strongest links.

Other factors should also be considered in the location of workstation components. These include placing important items in prominent positions, grouping components that

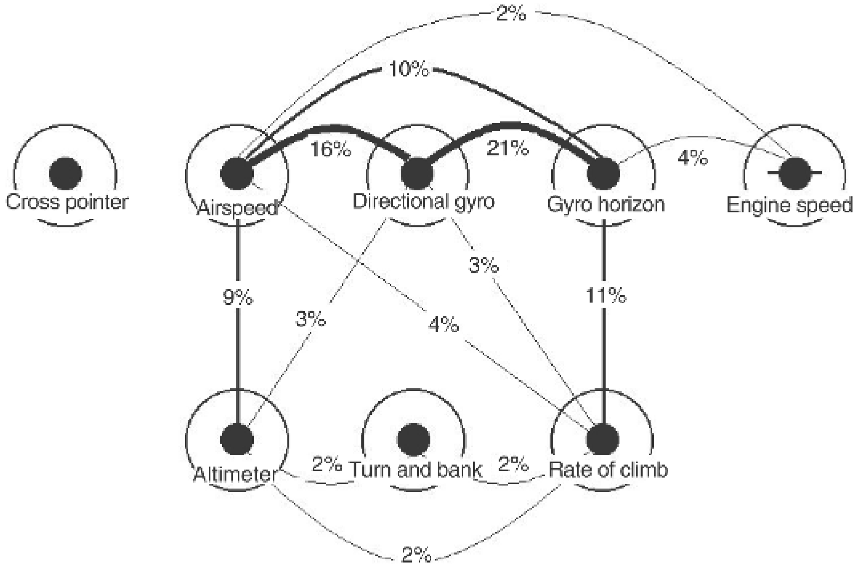


Figure 13.3 Two-dimensional link analysis: eye fixations of aircraft pilots (adapted from Jones et al., 1949).

are functionally related in the operation of the system, consistency, clutter avoidance, and control-display compatibility or collocation (see, e.g., Wickens et al., 1997). As mentioned earlier, many inefficiencies and obstacles to optimal performance can be identified and resolved by studying the sequence of the activities involved. In link analysis and OSDs, activities are normally tracked with the focus on the operator; however, operations of the larger system can also be examined. Operators assigned to tasks but not optimized as a team may self-organize based on parameters not essential to optimum performance, such as the personality of other team members, seniority, traditions, etc. Operational sequence diagrams are one part of ensuring optimum team performance. This type of analysis allows the analyst to define the functions, tasks, assignment of tasks to operators, and task sequences in an optimized way.

The first step is to determine the appropriate sequence and order of operations. This will be based on requirements such as those that drive the human and system performance. Performance criteria in the form of error rates and time to perform should also be considered.

Once the activity is formatted in the proper order with the sequential relationships established, it can be readily analyzed for human effectiveness. The key to designing a system, product, or process to be optimally operated by a human is to design the task around the operator. Therefore, OSDs should be structured from the human's perspective. This may be different from other analytic methods that are focused on constraints that are external to the human and the immediate task. Kirwan and Ainsworth (1992) is a good source for more information about OSDs.

When designing a computer interface or a computer-controlled system, OSDs can be very useful for considering the sequence of information required by the automated systems. The sequence should include what user input is required as well as actions taken by the automated system. Computer systems may have very strict information, time, and sequence requirements, but human capabilities and expectations do not always match these requirements. Thus it is important to consider the human user when designing computers and computer-controlled systems. For example, human perception of sight and sound is limited and variable. Stimuli (e.g., the flash of a pixel on a screen or a noise) must be of sufficient intensity and duration to register and be perceived. This assumes that the user's attention is not directed elsewhere and that the stimuli are understood after they are perceived. So the computer interface and sequence must present stiumuli that the user can perceive and that will attract his attention.

The interface must also consider the cognitive profile of the target audience such as the user's experience, expectancy, and ability to recognize and apply metaphors. Many of these items are very dependent on cultural and educational backgrounds. Context sensitivity is important in the usability of computer systems. How users arrived at a point in a user interface as well as their previous experience in using that and other user interfaces can affect how they expect the computer system to respond. The user will draw conclusions from information presented and make decisions at nonreversible decision points depending on the goal of the task.

Perhaps the most important factor for handling this problem is elimination of sensitivity to sequence on the part of the hardware and software system. In situations where elimination of sequence sensibility cannot solve all of the issues or when it introduces unacceptable complications, the presentation of information in dialog boxes along the way can help assist operators in choosing appropriate sequences. Operational sequence diagrams can be helpful with both of these methods.

13.2.3 Task Analysis, Function Allocation, and Workload Analysis

Task analysis refers to a listing and examination of the basic actions a person must perform to accomplish a job. In terms of detail, HFE tasks usually are defined as an action (e.g., turn, lift, push, toggle) performed on an object (e.g., a wheel, lever, button, crank). Task analysis begins with a task list that may be generated using any number of techniques such as document review (user's manuals), interviews (users or designers), observation of personnel using the system, or cognitive walk-throughs and may represent physical as well as mental tasks. The method used and the amount of detail depend on the analysis questions that will be asked (i.e., the reason for the task analysis).

One of the most popular methods is simply a top-down hierarchical method. In this method, a general mission is broken down into increasingly detailed actions required to perform the mission. Until the mission breakdown reaches the level of an action on an object (task) assigned to either a person or a machine, the elements are referred to as functions. Examples of functions are drive, communicate, and engage target. Examples of tasks are turn steering wheel, apply brake, and push "talk" button. It is usually more efficient to gather time data (time-and-motion study), sequence information (OSDs and link analysis), task demands, skills required, etc., at the same time that the task list is generated.

Another popular method is *cognitive task analysis*. In contrast to traditional task analysis, this method is aimed at understanding the underlying thought processes required to perform observable tasks. In some cases the aim is to understand the knowledge, user experience, or biases that went into an observable action. Cognitive task analyses are conducted for many purposes such as design of computer systems and training. The idea is to support performance of tasks such as decision making and control of complex systems by understanding the mental aspects of how the tasks are performed. Those interested in cognitive task analysis may wish to visit the Cognitive Task Analysis Resource website at http://www2.ctaresource.com.

Once the task list is generated, it must be analyzed to be useful. Task data form the basis of many HFE methods, but the purpose of a task analysis is often for function allocation or workload analysis. When observed in the context of a task analysis, goals (what you are trying to do), human behaviors (how you are trying to do it), and environment (conditions under which you are performing) associated with each task are identified and reviewed for compatibility with each other. If there is a significant incompatibility among the physical or mental abilities of the target audience, established goals, or environment and design, the discrepancy becomes more obvious since the details of task goals, performance, and conditions have been specified. For example, if the design requires a person to reach for three widely spaced switches at a height of 8 feet all at the same time, this is not likely to be a reasonable requirement. Most people are not able to reach to 8 feet, and no one has three arms to activate three switches at the same time. The most effective forms of task analysis include improvement recommendations that are traceable to specific issues identified via the task analysis. In later phases when test and validation are conducted, the findings of the task analysis can help guide test issues to either confirm or refine the issue. Kirwan and Ainsworth (1992) provide numerous methods and examples of task analyses.

Function allocation is aimed at deciding which jobs (groups of tasks) should be assigned to humans (and which human if there are several available) and which to machines. The idea is that people are better at certain task types (e.g., dynamic decision making) and machines at others (e.g., tedious, repetitive tasks). But the state of the art in automation is advancing rapidly, causing significant changes to the manner in which tasks can be performed as well as affecting the types of tasks that can be automated. Current thinking (Parasuraman et al., 1996) is that adaptive aiding in which the function allocation is dynamic depending on the needs of the human may be required for performance in high-paced, information-rich, highly automated environments.

Workload analysis is used to ensure that people do not have too many (overload) or too few (underload) tasks and information to handle at any given time. Workload analysis considers the fact that a person's mental processing capacity is limited and not all tasks are purely physical. Accomodating these mental processing limitations is an important design constraint. This analysis may be as simple as counting the number of tasks that a person must perform at any given moment. However, more complex analyses consider the nature of the task (e.g., visual, auditory, cognitive processing, psychomotor control, or physical) and the difficulty in performing different types of tasks simultaneously. Other analyses consider novel versus highly learned tasks (i.e., higher workload until well learned) and dynamic management of workload (i.e. strategies used by people to attempt to keep workload at a comfortable level). See Damos (1991) for more information on workload analysis.

