Ergonomics in Manufacturing

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abstract

This article argues the need for human presence in various capacities in modern day manufacturing, and identifies the key issues concerning human integration in advanced manufacturing technology. In addition, we provide methodologies, guidelines and conceptual models to stimulate discussion (especially in manufacturing engineering forums) of issues involved in integrating humans in advanced manufacturing systems.

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INTRODUCTION

Broadly, manufacturing can be defined as the conversion of raw materials into finished products. It involves a variety of activities such as product design, process and material selection, production planning and control, materials handling, inspection and quality control, packaging, and marketing and sales. In this conversion process, the key factors that dictate the productivity and competitiveness of one manufacturer over another are the ease, the quickness, and the economy of manufacture, of a quality product. These factors are especially important for American manufacturers owing to the increasing globalization of all aspects of product manufacture including technology, labor and market.

To achieve ease, quickness, economy and quality in manufacture, manufacturing practitioners and researchers, have, in the past, advocated complete automation of all manufacturing activities. The use of advanced technology was seen as the key to achieving a competitive edge in the world market. In addition, the general belief that human workers had difficulty in providing the required quality, uniformity, reliability, repeatability, and documentation, for competitive manufacturing, made the case for complete automation of all manufacturing activities complete. While this thinking was not narrowly confined, fully automated factories based on hard automation are not yet viable due to technical, economic, and cybernetic reasons.

Hard automation does not yield itself to situations where a product is to be changed frequently because of user needs, costs, or engineering improvements. Also, automated equipment, such as robots, vision systems for inspection, etc., provide flexibility but not capability. For robots to be capable, for instance, they must have the necessary intelligence and must be able to sense the working environment to see, touch, feel pressure, and sense their own movement; acquire knowledge and judgement to carry out tasks properly and act according to the knowhow of the skilled worker (for example, accept parts that may not have the exact tolerance, or are not properly oriented); perform tasks reliably to impart the required 3-D motions to the product; and communicate with the operator by voice, written sentences, and other appropriate forms of communication. Currently, humans must either work with automated systems or supervise them and must intervene when problems develop (e.g., when a robot drops a part, or when a computer is unable to make an inspection decision after searching for and identifying a defect).
The economic viability of automated systems has also been shown to be questionable. For instance, in the case of assembly, numerous studies comparing human and robot performances have shown manual assembly methods to be economically more attractive than the automated option (Mital, 1991a, b). In the case of automated inspection, another major area ripe for complete automation in industry, the high development costs of such systems, and the inability of such systems to amortize themselves over many applications, have proven to be the undoing of many such commercially available systems (Newman and Jain, 1995). The economic advantages of one method over the other are a function of the factors such as performance times, wage and interest rates, and equipment reliability. In general, the economic disincentives of automated option are primarily due to low reliability, high interest rates, and low declining wages. Should these factors change and move in the other direction (e.g., a decline in interest rates), the automated option could become economically attractive.

From a cybernetics perspective also, it appears that complete automation will be a sub-optimal solution for manufacturing organizations, at least for the foreseeable future, when compared with production methods that involve humans, machines, and computers in an effective partnership (hybrid systems). Humans have been shown to be important components for system control, and for innovation, in manufacturing systems in production systems worldwide. The cybernetics case has been detailed by Mital et al. (1994b) and can be summarized as follows: the Law of Requisite Variety states that for any system to remain under control, the controller of that system must be able to absorb the entire range of inputs that may affect the system (i.e., the system or the control process must be at least as complex in its behavior as the system it is trying to control). Given that a manufacturing organization is an open system, it is affected by its physical, commercial, legal and social environment as well as its own environment. The control system, therefore, must remain in a stable state. Quite apart from the nature of such inputs (most of which exist in human-compatible form, but many of which can be made computer-compatible), there is the content of this input. Within the organization, the decisions to be made vary in importance, and hence the type of information required for decision-making also varies. The information content varies from very low level of detail (e.g., 'the tool has engaged the workpiece') to very high level of detail (e.g., 'the recent government legislation carries the following implications for our business'). It is difficult to see how any automated system could deal with high-level information of the latter type, and make the necessary deductions and other inferences without massive investments in background knowledge stores. Further, the unexpected nature of some inputs (e.g. 'a hurricane has blown the roof in') will require human-like intelligence for controlling the situation, unlikely to be available from automated systems in the foreseeable future. There are also the system improvement, system monitoring, and system maintenance roles to be performed within manufacturing units. Again, these roles require human-like
intelligence, and great manipulative skills for their performance. It is difficult to see how such roles could be performed automatically.

It is evident, therefore, that humans will remain an essential and an integral part of manufacturing for a long time to come. Given that humans will remain essential for efficient and error-free functioning of manufacturing systems, the key questions to answer are: what are the human issues a designer should consider when designing manufacturing systems involving humans, and how should one address these issues when integrating humans in manufacturing systems, even at the manufacturing systems design stage? The science of ergonomics, which we define as the "application of technology to the appropriate extent to assist the human element in work," provides guidelines and methods to address these questions.

In order to identify the issues involved in human integration in advanced manufacturing, in 1993, a National Science Foundation sponsored panel of industry, academic, and government experts convened in Cincinnati, USA (Mital, 1995a). The panel identified five major areas in manufacturing companies that require human intervention. They are:

- Design for manufacturing
- Cost-benefits and productivity
- Preparing companies for emerging technologies
- Human issues
- Training

Within each area, several key issues were identified as needing further research. The major items are listed below.

