Work Design: Barriers Facing the Integration of Ergonomics into System Design

L.J. Steiner and C. Vaught
National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory, Mining Injury Prevention, PO Box 18070, 626 Cochrans Mill Road, Pittsburgh, PA 15236-0070, USA

1. INTRODUCTION

Many industrial injuries and illnesses can be attributed to poor design features. Mishaps are often the unintended consequences of either using or misusing designed products. At times these mishaps result in fatalities that are attributed to "human error." The question is error on whose part, the victim's or the designer's? The designer's job is to forecast potential uses and misuses of products through design. The integration of ergonomics principles at the product or process development phase helps to minimize unintended consequences. This attention at the design phase reduces and even prevents injuries and illness among end users. If ergonomics is to be integrated into the design process, however, organizational principles must be integrated into the design factors. This process is difficult and the barriers are multiple.

2. RELEVANCE

The main goals of any design effort are that the product works as it is intended to, trains easily, and performs safely when used (Broberg 1997). A product needs not be only beneficial but must possess no harmful side effects. Sometimes even these goals are not met. The automobile air bag is a good example. The goal was to protect automobile occupants during sudden impact. *Product requirements* documents spell out how the product will function. *Product specifications* stipulate the product's construction and performance. From an engineering standpoint, when the product meets these two sets of criteria it is considered a success. The air bag does function exactly as the design parameters said it would except that it sometimes kills small women and children. Any repercussion will not come back on the designer, but rather stops at his/her project manager. The design engineer is isolated from feedback until information for new specifications is received. The organization writes off its liability until the public or government becomes involved. This process, including the assignment of work roles and administrative procedures that shape the organization's social culture and conduct of work activities, is part the overall organizational structure.

Organizational structure and the thinking that reflects it play a major role in shaping the product development process. Broberg (1997) described the multistage and interconnected manner in which a concept becomes a product. Product requirements and specifications guide the development mechanism. These two basic design inputs were described earlier. What is missing from the process is a third document that sets forth *use parameters*. Dekker and van den Bergen (1996: 301) suggested that "integrity, reliability, efficiency, and usability" must all be characteristic of an interface that protects humans and optimizes their performance. Yet, the product–human interface does not show up in company standards governing the design process. Therefore, designers may continue working within their normal organizational framework and face little pressure to develop products with ergonomic input. What they do experience is social encouragement to repeat design approaches that have worked in the past (Broberg 1997).

The purpose of this chapter is to provide insight into barriers facing the integration of ergonomics into design. It is also intended to create an awareness of consequences that can result from ignoring ergonomics during the design process. Mistakes made by users are often invited by the way the process or product was designed (Chapanis 1996). Working through these implications and understanding how design engineers function may help determine how to expand the design approach to include ergonomics criteria.

3. ENGINEERING APPROACH TO THE PROBLEM

Typically, a design engineer is presented with a deadline to build a product that will do something. S/he conceptualizes it, and gathers whatever resources are necessary to achieve this goal. The designer will focus mostly on whether the product does what it is supposed to do. The concern is to make a product that is used according to the ideal manner in which it will be demonstrated. A designer's success or failure is measured by whether the product does what it was supposed to do and whether it was delivered in a timely manner. Such design approaches overlook the fact that ultimately, people use products. A typical engineering process does not consider this until the end of development, during usability testing. The product's team develops this testing with limited knowledge of the human element and in a controlled environment. They possess the same knowledge they had when designing the product, and, because of their familiarity with it, may be shortsighted as to how the product should be tested. Under such conditions, human interface problems will be hidden rather than highlighted.

4. BARRIERS TO INTEGRATION

The organizational structure is not supportive of ergonomics in comparison to other design parameters, and the lost benefits of such support are not recognized. Often designers are working under severe time constraints, and project managers assume that if the product functions as it was planned to function, ergonomics will work itself out. At best, the design can only be "tweaked" after completion. Design engineers may be lacking ergonomics knowledge or training, and simply not know the right questions to ask. Unless the organization's expectations reflect a necessity for ergonomics, their thinking will remain the same. Designers will continue to use the same tried and true methods for development. When there are product failures or customer complaints, design engineers are the last to know. When a developed product is determined to work but there are still usability problems, these issues are often blamed on the end user's inability to use the product properly. Products are almost never evaluated for their intended and unintended consequences. Sound ergonomics methods can be used to predict uses and misuses.

Unintended consequences are not brought back to the designer unless a re-design is demanded. The problem created is that the designer never gets a chance to build a database of ergonomic knowledge or cause for failure. Therefore, s/he believes the design process works well and will use this belief in future designs. This practice encourages a "tunnel vision effect" because the designer is using a one-dimensional approach based on his/her previously tried and true algorithms. This thinking supports "blind spots" by not allowing peripheral information to enter. Blind spots keep the engineer from asking the right questions and allows him/her to ignore "extraneous" information. Most organizational structures tend to encourage this type of thinking. In the long run, though, the earlier human engineering is introduced into the design process, the better the product will be. Redesign for usability is more costly after production.