13.2.4 Accident and Incident Analyses

The study of incidents and accidents is a key HFE method. Performed properly, the analysis will be a valuable indicator of system behavior. The focus is on unplanned-for and unanticipated, undesirable system performance. Incidents typically involve near misses, accidents, and full-blown system failure. Many analytical constructs are devised and used to forecast the possible outcomes of a functioning system. However, no technique or approach can be all encompassing and anticipate all uses and combinations of variables. For those situations, accident and incident analyses will be the most useful methods, because the focus is on how the system is actually used and how that use led to a near miss or system failure.

This type of study is focused on finding important information from man–machine systems that are not doing what they were intended to do. It can be a system that is (1) under performing compared to the design performance specifications, (2) producing defective results, or (3) yielding undesired side effects. Frequently, these analyses are performed on a specific system with recurring problems or on a design that is in multiple locations and is experiencing one or more common problems.

When possible, conclusions should be drawn from multiple occurrences of similar incidences. The selection of sampling techniques and data collection process across the incidences is very important. Data structures and resolution should be tailored to assure that there is sensitivity in areas that are being studied. Additional attention should be paid to isolating those variables that are fixable within the context of the available solution set.

Emphasis must also be placed on the individuals performing the investigations and data collection. Collection of data by individuals that can be personally affected by the outcome of the investigation should be avoided. In other words, if the facts surrounding the incident will yield findings attributable to the behavior or performance of an individual or his or her direct associates, then this person should not be involved in the data collection and reduction. This will prevent possible reporting distortions and inappropriate leading of the investigation.

In addition, there should be a level of anonymity to many of the sources of the data collected. Information will be much more objective and useful if those providing it know that there will be no punitive outcomes regardless of personal involvement. This is a factor where the information providers might try to protect individuals from an organization or power structure based on perceptions of fairness. To avoid these effects, anonymity will assure there is no linkage between data collected and the personal well-being of the information sources or their direct associates.

Incident analysis is one of the most telling of the analytical methods. It allows the analyst to construct a specific scenario where the outcome was undesirable (i.e., an accident, near miss, etc.). By decomposing the factors contributing to the undesirable outcome, the analyst can identify specific causal factors and initiate solutions for prevention. While seemingly clear, there is some level of complexity to all incidences where human behavior is present. Therefore, measured trial-and-error fixes may be required before the optimal solutions are actually achieved. Flanagan (1954) was the first to use incident analysis in his study of near misses in aircraft. (See Chapter 14 for more information on causal analysis.)

A number of risk and human reliability assessment techniques have been developed. These techniques can be useful in analyzing accidents and incidents in more detail. See Wilson and Corlett (1995) and Kirwan (1988) for specifics on particular techniques and evaluation factors for selecting among them.

13.2.5 Anthropometric and Biomechanical Analyses

Anthropometric and biomechanical analyses are used here to refer to a group of methods and principles all dealing with the application of information about the size, shape, and physical abilities of people to the design of workstations, products, and jobs. Information about size and shape refers to reliable measurements of a person's body such as overall stature, limb lengths, functional reaches, and girth of body parts. These measurements are (ideally) collected according to very specific procedures and landmarks. Data are often summarized according to populations surveyed and reported as means, standard deviations, and percentiles. (Note that there is some controversy over the value of using percentiles for anthropometric analyses. See Section 13.6.)

Recent trends are to use three-dimensional laser scanning to collect detailed body surface measurements. Three-dimensional scanning works particularly well for obtaining girth and contour measurements for an individual in a static posture. A notable example of an anthropometric survey using three-dimensional scanning technology is the Civilian American and European Surface Anthropometry Resource (CAESAR) coordinated by the Society of Automotive Engineers. Physical ability data refer to characteristics such as strength (e.g., lift, push, pull) and range of motion for a particular body part.

The idea behind anthropometric and biomechanical analyses is to use these data to set design limits that will fit the target population and will not exceed their capabilities. The importance of knowing the anthropometric and biomechanical characteristics of the target population cannot be emphasized enough, especially when the characteristics are very different from those of the designer. For example, if the designer of an airplane seat is a Dutch male who is thin and strong and has long legs, he might not consider seat breadth to be as important as leg clearance. If the target population includes older North American females (greater hip breadth and shorter buttock–knee length than Dutch males), seat breadth is likely to be as critical as leg clearance. The designer might also underestimate the criticality of being able to reach an overhead bin without having to assume a weak posture (lifting arms over one's head). But if the plane were being designed for a population that includes Japanese women (shorter on average, and women on average have less upper body strength than men), this would be a very important design issue.

Insensitivity to user characteristics is often a problem when the target population includes children, the elderly, or disabled. If this designer did realize that these dimensions were important, how would he or she know what their limits should be? Designers can access anthropometric and biomechanical data sets to establish statistical limits so that a specified portion of a population (e.g., 90, 95, and 99 percent) will likely be accommodated by the design. Texts such as Sanders and McCormick (1993) and Wilson and Corlett (1995) provide more detail on traditional anthropometric and biomechanical analysis accommodation methods. Many traditional anthropometric data sets exist. One large survey is the 1988 anthropometry survey of U.S. Army personnel (Gordon et al., 1989). The *Directory of Databases Part I—Whole Body Anthropometry Surveys* (1996) lists whole body anthropometric surveys and provides current sources for the survey raw data and summary statistics.

13.2.6 Field Study, Survey, and Usability Analysis

Field studies are quasi-experiments (quantitative, yet without true randomization to control for various threats to validity) and are conducted in a setting as close as possible to the actual conditions under which the final product will be used. They are valuable because they allow the system (people and equipment) to be tested quantitatively against system performance requirements in a realistic environment. The price for this realism, however, is a lack of control over sources of bias and error. Field studies yield powerful insight into the situations and the environment of the human activity, process, or product that is being considered. Keep in mind that subject matter experts of the product, process, and environment will most likely be ill equipped to analyze their situation in a way that can be applied analytically to the overall target audience. Those conducting field studies are often faced with changes in conditions, participants, equipment, etc., on very short notice and must be knowledgeable of basic experimental design methods to minimize threats to validity when conducting the field study and responding to these changes. Only a combination of trained sensitivity to human issues, experimental design, and direct observation will produce valid and useful data.

Surveys are designed to ask people directly about their attitudes, opinions, or behaviors regarding some activity, product, or system. Surveys usually take the form of a questionnaire. It is easier to design a bad survey than a good one, which typically happens by introducing bias or too much length. Questions should be unambiguous and only those that are needed should be included. It is critical that a trained analyst plans and creates the questionnaire. It is also important that the administration of the survey be performed using a controlled, unbiased process. Charlton (1996) provides an excellent summary of questionnaire techniques. When survey data are analyzed, one should keep in mind that the data are subjective. Improper execution of the survey can easily bias results and lead to a reinforcement of preconceived notions if conducted under uncontrolled conditions.

Usability analysis typically involves the mock operation of a product by a target audience member or a subject matter expert. This analysis is a critical activity for comparing the suitability of a product or process with the target audience and environment. Used extensively in the development of consumer products and in the computer industry, it is a process of mocking up or simulating the entire environment that a user or customer will experience. This allows the user to experience a more complete representation of the product (in terms of factors that could affect performance) than is typically present in classic human experiments.

Classic experiments seek to control sources of error by keeping some aspects of the experiment (variables such as time of day or test environment) equal or constant, but important factors may be left out through this control. Usability analysis is favored by marketing organizations as a way of obtaining information about corporate and brand images of products. In this analysis, trade-offs of performance versus image are sometimes made in favor of advertising opportunities such as those commonly found on web pages. Subjective and objective results will be evaluated later and decisions will be made based on trade-off criteria of the usability project. Frequently, performance data in terms of errors and intervals to achieve an objective are not the primary goal of the activity. Instead, information such as desired features, use cases, and unanticipated behaviors may be of more interest. A user jury, if properly conducted, can be considered a form of usability analysis.

Usability laboratories are typically used to conduct these studies. A usability laboratory usually consists of two compartments. The first compartment contains the subjects, and the second compartment contains the test evaluators. The test subjects are positioned in a manner typical of how they would use the product being tested. The evaluators have visual and audible access to the test and also have test equipment, data collection, and other test apparatus at their disposal. A controlled training session will precede the activity and varies vastly among practitioners in terms of rigor and documentation. Sufficient documentation must be recorded to assure repeatability as well as to provide the scientific basis for assessing the training demands of the product. After being trained and prepared, the subject(s) operates the product under the surveillance of evaluators. In addition, video data recording equipment may be used to collect moving images and allows for time-sensitive recording of associated data. The evaluators and the associated equipment are invisible to the test subjects.