**Design for manufacturing**

- Ergonomic issues in designing for manufacturability.

Some of these issues associated with ergonomics have been discussed at length by Mital and Anand (1992).

- Designing products for usability, maintainability, and environmental friendliness.
- Designing for accessibility, safety, standardization of components, and increased reliability.
- Development of repair manuals.
- Knowledge extraction leading to new designs.
- Converting business/market needs into product/process designs.
- Determining optimal combinations of automation and manual work.
• Ways to provide the necessary design information to designers to aid the design process.
• Ways to organize the design information in a usable form.
• Ways to get the information from interest groups, suppliers, workers on the line, etc into the design process.
• Outlining the design process people use.
• Making the design process friendly.
• Effective ways to provide on-line design advice.
• Determining manufacturability of parts.
• Developing on-line cost options for alternate designs.
• Perform on-line check for the existence of alternate designs.
• Capturing the creativity of the entire design team.
• Evaluating the impact of design tools on designers’ performance and creativity.
• Translating design thumb rules into product design features compatible with user requirements and user needs.
• Making consideration of human needs and requirements an integral part of the design process.
• Designing for humans.
• Determining the effects of manufacturing deviations from the design on workers' performance.
• Designing packaging to minimize negative impact on the environment, handlers, users and customers.

Cost-benefits and productivity

• Assessing the costs and benefits of making improvements that enhance human performance and safety.
• Quantifying intangible benefits and costs of human work.
• Determining the tradeoffs in productivity with poor human accommodation.
• Determining what factors have a negative effect on productivity.
• Determining optimal workers' stress levels that maximize productivity.

Preparing companies for emerging technologies

• Providing the environment to facilitate the transfer of technologies.
• Identifying the support (human and equipment resources, technological and training support, finances, market potential and readiness, etc.) needed.

Human Issues

• Determining what kind of assistive devices are needed to enhance human performance (inspection, assembly, machine loading, etc.) and how to design them.
• Determining supervisory needs.
• Determining human considerations to account for during manufacturing planning.

Training

• Identifying the kind of training - cross-training versus retraining.
• Training workers and supervisors to adapt to automation.
• Measuring training performance and effectiveness.
• Identifying the role of worker(s) in the production process.
• Determining the necessary training support.
• Developing training documentation.
• Determining documentation, aids, etc., needs.
• Preparing workers for change.

While some of the issues identified above need further researching, decades of ergonomics has provided guidelines for addressing some fundamental and important questions involving human integration in manufacturing. In the remainder of this article, we address in detail four such important issues: function allocation between humans and machines, human considerations in product design, human training for changing manufacturing technology, and education of manufacturing and other engineering professionals about ergonomics.

Function allocation between humans and machines

Undoubtedly, with the advances taking place in information technology, many activities and functions that are currently performed by humans will be taken over by automation, and this is indeed to be welcomed (in general, these will be functions that are fairly well proceduralized, require little creative input, and permit algorithmic input). The functions that will not be automated, at least in the foreseeable future, will be those requiring cognitive skills of a higher order: design, planning, monitoring exception-handling, and so on, and will still be performed by humans.

While it is easy to comprehend the need for large capital investment associated with the automated option, the technical reasons are not always evident. The prime requirements for automating any function are the availability of a model of the activities necessary for that function, the ability to quantify that model, and a clear understanding of the associated information and control requirements. One cannot simply automate functions by mimicking what people do (Nevins and Whitney, 1989). According to Nevins and Whitney, there are several reasons why automation purely/largely based on what people do does not work well:

(1) In many cases we really do not know exactly what people are doing.
We are limited by technology to build machines that are comparable to human capabilities, particularly in flexibility and decision-making, and mimicking their techniques.

People have unique means of sensing capability for instance.

People are often too innovative or resourceful and improve processes in ways machines cannot perform—mating parts that do not quite meet the tolerances; finding ways to prevent errors or inefficiencies in process (the *poka-yoke* attribute).

Some manufacturing researchers and practitioners, in fact, openly admit that human is the most versatile component in the manufacturing system and products and systems redesigned with this fact in mind can tremendously reduce cost while improving quality (Coleman, 1988). The question then is how to systematically determine what functions humans will perform and what functions should be allocated to automated equipment.

However, because complete automation is not yet a practical alternative, as discussed in the previous section, it does not necessarily mean that no functions can be automated or all functions must be performed manually (Mital et al., 1991). Clearly, there are some functions that should be performed by machines because of:

1. design accuracy and tolerance requirements,
2. the nature of the activity is such that it cannot be performed by humans (e.g., water jet cutting, laser drilling),
3. speed and high production volume requirements,
4. size, force, weight, and volume requirements (e.g., materials handling),
5. hazardous nature of the work (e.g., welding, painting),
6. special requirements (e.g., prevent contamination), etc.

Equally, there are some activities that should be performed by humans because of:

1. information-acquisition and decision-making needs (e.g., supervision, some forms of inspection),
2. higher level skill needs (e.g., programming),
3. specialized manipulation, dexterity, and sensing needs (e.g., maintenance),
4. space limitations (e.g., work that must be done in narrow and confined spaces),
5. situations involving poor reliability equipment or where equipment failure could be catastrophic,
6. activities for which technology is lacking (soil remediation), etc.

This leaves a very large number of activities that could be performed either by machines or people. These activities must be reviewed carefully and then
assigned either to automated equipment or humans in a systematic manner for smooth and trouble-free operation of a manufacturing organization.