Some usability practitioners ask the subjects to talk through the problems as they occur. This is not recommended for systems or products that have cognitive workload constraints. Verbalizing actions will alter the instantaneous workload of the subjects and have a confounding effect (i.e., artificially increase their workload). Postsessions (i.e., review with subject following testing) can be helpful in identifying specific problem areas without impacting the operational session. Follow-up questionnaires may yield additional anecdotal and open formatted information. Postsessions should be conducted away from subject waiting and testing areas to avoid prejudicial effects on pending trials. The resulting data will be of several types (subjective and objective), and media formats should be reduced, analyzed, and compiled by an experienced practitioner in order to assure clarity, accuracy, and validity of the results.

Hix and Hartson (1993) are one source of additional information about ensuring usability of products, particularly software user interfaces. See also, Part III of Wilson and Corlett (1995).

13.3 HFE TOOLS AND TECHNOLOGIES

As HFE methods evolved, a variety of tools and technologies were developed to make application of the methods easier. The tools range from paper-and-pencil checklists to graphically sophisticated computer-based modeling tool suites. These tools and technologies generally are matched to one or more of the basic methods discussed in the previous section.

Before we discuss classes of tools and technologies, the point must be made that none of these tools do the thinking for you. A trained human factors practitioner is required to use them properly. So what good are these tools and techniques? What they do is structure, organize, describe, and provide the capability to visualize your system, but they do not interpret the results and typically do not tell you how the system must be changed to improve it. Even the best hammer and chisel will not produce a great carving in the hands of an unskilled craftsman. Just as it would be unwise to expect a psychologist to use a finite-element analysis tool to analyze a structure, it is unwise to expect a computer scientist or engineer to use an HFE tool with no training. The tools, especially those that are computer based, contain assumptions and qualifications that impact validity of results if misinterpreted or ignored. Many contain technical terms that may be familiar only to those in human factors or subfields of psychology. These tools should not be used unless the analyst understands the basics of the method and techniques underlying them (i.e., could perform the analysis by hand if given sufficient time).

Table 13.1 provides classes of tools in a list that helps provide some structure for our discussion and is not intended to be either comprehensive or orthogonal.

13.3.1 Guidelines and Standards

There are many guidelines and standards that apply to human engineering. The difference between guidelines and standards is that standards are usually mandatory and compliance is required while guidelines are generally only recommended practice. Many human engineering guidelines and standards have been developed and maintained by industry standardization groups [e.g., American National Standards Institute (ANSI), the Society of Automotive Engineers (SAE), and the International Organization for Standardization (ISO)]. Several standards groups also exist within the U.S. government [e.g., National Institute of Safety and Health (NIOSH), DoD, and National Aeronautics and Space Administration (NASA)]. Occupational health and safety standards are also covered in Chapters 14 and 15.

TABLE 13.1 Classes of HFE Tools

Guidelines and standards
Checklists
Subjective assessment tools
Simulation—unmanned
- Task network tools
- Perceptual models
- Congnitive process models and architectures
- Graphical human models
- Integrated tools
- Human behavioral representations (HBRs) in simulation federations
- HFE tools embedded in computer-aided design/computer-aided engineering (CAD/CAE) suites

Simulation—human in the loop
Miscellaneous analytical tools

Some important human engineering standards are

- MIL-STD-1472F (DoD, 1996), DoD design criteria standard: *Human Engineering*;
- NASA-STD-3000 (NASA, 1995), *Man-Systems Integration Standards (MSIS)*; and
- MIL-STD-1474D (DoD, 1997), DoD design criteria standard, *Noise Limits*.

Examples of human factors–related guidelines include

- MIL-HDBK-759C (DoD, 1998), *Human Engineering Design Guidelines*;
- Numerous guidelines related to office ergonomics such as ergonomic requirements for office work with visual display terminals and ANSI B11, (ANSI, 1994) *Ergonomic Guidelines for the Design, Installation and Use of Machine Tools*[1]; and
- *The Human Factors Design Guide for Acquisition of Commercial Off-the-Shelf Subsystems, Non-Developmental Items, and Developmental Systems* (Wagner et al., 1996).

One problem with guidelines and standards is that not all cases and combinations of factors can be anticipated and their appropriate resolution specified. Also, the source and assumptions for some of the recommendations can be buried or lost so the HSI practitioner will not know how applicable the recommendation is for his purpose. For example, he or she may find a standard for the size of lettering you need so that a sign is readable at a distance of 30 feet but the standard might apply only to 20/20 corrected vision under ideal (clear) atmospheric conditions for a person (reader) standing still. It is unlikely that this standard will be appropriate for a person reading the sign from a moving vehicle on a foggy day.

13.3.2 Checklists

These tools consist of paper or computer-based lists of issues or design parameters that should be evaluated in the course of a human engineering program. These lists are based on prior experience and are often an attempt to capture human engineering subject matter expertise. Checklists may also take the form of "lessons learned" documents or branched question-and-answer tools and may even be labeled as guidelines. Examples of human engineering checklists are *Human Factors Evaluation Checklist for Tanks* (Clingan and Akens, 1986) and some aspects of the Cornell University ergonomic guidelines for arranging a computer workstation (http://ergo.human.cornell.edu/ergoguide.html).

Similar to guidelines and standards, checklists are limited in their ability to anticipate and cover all combinations of variables and conditions that may apply to a given design problem. They cannot capture the variability and dynamics of human performance. They are usually shorter than guidelines and standards and are generally geared to quicker evaluations. As such, they may not be detailed enough to capture very specific design problems. Their utility lies more in guiding inexperienced practitioners through a quick basic evaluation. A few checklists are quite elaborate and include references to more detailed analyses such as one developed by Kearney (1998). Therefore, they cross into the realm of process guidelines.

13.3.3 Subjective Assessment Tools

These tools are typically dependent (performance effect data) measures used during the conduct of a study. Those cited here are used most often during simulator or field studies. The best of these tools include guidance on how to administer and score them and then interpret results. Subjective assessment tools commonly involve feedback or ratings from participants. Examples of subjective assessment tools are questionnaires, workload measures such as the subjective workload assessment technique (SWAT) (Reid and Nygren, 1988); NASA task load index (TLX) (Hart and Staveland, 1988); the modified Cooper–Harper workload scale (Wierwille and Casali, 1983); and situation awareness (SA) measures such as the cognitive compatibility situation awareness rating technique (CC-SART) (Taylor et al., 1997) and the situation awareness global assessment technique (SAGAT) (Endsley and Garland, 1999). Objective metrics are usually measures of performance such as reaction time and error rate or the physiological state of participants that have been correlated with changes in performance of various task types. Examples are heart rate, eye blink, blood pressure, hand steadiness, and electromyogram. Performance assessment batteries that combine various measures from the subjective and objective categories have been developed to provide multidimensional insight into performance. Examples of performance assessment batteries are the complex cognitive assessment battery (CCAB) (described in Kane and Kay, 1992), COGSCREEN™ (described in Kane and Kay, 1992), and the delta battery (Turnage and Kennedy, 1992).

13.3.4 Simulations

Simulation offers the ability to create virtual elements of a future situation before they are readily available. This provides important answers about the situation, process, or product in a time frame when the design is still being formed. For example, in traditional product development programs, many months of designing would precede the availability of a prototype. Using simulations before the physical prototype is fabricated can lead to many important and timely discoveries.

A key to effective simulation is to find the right degree of simulation (include critical elements) and fidelity (model those elements to the correct level of accuracy) to make it representative but not more so than is necessary. The important items that require the maximum fidelity should be identified in the planning stages. Those findings should be forwarded to the simulation specifications. If the simulation has too much in it, it will be excessively costly and take too much time and resources to accomplish the objective. This will undermine a key benefit of using the technique (i.e., cost savings).

Human engineering simulations fall into two main categories: manned and unmanned. Manned simulations will include a real human as part of the execution of the model. Unmanned will have a part of the software that represents human activity.

Unmanned simulations are usually computer programs in which models are built. The models represent the environment within which the operator performs, contains a task or task network, and also has some representation of the human. The representation will depend on the purpose of the modeling activity. Physical and cognitive human behavior will be represented.

Exercising the model will yield results that forecast the output of the man–machine system. If the output is not satisfactory, then factors related to the environment, tasks, or human attributes can be modified. Such modifications are made to determine sensitivity of elements and will result in solutions to the system design problems. Usually the design is modified based on early runs. Subsequently, the model is updated to the new design and rerun in the simulation to validate and quantify the improvement. This process is most effective when schedules and availability allow for multiple iterations and collaboration between the members of the design team.

Unmanned Simulation Models There are several types of models that belong in this category. Below, we briefly describe several of these types. More information can be found in other chapters of this book, as well as in the publications that are referenced.

Task Network Modeling Tools Task network modeling is a technique that allows predictive modeling of activities that can be subdivided into discrete elements (or tasks). Once defined, estimates of performance ranges (e.g., time, accuracy, workload) are attached to the lowest level of the decomposed hierarchy. The tasks are then simulated using a discrete-event simulation process and are typically subjected to a range of scenario events in order to trigger unique combinations of tasks. The end result of the simulation is a system-level performance estimate that is applicable to a broadened range of scenarios. Tools in this class are used for task analysis, function allocation, and workload analysis. Several tools exist that provide task network modeling environments, including Improved Performance Research Integration Tool (IMPRINT), WinCrew, and the Integrated Performance Modeling Environment (IPME). These tools are described in Chapter 11.

Perceptual Models These are models of how people register input stimuli from the environment. Perceptual modeling tools can help designers compare these stimuli to what their target audience can perceive. These sorts of models are often referred to as “first-principle models” and usually do not have an embedded sense of time. For this reason, they are not typically considered simulation models but are more often mathematical algorithms designed to help designers predict what a person can see or hear in a specific environment.

Cognitive Process Models and Architectures This family of models focuses on describing and predicting cognitive behavior and often includes a representation of memory. Currently, these models are best suited to modeling very detailed and short (several seconds) tasks, simply because they require a significant amount of effort and are not intended to predict psychomotor performance. Very few models in this category have been commercialized, and they require a great deal of expertise in cognitive psychology and, in most cases, computer science to use effectively. Several examples of these models and architectures are provided by Pew and Mavor (1998) (e.g., see atomic components of thought—rational (ACT-R), executive-process interactive control (EPIC), cognition as a network of tasks (COGNET), and Soar).

Graphical Human Models This class of models provides unique capabilities in visualization and is extremely helpful in evaluating and communicating the “fit” of the human into an existing or notional crew or workstation (anthropometric analysis). The tools typically have some limited CAD capability for creating an environment to represent the crew or workstation. Usually, the item being evaluated is imported from a more sophisticated CAD package, and if not well planned, this process may consume significant project resources. The most well known were developed to run on UNIX platforms such as

SGI (Silicon Graphic Inc) machines, but many have begun to migrate to more powerful personal computer platforms, and this is clearly the trend for the future. Common features of the tools include creation of different-sized figures from various anthropometric databases (including male and female), ability to see through the eyes of a figure, positioning figures into a limited set of predefined postures, limited predefined animated behaviors using scripting (e.g., walking a level path identified by start and end points), and specification of range-of-motion of joints. Most of the models have some level of embedded biomechanical representation. Some employ techniques such as inverse kinematics so that the body parts may be positioned with less user input and several can use data from various motion-tracking systems to replicate human movement. Biomechanical definition may include various degrees of simulation in the number of joints, degrees of freedom about each joint, and range of motion. Some of the models include modules that use algorithms for analyzing strength and lifting. Examples of graphical human models are Jack, Safework® Pro™, Ramsis, and Mannequin Pro (refer to the Directory of Design Support Methods and company websites for more detail[2]). See also Chaffin (2001) for examples of application of graphical human models.

Biomechanical Models Some graphical human models are primarily biomechanical models. They are typically used to predict occupant motion in crash test or ejection seat simulations. Primary examples of whole-body, biodynamic models include mathematical dynamical model (MADYMO) (Happee et al., 1998, and http://www.madymo.com) and articulated total body (ATB) (see Cheng et al., 1998, and http://www.atbmodel.com). Other biomechanical models represent specific parts of the body (e.g., spine, bones, joints, shoulder) in more detail. Similar to graphical human models, there are biomechanical models (some graphical and some just parameterized algorithms) that are intended to help predict the acceptability of a lift. Examples are the 3D Static Strength Prediction Program™ (3D-SSPP) (http://www.engin.umich.edu/dept/ioe/3DSSPP) and the NIOSH lifting equation (Waters et al., 1994). (See http://www.industrialhygiene.com/calc/lift.html for an on-line version of the equation.)

Integrated Models At a workshop held in 1985 (Kroemer et al., 1988), the National Research Council made several recommendations toward establishing an integrated ergonomic model. Their recommendation provided clear indication that models of the task environment or work process (i.e., task network models) would benefit from combination with theoretically correct models of cognition and perception. Additionally, graphical human models could be used to view a dynamic representation of the human interacting with the simulated environment. Since this report was published, a comprehensive human model has not been developed, but some progress toward that end has been made. One of the earliest and most ambitious integrated model efforts is Man–Machine Integration Design and Analysis System (MIDAS). MIDAS was designed primarily to answer questions related to the design of aviation cockpits and includes representations of pilot perception, cognition, and anthropometry (Hart et al., 2001). More recently, the U.S. Army Research Laboratory Human Research and Engineering Directorate (ARL HRED) has supported the development of a crewstation design tool intended to put HFE tools and models on the desktop of systems designers. A unique aspect of this effort is the inclusion of a library of controls and displays, indexed by human resources (e.g., visual, auditory) and associated with HFE standards and guidelines. In addition, NASA has made great progress toward integrating task network and cognitive models under their human error modeling program (e.g., IMPRINT and ACT-R), and this area of product development shows much promise.

Human Behavior Representation (HBR) in Simulation Federations In a class of models closely related to integrated tools, discussed above, another approach is to develop separate models that excel in one particular aspect of a problem and then share modeling results from one model to another to improve the degree and fidelity of all the simulations. This type of model has been used extensively in high-fidelity, force-level simulations. A particular and interesting challenge of this environment is the challenge of clock synchronization. The combination of task network models (which are typically discrete events in which the clock "jumps" from event to event at irregular intervals), system model, (which are typically continuous in which the clock "ticks" along at regular intervals), and first-principle models (which usually do not have any internal concept of time) is a complex and difficult effort. Nonetheless, many organizations are showing significant progress toward this end aided by higher level architecture (HLA) compliance. Examples in the human factors area are IPME and the combined Combat Automation Requirements Testbed (CART) IMPRINT effort (Martin et al., 1999).

HFE Tools Embedded in CAD/CAE Suites A more recent trend in human factors simulation tools is the inclusion of tools such as graphical human figure models as modules in larger computer-aided engineering (CAE) tools suites. This has positive and negative aspects. One of the largest risks in this approach is in exposing the quality of the human figure model database, which has direct consequences on the quality of the computer-aided design (CAD) assessment of human "fit." If the human figure model is not valid (e.g., torso is too long or too thin, arms are not proportional), then the end result could be an unfortunate combination of good intentions and misinformation. In fact, it could appear as though a thorough human factors analysis was performed when, in fact, the human factors assessment was completely lacking.

Simulation—Human in the Loop Simulations are a key tool in the design of future products, processes, and almost any development activity. Simulations consist of hardware and software that are configured to reproduce a set of circumstances or an environment under which a task or activity is performed. The environment is constructed specifically to replicate a realistic and often complex set of conditions. Manned simulations usually consist of mock-ups, hot mock-ups, desktop simulators, or full simulators. In manned simulation, it is critical to have an appropriate experimental design, rigorous experimentation controls, and subjects that represent the target audience. It is difficult but extremely valuable to test simulated manned systems and get valid results. This activity is best left to trained human factors engineers or other professionals with the experience and awareness of experimental design to control confounding variables, especially those introduced by last minute changes.