Some of the activities that may generally fall under the category of activities that can be performed by both humans and machines are:

(1) assembly of parts and subassemblies,
(2) routine on-line inspection,
(3) packaging and shipping,
(4) palletizing and stacking,
(5) materials handling,
(6) sorting, etc.

In order to resolve the dilemma of human or machine, a functional database of all the operations performed in a manufacturing unit needs to be created and specific procedures and guidelines should be established and followed for efficient and effective allocation of functions between humans and machines.

According to Mital et al (1994b), the assignment of tasks to humans and machines must be based on in-depth analysis of:

(1) information and competence requirements of the activity,
(2) capabilities and limitations of humans and the automated equipment,
(3) availability of technology,
(4) safety and comfort,
(5) the design principles for "good" jobs, and
(6) economics.

In the context of narrowly defined manufacturing activities, such as material handling, material processing, inspection, assembly, packaging, shipping, and improvement activities, Mital et al. (1994a) have developed a series of decision-making flow charts that lead to an optimal assignment of functions. As a part of the decision-making analysis, a set of mandatory, generic questions must be answered (as outlined in Figure 1). These include:

(1) Requirements of complex decision making, experience to efficiently perform the task: If a task requires complex decision making and experience, then it must be assigned to humans (due to present technological limitations). However, with further developments in the field of artificial intelligence, the automated option may become a viable (if perhaps a costly) choice in the future.

(2) Physical ability of humans to perform the task: A detailed assessment of the capabilities/limitations of humans versus those of the automated equipment for each of the activities listed above must be performed. If it is determined
that humans are capable of performing the task then further analysis must be performed; if humans are determined incapable of performing the function, the function must be allocated to automated equipment. An important decision that the company must take is whether in this process the company should consider humans in general, or those that work for the company. If labor turnover is fairly rapid, or seasonal, it would be sensible to consider all humans. If the staff are relatively permanent, it would be sensible to consider only those working in the company and likely to be affected by the project.

(3) Safety considerations: If it is determined that both the human and automated options can be used to perform the task, safety of the human operator must be considered. A detailed safety analysis must be carried out to determine the severity and likelihood of potential injury to humans. If performing the function is determined to be unsafe for humans but technology is available to automate the function, the function must be assigned to automated equipment; otherwise the job can not be performed as specified. In this case, the functions to be undertaken should be re-analyzed and respecified; it is always possible to devise more than one way to solve a problem. Figure 2 provides a decision-making flowchart for allocating functions based on safety considerations.

(4) Economic consideration: If it is established that there are no safety hazards, and both the human and automated options are still viable, the decision must be based on systematic economic analysis. Standard engineering economy techniques, such as economic evaluation of alternatives, should be used. Figure 3 shows a flowchart for some of the economic considerations in function allocation.

The flow chart in Figure 1 shows the generic process of function allocation. Detailed flow charts showing capability/limitation considerations for important manufacturing activities such as materials handling, inspection, assembly, packaging, shipping, etc., have also been developed and recently become available (Mital et al. 1994a).
Figure 1. Generic function allocation
Figure 1 (contd.)
Figure 1 (contd.)

Can/should humans perform the activity?

Yes

Is technology available?

Yes

Automate

No

Improve human performance

Is it safe?

Yes

Is it possible to make it safe?

Yes

Make it safe

No

Make it safe

Is human performance economical?

Yes

Assign the task to humans

No
Safety Flow Chart

1. Can task be automated?
   - Yes: Automate
   - No: Revisit and replan task

2. Is there a hazard of acceleration due to inadvertent operation or translation of loose objects, etc.?
   - Yes: Is the level of risk acceptable?
     - Yes: Can it be made acceptable?
       - Yes: Reduce risk by:
         - Use of two handed control switches
         - Use of photoelectric sensing device
         - Use of personal protection
       - No: Revisit and replan task
     - No: Can it be made acceptable?
       - Yes: Reduce risk by:
         - Use of two handed control switches
         - Use of photoelectric sensing device
         - Use of personal protection
       - No: Revisit and replan task
   - No: Is there a mechanical hazard due to sharp edges, rotating parts, or part malfunction, etc.?
     - Yes: Is the level of risk acceptable?
       - Yes: Can it be made acceptable?
         - Yes: Reduce risk by:
           - Installing HVAC unit
           - Use gloves
           - Improve ventilation
           - Provide local cooling jackets
         - No: Revisit and replan task
       - No: Can it be made acceptable?
         - Yes: Reduce risk by:
           - Installing HVAC unit
           - Use gloves
           - Improve ventilation
           - Provide local cooling jackets
         - No: Revisit and replan task
     - No: Reduce risk by:
       - Installing HVAC unit
       - Use gloves
       - Improve ventilation
       - Provide local cooling jackets
       - Etc.

3. Is there a hazard due to excess heat from hot metal, hot gases, inflammable gases, etc.?
   - Yes: Is the level of risk acceptable?
     - Yes: Can it be made acceptable?
       - Yes: Reduce risk by:
         - Installing HVAC unit
         - Use gloves
         - Improve ventilation
         - Provide local cooling jackets
         - Etc.
       - No: Revisit and replan task
     - No: Can it be made acceptable?
       - Yes: Reduce risk by:
         - Installing HVAC unit
         - Use gloves
         - Improve ventilation
         - Provide local cooling jackets
         - Etc.
       - No: Revisit and replan task
   - No: Revisit and replan task

Figure 2. Function allocation based on safety
Figure 2 (contd.)

Is there a hazard due to leaks and spills or toxic, corrosive, inflammable, or slippery substances?

Yes: Is the level of risk acceptable?

Yes: Can it be made acceptable?

No: Reduce risk by:
- Proper storage of flammable and combustible substances in ventilated metal cabinets,
- Proper sealing,
- Proper ventilation,
- Installation of fire extinguishers,
- Use of personal protective equipment,
- Better housekeeping,
- Training,
- Adequate warnings

No: Reduce risk by:
- Better designed hand tools,
- Isolating the person from the source of vibration,
- Avoid frequency below 1000 Hz,
- Use vibration attenuating gloves,
- Try source enclosure,
- Use damping material to reduce vibration transmission, etc.

Is there a hazard of vibration due to high noise level, flow or jet vibration, etc.?

Yes: Is the level of risk acceptable?

Yes: Can it be made acceptable?

No: Reduce risk by:
- Following safety procedures as per OSHA standards,
- Making employees aware of the properties of all chemicals used and training them in the use of these chemicals and also the necessary actions to take in case of accidental spills,
- Etc.

No: Reduce risk by:
- Better designed hand tools,
- Isolating the person from the source of vibration,
- Avoid frequency below 1000 Hz,
- Use vibration attenuating gloves,
- Try source enclosure,
- Use damping material to reduce vibration transmission, etc.

Is there a chemical hazard due to fuels, oxidizing agents, ignition sources, high pressure gases, etc.?

Yes: Is the level of risk acceptable?

Yes: Can it be made acceptable?

No: Reduce risk by:
- Following safety procedures as per OSHA standards,
- Making employees aware of the properties of all chemicals used and training them in the use of these chemicals and also the necessary actions to take in case of accidental spills,
- Etc.

No: Reduce risk by:
- Better designed hand tools,
- Isolating the person from the source of vibration,
- Avoid frequency below 1000 Hz,
- Use vibration attenuating gloves,
- Try source enclosure,
- Use damping material to reduce vibration transmission, etc.
Figure 2 (contd.)

Is there an electrical hazard due to electrocution, danger of sparks, etc.?  
Yes: Is the level of risk acceptable?  
No: Can it be made acceptable?  
Yes: Reduce risk by:
- Proper sealing of all cables,
- Install overcurrent devices, ground fault current interrupters,
- Double insulation of all wiring,
- Reduce moisture,
- Separate inflammables / combustibles from source of ignition,
- Regular preventive maintenance.
No: Humans can perform this activity.

Is there a hazard of fire due to fuels, oxidizing agents, accidental mixing of chemicals, etc.?  
Yes: Is the level of risk acceptable?  
No: Can it be made acceptable?  
Yes: Reduce risk by:
- Proper storage of flammable and combustible chemicals in ventilated metal cabinets,
- Proper sealing,
- Proper ventilation,
- Installation of fire extinguishers,
- Use of personal protective equipment,
- Better housekeeping,
- Training,
- Adequate warnings,
- Etc.
No: No further action needed.
Figure 3. Function allocation based on economics

Consider the following factors:
1. Production quantity
2. Production rate
3. Standard time per unit
4. Total number of humans needed to meet the demand
5. Wage rate
6. Incentives
7. Fringe benefits
8. Salary raises
9. Cost of quality due to human error, poka-yoke devices etc.
10. Training cost
11. Recruitment cost
12. Cost of injuries
13. Design and layout of workstations
14. Job support (manual, tools, etc.)
15. Etc.

Consider the following factors:
1. Production quantity
2. Production rate
3. Time per unit including setup time
4. Capital investment
5. Interest rate
6. Inflation
7. Depreciation
8. Maintenance cost (spares and labor)
9. Operating cost
10. Local tax laws
11. Cost of lost production due to breakdown
12. Worker displacement due to automation
13. Cost of injuries
14. Design and layout of workstations
15. Etc.

Compute annual cost of the manual

Compute annual cost of automated option

Compare the two alternatives
Human considerations in product design

Both conventional product design, and the product design process for concurrent engineering, are limited in that they do not consider the human user in the process. The major problem with currently practiced design procedures is that while designers consider users to some extent, the information available to design teams is invariably insufficient to understand the user properly. This is particularly true in the case of nonexpert users. Furthermore, designers and manufacturers these days tend to focus more on increasing the functionality of the product (increasing the variety of things the products can do). This leaves the users more confused and frustrated, and the products become beyond their capabilities to operate and use. Product usability considerations must make users the focal point of the design. If a design is complicated and requires significant learning and skills to use, users will tend to cast it aside. Products that are easy to use, however, will become more popular and should have a longer life. It is important to remember that products are designed to fulfill user needs. In order to accomplish this, user attributes must be matched with the product attributes and the product design process must be redirected towards a consideration of the user by taking into account the opinions and advice of user experts; the users and designers must become partners in the design. Furthermore, user involvement would force an iterative approach to product design. Figure 4 provides our model of product design incorporating the human user considerations (Mital and Anand, 1992). The goal is to design products that will allow users' needs to be met. It emphasizes user needs analysis and usability testing. The process must begin with collecting as much information as possible about who the users are, what their needs are, what their preferences are, what kind of tools they use, what the environment is within which they work, what situations commonly arise during their normal activities, what existing products meet their needs, what the limitations/advantages of these products are, etc. On the basis of this information, product usability requirements can be established. These, coupled with design requirements, provide information for the product design.