13.3.5 Miscellaneous Tools

Some tools do not fit into the classification structure well, because they address either a specific method or a technique not covered in this chapter. Examples are protocol analysis tools, Locate II, and the Work Domain Analysis Workbench (WDAW). Protocol analysis tools such as MacSHAPA (Sanderson et al., 1994) are designed to support encoding and analysis of multiple sources of task performance data such as verbal communication, equipment logs (e.g., keystrokes), task sequence, and observable physical action. Typically data are encoded with a time stamp of who performed the action or who received the information. Then the tools can be used for data filtering and visualization, which are particularly useful in time-and-motion studies and task analysis. Locate II was developed specifically to facilitate using link analysis type data to arrange workstations within a two-dimensional (one plane at a time) workspace such that good movement patterns and visual, audible, and tactile communication are facilitated (Hendy, 1989, and http://www.interlog.com/ ~ jle). The efficiency of layouts is compared using cost function values. The WDAW (developed with the support of the U.S. Air Force Research Laboratory and then the Australian Defense Sciences Technology Organization) was developed specifically to conduct work domain analyses (WDAs). (For information on WDA, see Rasmussen et al., 1994.) The tool uses a graphical interface to help an analyst with a working knowledge of cognitive engineering and cognitive work analysis to perform a WDA to examine issues such as potential conflicts (e.g., in information needs) across system or subsystem goals and functions. For information on the WDAW, see Sanderson et al., (1999) or http://www.it.swin.edu.au/schil/WDAW/wdaw.html. Note also that risk assessment tools and techniques are covered in more detail in Chapter 14.

Any written reference will be out of date before it is published due to accelerating developments, particularly with computer-based tools. Fortunately, several on-line databases of tools exist as resources to update information about HFE tools. One of the better (comprehensive and frequently updated) databases is the Directory of Design Support Methods and Liveware Survey maintained by the Manpower and Training Research Information System (MATRIS) Office of the Defense Technical Information Center (DTIC). Another is the Manning Affordability Website: www.manningaffordability.com

13.4 SELECTING TOOLS AND TECHNOLOGIES

How are HSI practitioners supposed to find the right tools for the job and determine whether or not a marketed or proposed tool or piece of software is really appropriate for the project?

The first step in tool selection is to identify the right class of tool from the methods and techniques discussed previously. Then, a search for currently available tools is performed (possibly through one of the on-line tools databases referenced earlier) to develop a list of candidates. Then, the following questions should be used to sort through the list of candidates:

1. *Original Purpose* Is the tool or model sensitive to the parameters that you are interested in varying? Can it be used or adapted to address your primary areas of interest?
2. *Degree of Accuracy* How accurate does my answer have to be? What is the tolerance for error? The answer will depend on the type of system being analyzed (e.g., the manufacturing tolerance in the cockpit of an airframe is much higher than in a workstation on a ship) and how early it is in the product life cycle (i.e., the more mature the design, the less tolerance for error).
3. *Level of Resolution* What is the scale of resolution? When tools are developed, a level of detail in problem investigation is often assumed. For example, a tool designed to help optimize the location and type of switches on a particular control panel in a cockpit might be ill suited to investigate the layout of workstations on an aircraft carrier.

4. *Validity* Are the data and algorithms valid for my application? Models are limited by the data from which they were developed. Care must be taken to match those data to the target audience. For example, it is inappropriate to use a database on the size of Japanese females for an analysis on stature accommodation of Dutch males. This may sound obvious, but often the underlying assumptions and databases of a model are not well documented or easy to trace.

5. *Realistic Resource Requirements* If the tool is software based, what does it take to run and use it (compared to resources available for your project)? Resources to consider include personnel with skills to learn the model and related packages (e.g., UNIX, CAD packages, basic programming), time, and computer platforms.

6. *Information Availability and Data Format* What data are required as input? Do you have access to these data or sufficient resources to develop them? If you have large amounts of data, consider whether the tool can read the data in as an electronic file. If so, what file formats are supported?

7. *System Compatibility* If the tool is software based, what platform(s) does it run on? This is becoming less of a problem as tool developers work to make their products multiplatform compatible, but not all applications run equally well on all platforms. For example, very large files on a Windows NT platform might overwhelm a graphical human model originally developed to run on a high-end UNIX platform.

8. *Cost* The cost of tools ranges from no cost for paper-and-pencil government-developed methods to over $70,000 for sophisticated human figure modeling software packages. Other cost issues to consider are as follows: Is other software necessary to use the tool? If you do not have that software, you will have to buy it as well. Are you buying one seat (one copy limited to use on one machine at a time) versus a site license (permission to use multiple copies throughout your organization)?

9. *Output Format* What output is needed? In what format? Consider what type of information you will need for output. Does the tool produce this output in a preformatted report or visualization or will you have to generate it yourself? Does the tool produce the data necessary to feed the report? If the output is needed in electronic form, does the tool produce files of that type? Incompatibilities in file format or having to generate them yourself can use up valuable resources in a project.

10. *Software Compatibility* If the tool is software based, does the model need to run in real time and is dynamic interaction with other simulations necessary? A stand-alone tool that runs faster than real time (e.g., Monte Carlo simulation) may be sufficient, but several standards for communication between models have been established so that each one will not have to be comprehensive in representing the system(s) and the environment in which it operates.

11. *Verification and Validation* Is the tool developer committed to on-going verification and validation? Verification, in particular, is only good for a given version number and must be repeated with each software release. Are model assumptions well documented so that you can produce a model or analysis that you can defend?

Care should be taken to match the version number of the tool with the information being used in your evaluation and the version you intend to purchase. In other words, do not base your decision on a description of a previous version because the tool's capabilities and underlying assumptions may have changed. Current users of the tool should be polled to determine whether or not marketing claims are accurate. There are expert systems such as HOMER (although not fully implemented), WCField, and OWLKNEST (AGARD, 1998; *Directory of Design Support Methods and Liveware Survey*, 2002) that may be useful in helping the analyst select tools and technologies. (They ask many of the same questions that we have listed above.) However, unless these systems are updated, it is possible for their recommendations to be inaccurate.

13.5 PLANNING FOR ANALYSIS

Perhaps the most important step in preparing to conduct a human engineering analysis is understanding how to get the most out of the available analysis resources. This requires the analyst to (1) carefully consider what type of output is required to identify issues, (2) provide the right level of data to evaluate solutions, and (3) provide the impetus necessary to get design changes implemented. Once required output has been determined, methods and tools that support the output and necessary input data can be identified. Method, tool selection, and availability of input data drive resource requirements.

Determining required output is not easy. One way to start is to think about what output is required to address the issues important to the project. This begins by asking what alternatives are being considered as part of the system design. Sometimes initial questions are articulated by the customer but the questions are incomplete, are not user centered, or do not get to the root of system performance. It is up to the human factors engineer to use the clues in those questions to determine human factors issues.

For example, a project might have an initial question about whether a head-mounted display provides better vision than a cathode ray tube (CRT) monitor. The analyst might ask what types of data in which format will best explain what the problems are and what the solutions should be? Examples of possible formats are time to perform tasks with the displays, type and number of errors in performing tasks, two-dimensional graphs showing visibility of a reference object at various distances, three-dimensional CAD files showing field of view, and relative changes in workload or a specific situation awareness (SA) measurement.

Deciding what type of output is needed will affect the modeling and analysis. For example, if it is known that a project is considering the value of a speech detection system, the analyst's model should have tasks modeled to a level in which activation, feedback, etc., of the speech detection system are represented. Otherwise, one may only need to represent communication in a broader sense such as "communicate internal to vehicle" and "communicate external to vehicle." Similarly, with CAD-based analyses, equipment, workstations, clothing constraints, and even humans can be modeled in varying degrees of resolution. Evaluation of preliminary concepts may be fairly low resolution due to the immaturity of exact equipment measurements. Items that are not of high tolerance or criticality may be modeled with less resolution. More mature designs or workstations in which high tolerances are critical (e.g., a helicopter cockpit redesign) require higher resolution input and output.

Once the required output and the method to produce it are determined, one will have a good idea of the input data required. At this point, the availability of the data should be checked. If the data will result from another part of the design process (e.g., CAD), it should be asked to be in a format as close to that which will be needed as possible. This can be as simple as specifying a file type or format (e.g., vrml, .xls comma delimited, .stl) or as complex as giving specific instructions on documentation of assumptions and sources, grouping of CAD parts, resolution, etc. There are two advantages to asking for the data as early as possible. First, the analyst has a better chance of getting what he or she wants without having to waste resources generating or reformatting it. Second, the analyst will know if the data will be available at all. Asking early helps scope the resources required to obtain the required input for analysis. Often, getting the right input data is the most expensive part of the HFE process.

A good mechanism for asking for the input data is to include it as a contract requirement. Requests for proposal can include specific data elements useful in evaluating the human engineering merits of the proposal. Likewise, contracts should include requirements for data useful to evaluate design options both during system development and for reuse on product improvements.