The product design obviously has to go through engineering evaluation, prototype development, and engineering testing. The prototypes must then be subjected to user testing and evaluation. Usability can be tested through product usage scenarios and occurrences of usability defects (anything in a product that prevents the user from using it with reasonable effort within a reasonable time). Subjective and objective measures such as task completion time, errors that occur while using the product, verbal comments during the use, and visual scanning during use. Once the product has undergone technical and user evaluations, it may be released for distribution. The feedback from the market and from users at large must be reviewed for further eliminating usability and design deficiencies.
Human training for advanced manufacturing
Given the importance of personnel to manufacturing, it is indeed unfortunate to find that many companies have failed to properly cultivate this important resource. In fact, the failure of many companies to transition to modern competitive manufacturing organizations is primarily due to their mismanagement of human resources (Ettlie 1988: Majchrzak 1988). For example, instead of making the entire manufacturing operation efficient by utilizing people and other resources effectively many companies have achieved short-term productivity gains by laying off workers. This has been done time and again without any regard for worker welfare or consideration of long-term consequences on the local, regional or national economy. Specifically, many organizations have failed to upgrade worker skills to levels compatible with advanced manufacturing technologies (Butera and Thurman 1984; Gerwin and Tarondeau 1982). The workers, thus, have been left with fewer career options and limited economic opportunities. It has been shown that variables such as comprehensive training are essential to comprehensive human resource management practices, particularly in advanced manufacturing environments. Still, relatively few American industry workers receive training (if workers do receive training, the training budget is one of the first items to be cut when austerity measures are effective).

A survey of auto workers at a General Motors assembly plant revealed that less than 20% of production workers received technical training, although nearly 83% received some form of training. A survey of contract labor in the U.S. petro-chemical industry by the John Gray Institute (1991) revealed less than 33% of workers to have received company training upon entering the industry. Further, 20% of this same labor force reported receiving no on-going training throughout their employment.

It is also known that the amount of training is a function of professional position with managers receiving far more training than line workers (Carnevale 1991), and professional associations/status—union labor receiving significantly greater training than non-union labor (John Gray Institute 1991), and direct-hires receiving double the level of on-going training as contract labor (John Gray Institute 1991). It is important to note that Japan, a economic giant, second only to the United States, spends considerable time and effort in in-depth training of its workers in a variety of skills (Muramatsu et al. 1987). Such philosophy is rarely seen in industry in the United States; exceptions are plants using Japanese management techniques. Also of considerable importance is the fact that workers, in the present atmosphere of downsizing, need to be trained in a variety of skills to improve their chances of regaining meaningful employment. The want for such training has been reported in a study of workers at Toyota (Muramatsu et al. 1987).
A number of investigators have shown that worker skill levels are a direct determinant of levels of quality performance (Flynn et al. 1995; Hackman and Wageman 1995). It is also reasonable to suggest that investments in human resources should keep pace with the changing technology particularly if the workers are to take responsibility for quality, productivity, and customers (Majchrzak and Wang 1996). Existing American industry training programs not only provide inadequate training for success in contemporary manufacturing, they are generally not linked to product designs (determining the manufacturing technologies and skills necessary to produce a quality product). Without such linkage, it is not possible to optimize worker and, consequently, organizational productivity and product quality. Such a linkage will also assist in evaluating needs for updating and modernizing worker skills.

Optimal utilization of human resources requires that workers will possess the skills required to use the technology effectively. As discussed above, American workers are not getting adequate training to develop the necessary skills. Moreover, many workers do not even have the skills needed to make an effective use of available technology, particularly computer-based technology. According to the report of the Commission on the Skills of the American Workforce (1990) there is ‘considerable evidence that the current skill level of the industrial workforce leaves the United States less able to derive competitive advantage from new technologies than our competitors’. According to Adler (1991), there is a general trend towards higher skill requirements among manufacturing workers due to the speed of the automated equipment. The rationale for acquiring specialized maintenance skills is equally persuasive. At the very least, there is a perceived need for an increase in basic skills in mathematics, and verbal and written communication among workers (Jacobs 1991). These general findings are in agreement with surveys conducted by the United States Department of Labor (1993a, b), and the Hudson Institute (Johnston and Packer, 1987: Judy and D’Amico, 1997). According to the United States Department of Labor survey (1993a), indications are that future workers in manufacturing will need exceptional performance in the following five competencies:

1. Managing resources
2. Interpersonal skills for team problem-solving
3. Information science, including identification, integration, assimilation, and storage and retrieval of information from different sources; preparation, maintenance and interpretation of quantitative and qualitative records; and the conversion of information from one form to another and the communication of information in oral and written forms
4. Systems, including understanding the interconnections between systems, identifying anomalies in system performance, integrating multiple displays of data and linking symbols with real phenomena
Technology, including competence in selecting and using appropriate technology for a job, visualizing operations, and monitoring, maintaining and trouble-shooting of complex equipment.

While the training of workers to acquire such skills is therefore critical if the American manufacturing organizations are to remain globally competitive, a review of the training literature reveals the following:

1. Very little training-related work exists in engineering. Most research literature on training is concentrated in the behavioral sciences. Engineering training literature, whatever little there is, generally deals with the development of mathematical models for a flexible workforce, or surveys of human resource management practices in industries. The overall conclusion of surveys is that training the workforce is indeed essential. There are, however, no systematic investigations of training methods in the manufacturing context that have been reported in engineering literature.

2. Training research in the behavioral sciences has resulted in useful insights into considerations that should be taken into consideration when designing training experiments or training programs. Many of the approaches to training that have been discussed in the behavioral literature, such as the systems approach, and specific techniques and methods in training, including task analysis and job analysis, have been in existence and in active use in industrial engineering settings for job and work design for a long time. Application of these techniques in training research in manufacturing organizations, therefore, should not require developing new techniques and approaches.

3. No on-site training studies in manufacturing organizations were identified in the published literature. The bulk of training research in the behavioral sciences has dealt with non-manufacturing occupations, such as music, police work, training in the military, and languages. As mentioned earlier, while results from these studies provide insights into training methods, factors affecting training and influencing training outcomes, training performance measures, and human behavior, they provide very little insight into training practices, needs, methods, and evaluation criteria, that one would find useful in developing training programs for workers in a hardcore manufacturing environment. Such insights are vital in order to develop effective training programs and strategies for preparing the American manufacturing workers for global competition.

4. Besides the above deficiencies, the current deficiencies in the behavioral training research on training humans apply as well. The latest available review on training humans concludes that researchers are only now beginning to "...consider trainees as active participants in the system who interact with the environment before training, during training, and after training...". Further, there is a "...paradigm shift from research designed to show that a particular type of training "works," to research designed to
determine why, when and for whom a particular type of training is effective (Tannenbaum and Yukl 1992)."

Also, the conclusion of Tannenbaum and Yukl that training researchers need to consider the purpose of the training and the type of learning involved in training, is equally valid for any future training research in manufacturing. These reviewers also suggest that cognitive concepts, and high technology training methods are becoming increasingly popular in training settings. In addition, these reviewers conclude that the distinction between on-the-job training and off-site training is becoming blurred due to the development of on-line training technologies.

Based on the extensive review of the worker training literature we have conducted, we propose a framework (Figure 5) for training workers in manufacturing environments. It is based on the premise that for a manufacturing entity to compete effectively in a global market, it must manufacture quality products that users want and need. These products should be usable and reliable, and able to be produced quickly and economically. The very first requirement is to determine and consider users' needs and wants. The product design must consider these along with the function the product is supposed to perform.

Once it has been ensured that the product that has been designed meets the needs of the market, efforts need to be directed to the assessment of technologies available to manufacture it. The technology considered should include not only what is available in-house but also what is used by the competition as well. It is wise, at this point, to consider technologies that will be available in the short-term and long-term for product manufacture (technology forecasting). Knowing what technology is available in-house and what should be procured from outside to remain competitive will lead to determining investment needs.

The availability of capital will determine equipment and automation capabilities, which in turn will influence the method(s) of manufacture. The methods of manufacture in this context include the choice of materials, and consequently manufacturing processes, method of assembly, and quality requirements. The extent of automation must be based on economic justification (see for example Mital 1991a,b) as well as the capabilities of the humans and the equipment. The capabilities of humans and machines are essential for allocating functions (Mital et al. 1994a, b) and for the final determination of the equipment needed. This has consequences on product design which will need to be reexamined.

The allocation of functions also provides a basis for determining what skills the workers will need. A comparison between the available and needed skills will identify skill deficiencies that will have to be made up through training. In the
design and development of the training program, it would be worthwhile considering immediate, short-term, and long-term skill requirements. These skill requirements will be a function of available and upcoming technologies (technology forecasting).

Further, the design and development of the training module will need to consider at the very least, the following questions: (1) should workers be trained in several skills or only a specific skill?, (2) should the focus be on building up on available skills (retraining) or is the technology chosen such that it would amount to fresh training (for fresh training, the residual effect of older skills will need to be considered)?, (3) what kind of training method should be used (simulator, lecture, on-the-job, etc.)?, (4) what should be the performance measures training should enhance and how are they related to workers’ performance on the actual job?, and (5) what should be the criteria for evaluating worker proficiency during and after training?.

It should be noted that the training framework proposed in Figure 5 and briefly discussed above is solely based on the review of published training literature and deficiencies in the training research our review has identified. There are many issues that are still unresolved. For example, is it better to train workers in several skills (cross-training) or a specific skill (longitudinal training)? Such issues need to be addressed in future research. The fact that such issues are yet to be resolved, however should not restrict us from developing a generic training process framework. Such efforts, at the very least, will focus attention on issues of immediate concern that future research will need to address.

**Education issues**

Incorporating ergonomics education into manufacturing engineering curricula, ergonomics being the primary discipline for the scientific study of human interaction with any system, has profound implications for training current and future generations of manufacturing engineers. This section highlights the important role ergonomics has to play in modern day manufacturing and proposes a sample curriculum for graduate study in manufacturing engineering, including courses in different aspects of ergonomics.

Current training and education in manufacturing engineering deal with traditional manufacturing activities such as design conceptualization and design axioms, product functions identification, product modeling/CAD (graphical and analytical representation of the product), material selection (material properties and associated manufacturing processes), designing for efficient manufacturing by minimizing position requirements and considering assembly, dimensioning and tolerancing. In addition, these graduates also should receive training in management and business functions such as user/market needs and functions from product sales perspective, production and distribution control, total quality
management concepts and economic analyses for business. While areas mentioned above are important, and even essential, for successful engineering design and manufacture, productivity enhancements and market successes cannot be ensured without the knowledge of human issues. The science and application of ergonomics is frequently ignored in manufacturing education and training, or is assigned a secondary place due to two major reasons: (1) the misconception that ergonomics is only associated with expensive product design changes and marketing products, and that it does not provide economically viable manufacturing alternatives; (2) the failure of present day ergonomists to have adequate background in both ergonomics and manufacturing, resulting in their recommending ineffective solutions (solutions that do not take into account the effect of ergonomic recommendations on hardcore manufacturing issues such as manufacturing processes, materials, cost, etc.)