There is a wide assortment of methods and tools available to perform a wide variety of human engineering analyses. Each method and tool can be effective and useful as a stand-alone activity. However, the most powerful results can be achieved by using them in combination with each other. Once methods and tools have been selected to aid in human engineering for a program, a flow or management scheme for their application should be developed to maximize synergies among them. Basic texts on HFE (e.g., Wilson and Corlett, 1995; Sanders and McCormick, 1993; Wickens et al., 1997) should be consulted for standard approaches. Depicted in Figure 13.4, the following multiphase approach is recommended:

- Alpha phase—planning and task analysis;
- First phase—workload analysis;
- Second phase—anthropometric analysis;
- Third phase—human-in-the-loop simulation; and
- Final phase—design recommendation and documentation.

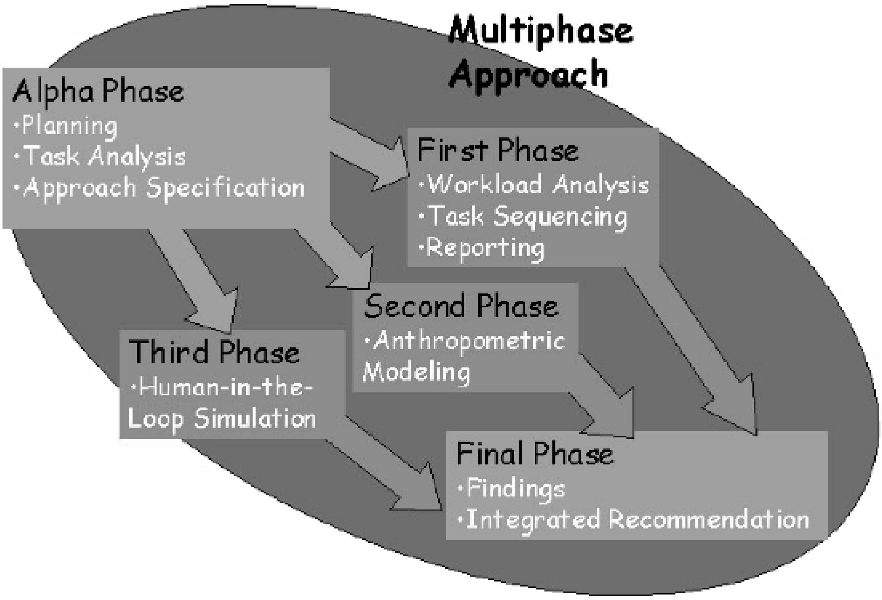


Figure 13.4 HFE analysis phases.

13.5.1 Alpha Phase: Planning and Task Analysis

The alpha phase is the key to a multiphase approach. It is characterized by precision planning and task analysis conducted as a concurrent first step. It results in a clear direction with a documented specification that indicates the inputs and outputs from each of the planned activities, establishes links between the activities, and creates a network of objectives that are optimized for efficiency and effectiveness. It involves extensive collection and analysis of several information sources. Part of the specification is an allocation of tools and methods mapped against the specific challenges presented by the tasks implicit in the product's operation and use.

The first step is to collect and manage the knowledge related to the project. Examples are

Product mission, purpose of the product, process, or system;
Functions the operator(s) and jobs the product must perform;
Acceptable and desired expectations for product performance;
Schedule available for changes to the design;
Budget available for changes to the design;
Schedule available to provide human engineering inputs;
Budget available for human engineering;
Simulation infrastructure, experimental design capability, and availability;
Anthropometric model software and the skill level of the available analyst;
Workload software and skills of the analyst;
Existing models that relate to the product;
Scenario(s) the product will operate under;
Target audience description data; and
Lessons learned from related projects.

During the task analysis, the analyst will list questions that will need to be answered to assure that each studied task will be performed to an optimum or prescribed standard. Each question will be allocated to one of the dimensions for analysis, resolution, and validation. After the alpha phase, the activity splits into a triad, and thus the multiphase aspect is in effect. The economies achieved come from the targeted addressing of the issues with the most appropriate tool or process.

13.5.2 First Phase: Workload Analysis

The first dimension is the workload model building, execution, and analysis. The activities in this phase are tailored to addressing those workload situations that are fixable within the context of the project and within the sensitivity range of the modeling tool and model.

Based on the task analysis from the first phase, an experienced analyst will start by reviewing and updating the plan that was created in the alpha phase. This will assure that the analyst is sensitized to the task sequencing and workflow problems that were identified. Combining this knowledge with an understanding of the modeling tool (such as WinCrew or IMPRINT), a vision of possible solutions should be generated. The solution set should be a generalized notion or zone of solutions that fit within the constraints of the project scope. The specific solutions will come later as a result of the use of the tools.

The workload analyst then builds the model to a scope somewhat larger than the focused activity would dictate. This is to assure that other elements not identified in the planning phase will be captured. It can be anticipated that some items will emerge from product development, operational scheme changes, and a variety of other areas due to project immaturity at the time of planning.

As the workload modeler builds and executes the model, the tasks and the respective interface issues should be identified and recommendations documented. Recommendations for mitigation should be accompanied with quantification of the problem and estimates of the likely improvement potential. Subsequent runs with postulated notional design improvements are essential parts of the process and should be preplanned in the original project scope. Also, tasks that cannot be fully modeled or solutions that are dependent on accurate representation of the target audience should be identified and forwarded to the manned simulation activity phase. This prescreens the problem set that will be simulated. The desired result is for analysts to address the maximum number of the issues in this phase where costs and schedules are most favorable.

13.5.3 Second Phase: Anthropometric Modeling

This activity is focused on achieving the maximum results from the modeling tool (perhaps using one of the graphical human figure models mentioned earlier) while expending the minimum resources. During task analysis, those tasks and sequences of activities that are relevant to anthropometry were identified and prioritized. For example, driving tasks may have been allocated to use of foot pedals in a driver's station. This is in contrast to workstations that have no foot-operated controls or have passenger-type seating space. Since the documented results from the task analysis phase will specify requirements for the anthropometric phase to focus on areas most likely to give interesting results, it will steer the anthropometrist toward detailed evaluation of foot space when foot controls are part of the workstation. In contrast, it will also prevent wasted efforts for detailed foot space evaluations in passive and passenger applications where a static foot does not contribute to the task. This is a simple example, but it is important that use of each evaluation tool and method be based on the task performed.

The result will be a tailored modeling activity that has high fidelity and attention to detail for those areas that are most sensitive to dimensional human accommodation and that can have an impact on the design process within the project budget and schedule constraints. See Chaffin (2001) for anthropometric modeling case studies and Green (2000) for procedures to follow in conducting a human model–based analysis.

13.5.4 Third Phase: Human-in-the-Loop Simulation

Based on the results of the task analysis, an update is made to the simulation plan during the onset of this phase. Only those areas that are most conducive to the benefits of simulation will be included in the final simulation plan.

The tasks that were allocated to simulation in earlier phases should be reviewed. Each task that requires issue resolution or design recommendation should be reexamined for alternative processes and reallocated back if appropriate. Once the list is set, the tasks to be simulated will drive the level and scope of the simulator fidelity.

Preexisting simulation facilities may not be designed for human engineering activities. Even cases where there is an available simulator with an operator's station represented, it may in fact be inadequate for some levels of scientific human experimentation. An analyst experienced in experimentation and simulation should evaluate the simulator with an eye toward the ability to collect and record errors and response times as well as log activities performed. The facilities should be evaluated for a variety of baseline capabilities and also for capabilities that can be added for the project at hand.

In addition to dimensional and feature inclusion, aspects such as image generator latency and simulator reliability should be considered. Image generator latency can lead to confusing results. The tasks in the plan should be evaluated for response time sensitivity, if latency is anticipated. Also, unplanned downtime during an experiment is very costly and will affect the schedule. Long simulation sequences with combined tasks will be much more vulnerable to simulator lockups than short snippets. Preplanning based on simulator performance and reliability is essential to the success of this phase.

Since the maximum number of issues were allocated to the other dimensions in the earlier phases, these experiments can now be short and of limited scope and fidelity. This contributes to optimal solutions.

13.5.5 Final Phase: Design Recommendation and Documentation

The last developmental phase is a documentation and recommendation summary. Each phase should result in some recommendations, but it is here that the issues are brought back together after being allocated to the appropriate phase. In many cases, issues can transcend more than one dimension. It is at this point where the interaction and combining of results must take place. This summary provides the glue that holds together a comprehensive and integrated solution set and body of recommendations.

The final phase and the alpha phase are the only phases requiring a specific sequence. Final must be last, and alpha must be first. The other dimensions can be conducted concurrently or in a tailored order to accommodate the specific needs of the project. This approach further supports the concept of schedule compression and cost minimization.

In summary, these approaches have a planning foundation on which each module is built and modified. Using these elements together and creating synergy between them will yield the maximum benefit at the minimum expenditure of resources.

13.5.6 Case Study on Importance of Method Sequence

During the development of an operator station for a loader backhoe, a sequential finding resulted in saving more than $30,000 in retooling costs. In the initial anthropometric analysis, before sequential analysis was performed, a leg space dimension was derived based on the largest operator in the target audience (95th percentile U.S. male, 1988). This operator station requires that the operator swivel the seat 180° from facing forward for the loader to facing rearward for the backhoe. When this leg space dimension was swept front to rear to allow the transition, an arc was described on the right side of the operator's station. This resulted in the design of a single concavity into the tooled console to accommodate knee clearance.

The problem with this arc was that it was based on an implied sequential assumption that was inaccurate. The assumption made was that the large operator would swivel the seat from the rearmost position on the track in both directions. Sequential analysis indicated that operators set the seat first in order to operate and then transition. This discovery led to the requirement for two arcs required in the console. The resulting design solution was improved to allow two different swivel positions on the seat track for the 95th percentile operator, one from each operator facing position as a starting point.

Corrections to the design before the tooling was released saved tooling costs. It also illustrates the critical link between sequence task modeling and anthropometric analysis, which is usually considered a static construct. This saving represented a total return of the cost of the human engineering activity for this project.

13.6 COMMON ERRORS IN PERFORMING HFE

Although not intended to be a comprehensive list, the following are common pitfalls for some of the more popular technology developments.

1. *Human Factors Is Just Common Sense* If this were true, then no one would have problems figuring out how to program a VCR or have difficulty reaching an ATM from their car. Norman (1988) shows just how prevalent poor design is. In reality, without training in a user-centered approach to design, engineers would not know that they should factor in parameters from physiology, psychology, anthropology, and other studies of humans when designing new technology. A related common problem is that many engineers and designers assume that just because they are human and know how to design and are logical, they are qualified to do human engineering. The misconception here is that there is no special knowledge of data or methods required to perform human engineering. We have shown in this chapter that that is not true. There is tremendous variation in the behaviors, expectations, and physical and mental capabilities of people. People and products are often part of much larger, complex systems. Consideration of all of these factors requires knowledge of the data that characterizes people and specific methods for making use of it. Above all, it is important to avoid the trap of assuming that because the engineer, designer, or developer is part of a target audience they can anticipate the concerns of the entire target audience. It is best to focus development decisions on data, findings, and analysis rather than solely on the opinions of those who are experts in the systems. They may know much about how *they* perform in the system but may know little about how to accommodate the entire range of the target audience.

2. *Anthropometric Analysis and Workstation Design* The phrase "accommodate the 5th to 95th percentile soldier" often appears in military specifications. What is intended is to accommodate the central 90 percent of the target audience and not worry about the 10 percent of people who fall at the extremes of the population (e.g., smaller, taller, weaker, stronger). The problem is that not all body measurements are perfectly correlated so that using a figure with many dimensions sized to the 90th percentile actually represents an extreme much greater than 90 percent. Testing workspaces with figures sized by setting each body segment to a uniform "percentile" length is misleading and invalid (Bittner and Moroney, 1975; Meindl et al., 1993). This issue is, however, poorly understood in the engineering and design communities. Approaches that have been used to address this issue are principal component analysis, boundary mannequins, and Monte Carlo simulation (Robinette and McConville, 1981).

Another common error is to create and use an "average" figure sized to represent the 50th percentile user. Again, body dimensions are not perfectly correlated, so a person having sizes matching many 50th percentile dimensions is unlikely to exist. While it is possible that an "average-sized" figure may be useful for some applications such as animation or work flow analysis, 5th, 50th, and 95th percentile figures are never correct and the nomenclature is misleading. Percentiles are meaningless unless they refer to a specific dimension.

Still, a common error is workstation design around static postures. Especially when using noninteractive human figure models or templates, engineers may position the human in one static posture (e.g., seated at a workstation) and optimize the location of components around that posture. The problem is that the workstation user may have to change position to reach for components or get in and out of the workstation (possibly even during an emergency such as a fire) but the workstation design makes it impossible to do so.

Figure 13.5 shows a driver trying to exit a vehicle crew station through a hatch. The crew station was designed for use with a night vision device. The night vision device is the object hanging down in front of the driver's face. When the driver is in a static seated driving position, the layout of the crew station is adequate. However, when the driver tries to exit the vehicle through the hatch and dynamics and motion come into play, the night vision device location becomes a serious obstacle. Exiting the vehicle through the hatch must be performed quickly in an emergency.

3. *Task Analysis* Not all task analyses are appropriate for all uses. The main reason for this is that task analyses may be performed to answer different types of questions. The resulting task list may differ in terms of detail, area of focus, etc., depending on what that analysis question was. So, a task list developed for use in developing a training program for a system may be useless for feeding a workload analysis of the same system. Another

Figure 13.5 Driver egress difficulty.

mistake is assuming that tasks must be listed serially. Many analysis methods that use task data as input can handle concurrent task performance. For some of them, such as workload analysis, this timing information is crucial. If task analysis data will be used to track and test compliance with system performance requirements, then the task must be clearly defined (clear definition of beginning and end points) and tied to relevant factors in design (e.g., what equipment is being used under what conditions) and measurement criteria (e.g., how fast, to what degree of accuracy, etc.)

4. *Use of Models* Care must be taken in applying models. By definition, a model is a simplification of the real world. The simplifications represent assumptions about which aspects of the real world are important. The assumptions on which a model is based should be identified and examined for compatibility with the target system and audience before the model is applied. For example, a human figure model developed for use by the U.S. military may use algorithms developed from a population of U.S. Army males. It is unlikely that this model will be equally valid for application to a product designed for Japanese females. This is one reason why it is meaningless to discuss the validity of a model outside the context of its intended application—just because a model has been "validated" does not mean that it is valid for use on any particular application.

Problems also arise when assumptions between modeling elements (within one modeling tool or when using multiple models) conflict. For example, the sizing data for a human model might be based on a military population but the feasibility of a lift analysis model might be derived from a civilian population. In some cases, this discrepancy may invalidate results. As stated in Section 3.5, models should not be applied without first determining the analysis questions that they will be used to answer. If these trade-off parameters and output measures were well thought out prior to modeling, issues related to the appropriateness of a model would be easier to resolve. For example, if we need to determine the feasibility of an arm lift for a military population but the model is based on a civilian population, we can check to see if the difference in lifting strength between the military and civilians is within an acceptable range for our analysis. This requires investigating the demographics of our target population (military) with the population used to derive the model (civilians) on the attribute for which we are interested (lifting strength of arm).

5. *Optimizing the Parts Instead of the Whole* When system design is broken down into subsystems and assigned to departments and disciplines, it is possible for total system requirements to be forgotten in favor of subsystem requirements. The result is a system with components that may work well when used separately but do not work at all when the system is used as intended. For example, during one phase of development of a new hatch and commander's weapon station for a main battle tank, the design of the vision blocks around the hatch was optimized for maximum viewing. This resulted in very tall blocks. Hatch operation was improved so that it allowed for easy adjustment into several positions, including one in which the hatch was partially open. A new machine gun mount just outside the hatch was also designed. Each individual component met design constraints but there was a system level requirement for the machine gun to be aimed when the commander was using the hatch in the partially open position. Because the view blocks were so tall and he could not get higher up due to the partially open hatch, the commander was unable to reach over the view blocks to the machine gun handles to aim at ground targets (see Figure 13.6).

6. *Misuse of the "User Jury"* A great deal of confusion seems to exist among human engineers regarding differences among user juries, experiments, and tests. The

Figure 13.6 Commander difficulty reaching machine gun.

most important differences among them lie in their purpose and the method used to achieve that purpose. A properly run *user jury* or focus group can help elicit information about the appropriateness of design concepts or directions from potential users. From them, engineers can get a general sense of the factors important to users, the operating environment constraints, and the reaction to expect from specific design options. User juries are *not* appropriate for determining the best design from all possible choices because it is impossible to present all choices for consideration. Andre and Wickens (1995) found that subjective feedback from users might fail to predict design features that improve performance. *Experiments* are aimed at controlled proof of hypotheses using the scientific method. Proper experimentation can define relationships among design parameters and performance to help determine the best possible design choice. In contrast, the purpose of *tests* is to determine whether or not a given design meets the system requirements. The test is generally set up as pass or fail against a specific performance requirement threshold. Tests are best at evaluating whole-system performance against a realistic use scenario. An example of a test is whether or not I can fire an arrow without injuring my son into the apple on his head at 20 paces when the wind is blowing at 5 knots on a clear day using the new and improved crossbow that I just designed.