We address issue (1) by highlighting below, a representative sample of ergonomic considerations from the broad discipline of ergonomics having relevance in a concurrent engineering setting for product manufacture and by proposing a sample curriculum for an MS degree in manufacturing engineering. Our sample curriculum incorporates courses in ergonomics that discuss the ergonomic considerations we highlight. Our proposed curriculum is also intended to better prepare a manufacturing engineer to be part of a concurrent engineering team. Figure 6 shows how factors in maintainability, an important ergonomic consideration, can influence the selection of the manufacturing process. This is but one example of why it is important to address issue (2) above. Readers interested in an in-depth discussion of issue (2) above, should refer to Mital (1995b).

In doing the above, we emphasize the need for training manufacturing engineers in ergonomics. Such training and education in ergonomics is essential for succeeding in a globally competitive market and ensuring the success of a product.
Figure 5. A proposed framework for training manufacturing workers

GLOBAL COMPETITION
- User Requirements/Needs
- Producing Economic, Reliable, Usable, Quality Products Quickly
- Improvements in Product Design/Redesign

IDENTIFYING THE BEST TECHNOLOGY
- Technology Forecasting
- Assessing Current Technology (Competition, Own)
- Investment Requirements

PROTOTYPE DEVELOPMENT REQUIREMENTS
- Methods of Manufacture
- Skill Requirements
- Automation Needs
- Capital Requirements

DEVELOPMENT OF A TRAINING MODULE
- Training versus Retraining
- Cross-training versus Longitudinal Training
- Evaluation of Training Methods
- Methods of Delivery
- Evaluation of Training Effectiveness

INVENTORY OF CURRENT SKILLS
- Immediate Skill Requirements
- Future Skill Needs
- Current/Future Skill Deficiencies
Product Usability Considerations

The ultimate success or failure of a manufactured and/or assembled product depends on how well the user of the product is able to achieve specific goals within a particular environment, effectively, efficiently, comfortably and in an acceptable manner (Booth, 1989). Product usability considerations primarily address issues such as how a product will be used, repaired and maintained. Designing products that will allow users' needs to be met is accomplished through a user need analysis and usability testing. The usability testing and analysis process gathers information on who the users are, what their needs and preferences are, what types of tools they use, what is their working environment, what situations commonly arise during the course of their normal activities, what existing products meet their needs, what the limitations/advantages of these products are, etc. The design, manufacture and assembly of products directly affect product usability and the associated costs. For example, a product that requires little repair or routine maintenance may not require complete disassembly, and the components of such a product may be suitable for fabrication as one integrated unit. Portability of products, inclusion of features such as handles, good packaging design, etc., are features that make a product more usable. These features are directly impacted by the shape, size, and weight of the product, and the type of materials used in manufacture (Mital, 1995b). For instance, some manufacturing processes may be unsuitable or uneconomical for large surfaces; manufacturing may have to be done in modules which may then have to be welded together. In order to machine a flat surface of a metal slab, for instance, shaping is an option only if the part is not very large; large parts will most likely require planing machines. Since product design really dictates decisions regarding manufacturing methods, materials, etc., the manufacturing designer and engineer need to know how to make a product more usable and what implications this will have on manufacturing. It is also our contention that present day ergonomists need to consider these factors before they make their recommendations to just "make the product usable," for their recommendations to have any impact at all on manufacturing.
Product Safety and Liability Considerations

The passage of the US Consumer Product Safety Act in 1972 has made it desirable for engineers to have knowledge of product safety and liability laws. Also, the life cycle costs of safety (cost of product safety from the time the product is conceived to the time it is disposed of) and liability (negligence, implied and express warranty, strict liability in tort, absolute liability, etc.,) have serious implications for the manufacturing professional (Hammer, 1989). At the very least, knowledge on the following is essential:

- impact of user/operator error, incorrect usage, accidental activation etc.,
- analysis of safety problems, failures, and malfunctions during testing,
- any hazardous characteristics of the product such as sudden forces, pressure hazards, radiation, vibration, electrical and fire hazards, etc.,
• impact of product usage on the environment, etc.

The manufacturing engineer should, through effective design, ensure that the above potential problems do not occur. When it is not possible to design safety into the product, the manufacturer must engineer safety devices, or warning devices for the user. Analytical methods for safety and hazard analysis such as preliminary hazard analysis, fault tree analysis, failure modes and effects analysis, and effective user interface design for safety, become a 'must-know' for the manufacturing professional.

*Maintainability Considerations for Production Machines*

Maintainability is defined as the degree of facility with which a machine is capable of being retained in, or restored to, serviceable operation. The factors that make designing for maintainability an important issue are:

• Improving reliability of individual components of a machine has not kept pace with the growth in product complexity (Imrhan, 1991).
• Maintenance remains the major means of reducing downtime and restoring the production machine to functional status.
• Most maintenance activities are still performed manually.