7. *Poor Experimental Methodology* When conducting usability analyses, user juries, and field studies, it is very easy to violate principles of good experimental methodology. This is a particular danger for engineers and physical scientists not trained in experimentation involving human participants. Human participants introduce numerous variables that are subtle and difficult to control in a field setting. Examples of common problems include too few subjects, not enough trials, poor control of motivation, order effects, and

experimenter-introduced bias. Typical sources of introduced bias are overtrained subjects, subjects with a personal stake in the outcome of the study (such as the designer), and subjects that have been coached. The worst candidates to conduct human system experiments are system designers because of the bias in favor of their own design. Martin (2000) is an excellent reference for readers unfamiliar with experimentation involving human participants. Weimer (1995) also covers experimental methods and discusses them in the context of human engineering application areas.

8. *Surveys* Questionnaires are very popular mechanisms for collecting subjective data, but a good questionnaire is difficult to find. The most common mistakes in developing questionnaires are

- Asking too many questions or "nice to know" questions (consider what you will do with the answers; how will they be analyzed?);
- Asking questions that are so vague that respondents are not sure what is being asked (e.g., how do you feel about the design?);
- Asking questions to which the answer can be misinterpreted (e.g., compound questions; did the respondent mean yes to both parts or just one part?); and
- Biased wording in questions (e.g., how much do you *like* the new design?).

9. *Focusing on System Operation and Ignoring Maintenance* When the system is analyzed, it is often the case that tasks required for maintenance actions are overlooked. Mental workload and time may not be an issue, but maintenance tasks may involve limited physical access to parts or openings, awkward postures, or heavy lifting. These tasks and analyses may have an effect on safety, error, and health hazards and should not be ignored. Biomechanical and anthropometric analyses are particularly useful investigating these issues. Problems with maintenance tasks may result in excessive costs (including manpower) to field a system, product liability, or unnecessary system downtime.

10. *Misunderstanding SA* Situation awareness refers to the user's level of awareness of his or her operational environment while performing a task or job. Designers sometimes think of SA as a static, one-dimensional aspect of the system they are designing, but SA levels are dynamic and can vary between individuals. As a concept, SA is context specific, so there is no one measure of SA that is appropriate all of the time and in all cases. Because of this, better measures of SA probe an operator's momentary awareness of a specific aspect of a specific parameter applicable to the context under which they are performing. For example, we might ask whether a pilot was aware of his altitude at a specific time or whether an automobile driver noticed a particular pedestrian crossing the street. To develop these questions that probe SA, it is often necessary to perform task and cognitive task analyses to understand the requirements of a job in context. Examples of context-specific SA metrics can be seen in the various versions of the situation awareness global assessment technique (SAGAT), e.g., air traffic control, air-to-air tactical, and commercial aircraft operation versions (Endsley and Garland, 1999).

13.7 BENEFITS OF MODELING FOR HFE

Modeling offers many benefits for the human engineer and for the success of system development projects. Proper implementation of an HFE modeling program should result in reduced resource expenditure, earlier identification and remediation of usability issues, and more readily accepted input from human factors engineers.

Most of the costs associated with an HFE modeling effort are incurred at the beginning of the effort, and the cost to produce derivatives of those models is often less. This is because once a model of a system, workstation, or product has been built, the data and labor needed to make modifications to that model to perform new analyses, answer new questions, or evaluate other design options are reduced greatly. This is especially true if future uses for the model are anticipated so that data reuse and increases in model fidelity are planned. For example, if a company uses modeling and simulation to develop a new system prototype on the speculation that it may be of interest to the DoD, the company will have those files to use as evidence of the soundness of its design in a proposal to the government. If the company wins a contract to develop the system, those same files can be modified and used to evaluate increasingly detailed designs as the system goes through the concept development, demonstration and validation, full-scale development, production, and product improvement phases. The cost of producing usable models is reduced for each phase because data and labor from previous designs have been leveraged and the corporate knowledge about those designs has been embedded in the models.

Human factors engineering modeling is also useful in evaluating the feasiblity of system performance requirements and is very effective in combating human engineering "requirements erosion." To better understand what is meant by requirements erosion, consider the following scenario. A design engineer asks for a lift constraint, (e.g., what is the heaviest I can make this part and still have a man lift it?), and an answer is given by the human factors engineer. The design engineer says she cannot meet the constraint, but how about going over by 5 pounds? A few months later, as weight constraints for the entire system get tighter, the engineer asks for a small 6 pounds on the lift constraint. The process is repeated and each time the engineer asks for a small compromise it may appear insignificant compared to the current limit, but when viewed against the original constraint, a small increase may be significant. The HFE specialists must remember to measure and present all requests for requirement, leniency against the original requirement, not against the previous number. Models can be used to document and illustrate the original constraint and each successive compromise.

Once the initial design phase begins, modeling benefits human factors engineers by allowing them to be proactive (rather than reactive) when identifying and resolving HFE design issues. If timed properly, use of predictive modeling results in identification of problems earlier in the design cycle before so many design constraints are set, thus limiting the options for problem resolution. In addition, human engineering modeling tools enable human factors engineers to participate more fully in concurrent engineering efforts. Instead of waiting for hard copies of design drawings or physical prototypes to evaluate for usability issues, human factors specialists can use modeling tools to evaluate computer-based designs as they are being developed by other engineering disciplines. Recommendations for modification can then be specified through changes to the same computer-based design files delivered to them rather than in written (and more easily ignored) text reports.

Models also benefit HFE by providing quantifiable results. Program managers use trade-off analyses that require numerical input and models help provide that numerical input. Even if the numbers output by the model are not accurate to the *n*th degree, these results help bound the problem and may be just as accurate as some cost or design parameter projections produced by other disciplines.

As stated earlier, in some cases, graphical output is more useful for acceptance of HFE recommendations than numerical or text reports. It is often difficult to convince other design and engineering disciplines that a problem is severe enough to warrant change. Sometimes it is difficult just to explain the problem. Graphical human engineering models illustrate these problems. Graphical human figure models are especially effective in showing inability to reach controls, fit in a workspace, or see displays and controls. Most people have no trouble putting themselves in the place of the human figure model and seeing the problem from the viewpoint of the model. Nonanthropomorphic graphical models such as task network models may not be as easy to relate to, but they are just as important to good design. Such models can help illustrate bottlenecks in task or information flow.

13.8 SUMMARY

Human factors engineering (HFE) and ergonomics are disciplines that focus on designing systems around users (i.e., user-centered design) and employing technology that acknowledges and complements human limitations and capabilities rather than forcing them to adapt to the technology. Well-designed, user-centered systems require relatively less training and aptitude to operate and maintain. They should also produce less errors when used. Human factors engineering is an engineering discipline that extends well beyond the application of common sense to design. Many HFE methods have been developed that center around understanding the thoughts and actions of the target audience of users. Several of the most commonly used methods are presented in this chapter. Tools (many computer based) have been developed to aid in application of HFE methods. Classes of HFE tools as well as factors to consider when deciding which are appropriate for a project are also described. The HFE tools are becoming increasingly integrated to more comprehensively represent the physical, mental, and behavioral aspects of human performance. Analysis templates and wizards are being incorporated into tools to aid in conducting HFE analysis and design. Despite the availability of adequate methods and an ever-improving set of tools, their application is not without problems. Ten common errors in application are identified to help program managers or those new to the discipline to avoid making these errors. Once the methods have been chosen and appropriate tools selected to apply the methods, it is useful to develop an HFE program plan to maximize use of HFE resources. A typical project flow is described to aid in development of an HFE plan. Finally, the chapter concludes with several points outlining the benefits of modeling to a successful HFE program.

NOTES

1. Examples of these guidelines can be found at http://www.iso.org/iso/en/ISOOnline.frontpage http://risk.das.state.or.us/ergoguid.htm, and http://www.usyd.edu.au/su/ohs/ergonomics/welcome.html.
2. Human figure modeling software changes frequently. For Jack, see http://www.plmsolutions-eds.com/products/efactory/jack. For Safework®, see http://www.safework.com/safework_pro/sw_pro.html. For Ramsis, see http://www.hs.tecmath.de/english/ramsis_eng.shtml. For ManneQuin Pro, see http://www.nexgenergo.com/ergonomics/mqpro.html.

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