Factors such as visual and physical accessibility to components and parts of a machine, clearances for tools, machine components and body parts, muscular force requirements to carry and lift parts, to open, loosen or tighten nuts and bolts, etc., leverage requirements for force exertion, and the need to prevent musculoskeletal problems to the user due to unnatural body postures (Deivanayagam, 1986) are some of the important ergonomic considerations in designing maintainable products, and should become part of the manufacturing engineer’s knowledge base. There is also the issue of skill level of the maintenance personnel and the training they are provided in maintenance activities. For example, a complex product with complicated maintenance needs will demand the services of a well-trained and skilled maintenance worker.

*Product Quality and Inspection Considerations*

Just as in the case of maintenance activities, elimination of manual inspection is still a long way from becoming a reality (Kopardekar et al., 1993):

• Automated inspection systems (computerized vision systems) are expensive and many small- and medium-sized manufacturers still cannot afford to invest in such systems.
• Machines are unable to classify parts as acceptable or unacceptable on a consistent basis, even though they detect more errors than humans.
Since manual inspection will still play a prominent role in contributing to the outgoing product quality, inspector variables such as visual acuity, age of the inspector, physical and environmental variables such as lighting and visual aids, organizational factors such as social pressure, feedback, rest pauses, and speed of working assume great importance. The complexity of the product and the probability of defects in the process influence outgoing product quality. As products become more complex, the inspection requirements for the product also increase and the performance of the inspector goes down. The decay in inspector’s performance is not arrested even when inspection periods are lengthened. Knowledge of the variables that affect product inspection and hence product quality should motivate the manufacturing designer and engineer to keep the design simple.

*Proposed Sample Curriculum*

We propose the following sample curriculum for a MS degree in manufacturing engineering. As already briefly stated, courses that provide fundamental training in areas in ergonomics that are most related to product manufacture and concurrent engineering, are included in this curriculum.

**Suggested Required List of Courses**

1. *Interface Design:* 3 semester hours
   Suggested topics in this course include evaluation and design of human-machine interfaces, controls and displays, design guidelines, interface surveys, usability analysis and testing, interface consistency etc.

2. *Ergonomics in Design:* 3 semester hours
   Suggested topics in this course include engineering anthropometry and its application in design, job analysis and job design, cumulative trauma of the upper extremities, posture, manual materials handling, fatigue, maintenance and inspection, economic justification of ergonomics, etc.

3. *Computer Integrated Manufacturing I:* 3 semester hours
   Suggested topics in this course include discussion of advanced manufacturing concepts such as group technology, process planning, numerical control, design for manufacturability, design for assembly etc.

4. *Advanced Quality Control I:* 3 semester hours
   Suggested topics in this course include introduction to various control charts such as X-bar and R, X-bar and S, cusum chart, multivariate control chart, etc., specification and tolerancing, principles of Total Quality Management, Quality Function Deployment, ISO-9000, the use of teams for quality improvement, etc.

5. *Advanced Engineering Economy:* 3 semester hours
Suggested topics in this course include engineering economy as applied to capital allocation in manufacturing and service sector systems, etc.

6. **Facilities Design:** 3 semester hours
Suggested topics in this course include problem analysis and design of material handling and distribution systems layout of physical systems, etc.

7. **Material Handling Engineering:** 3 semester hours
Suggested topics in this course include material handling system problem-solving, design, and analysis, developed through applied techniques and research.

8. **Production Planning and Control:** 3 semester hours
Suggested topics in this course include problem analysis and design of scheduling and control systems, concepts in production management, inventory systems analysis, etc.

9. **Thesis:** 6 semester hours

10. **Project (if student chooses a non-thesis option):** 3 semester hours

**Suggested List of Elective Courses**

1. **Computer Integrated Manufacturing II:** 3 semester hours
Suggested topics in this course include fundamentals of solid modeling and sculptured surfaces, applications in process planning, feature extraction, tolerance representation etc., based on fundamental research.

2. **Advanced Quality Control II:** 3 semester hours
Suggested topics in this course include review of research papers in quality control.

3. **System Safety Engineering:** 3 semester hours
Suggested topics in this course include introduction to fundamental concepts in risk management, application of engineering analysis techniques such as preliminary hazard analysis (PHA), failure mode and effects analysis (FMEA), etc., to identify system hazards and reduce system risk.

4. **Industrial Environment:** 3 semester hours
Suggested topics in this course include evaluation and control of individual environment, noise, illumination, heat, air, vibration, radiation, and ventilation.

5. **Simulation:** 3 semester hours
Suggested topics in this course include simulation modeling of discrete stochastic processes, random number generation, random variates, analysis of simulation results etc.

6. Safety Engineering and Product Liability: 3 semester hours
Suggested topics in this course include study of the control of product liability throughout the life cycle of the product, role of consensus standards and governmental regulations, product liability litigation, etc.

7. Topics in Manufacturing Engineering: 3 or more semester hours
Students can choose from among courses in engineering expert systems, neural networks, etc., and from among intensive offerings in individual manufacturing processes such as courses in welding, metal cutting, etc. The availability and the content of these courses will depend on faculty expertise in the department.

This proposed sample curriculum can easily be modified to suit either a BS degree in manufacturing engineering, and BS and MS degrees in industrial and other specialized branches of engineering as well.

Conclusions

Humans will be an essential part of modern manufacturing, though, they will increasingly have a supervisory role. Ergonomics, being the primary discipline for study of humans in work, provides scientific bases for design and operation of modern manufacturing systems. This article identified the most significant ergonomics issues in human integration in advanced manufacturing, and provided methodologies and conceptual frameworks for designing "human-centered manufacturing systems," where system goals are subservient to human limitations and capabilities.

References