5. CASE ANALYSIS

Some of the ideas mentioned above can be illustrated by a program, begun in the early 1970s, to develop an oxygen breathing apparatus for US coal miners. There were some scientific and engineering principles that could not be violated during development and the process seemed to rely on past successes. Because there was little or no ergonomics involvement, it cannot be known how much impact ergonomics might have had on up front engineering design. However, it could reasonably be deduced that some user problems could have been avoided.

> Barrier: Because people are considered to be adaptable, there is no demand for use parameters. Users are therefore forced to adapt to designs that "make sense." A failure to understand that ergonomics is not just "commonsense" leaves the interface problem unrecognized.

Since its creation in 1910, the US Bureau of Mines was active in setting requirements and performing certification tests on oxygen breathing apparatus. These were intended to help workers survive irrespirable mine atmospheres. The weight and size of the devices proved to be too much for the typical mine worker and the daily apparatus came to be used only during rescue attempts. A succession of deaths among would-be rescuers underscored the fact that miners had little or no training in apparatus usability. The loss of lives led to the adoption of mine rescue standards in 1921. These standards provided a baseline for instruction. The schedule for initial training, which required 20 h over 5 days, included 9 h of practice wearing the device. The Bureau recommended additional instruction and practice every 6 months (Parker *et al.* 1934). Over time, mine rescue apparatus became more refined and rescue team members better trained in its use.

> Barrier: Even when a problem with the machine/human interface is recognized, the tendency is to believe it can be "trained out." Training then becomes the stopgap for product inadequacies.

In 1924, to encourage miners to wear the breathing device continually, the Bureau approved a different type of apparatus. This one measured 3 x 4 x 6 inches and weighed just 2.5 lb. Since then, the basic design has remained unchanged. Although the "filter self-rescuer" or "FSR" can easily be carried on the miner's belt, it does not provide oxygen. It converts carbon monoxide (CO) to carbon dioxide (CO_2) and provides some protection from hydrogen chloride gas. The FSR is of no use in oxygen deficient or highly toxic mine atmospheres.

> Barrier: The perceived solution to a complicated user problem, from an organizational standpoint, may be to make tradeoffs. Many times, the tradeoff criterion is arrived at non-inclusive of all critical parameters.

With passage of the 1969 Coal Mine Health and Safety Act, money became available to develop a self-rescue apparatus that supplies oxygen. During the requirements phase, officials established that the unit must be small, durable and weigh < 4.5 lb. Finally, the device had to provide complete respiratory protection. Performance specifications for the proposed apparatus were contained in Schedule E of the Federal Register. Schedule E set stringent metabolic requirements for oxygen delivery. In sum, the Bureau was aiming at an acceptable tradeoff that would supply oxygen like the mine rescue apparatus (for at least 1 h) but be worn like the filter self-rescuer. Lockheed Independent Development built a KO_2 (potassium super oxide) prototype under contract. According to Lockheed's Senior Research Engineer, human factors considerations heavily influenced the development of this device. "When an emergency situation arises, the unit can be activated quickly, even by an untrained and/or excited person. Once deployed, the breather is comfortable to wear, does not interfere with the user's activity, and gives the user confidence that it is working properly" (Perry and Wagner 1973). The Lockheed rescuer caught fire during a demonstration, leading to further research and development, as well as a need to defend similar apparatus. Another KO_2 unit widely used by Russians supposedly was used underground without any known problems. Also, the Chemox unit had been used for 30 years without technical problems in the unit itself. However, it was mentioned that there were problems with training and usage of it (Stein 1978).

> Barrier: When there are no carefully controlled studies, one is likely to see what one wants to see. Outside studies and suggestions helpful to building more sound designs are not welcomed by the organization research team leading to repeated designs that are ineffectual.

Despite the Lockheed engineer's endorsement of human factors, there is little evidence that the human/product interface was explored much beyond metabolic concerns. Lockheed never went to production with their rescuer but sold the technology to another manufacturer. In 1981, a federal law mandated that mines would provide miners with a one-hour oxygen delivery device. By the time of the Wilberg mine disaster in 1984, there were two types of oxygen delivery apparatus (chemical and compressed oxygen) and five different brands in US coalmines. All came to be commonly called "self-contained self-rescuers" or "SCSR." SCSR were readily available to the 27 miners who died at Wilberg, but investigations suggested they had not been able to use them. Since the suspect apparatus functioned properly when tested after the fire, inadequate training emerged as a determinant in the workers' deaths. Only later did the general question of usage emerge.

> Barrier: Time pressure and regulatory or other constraints might lead to solutions that seem neat and expedient, but are inappropriate and ineffective.

In 1986, researchers at the University of Kentucky (UoK) began a project in cooperation with the Bureau, several other agencies, and original equipment manufacturers. This study started with a task analysis and soon turned into a full-scale scientific investigation of worker proficiency with SCSR. In the study it became clear that none of the apparatus was user-friendly. These devices were different in design, but all shared some traits with the earliest mine rescue apparatus that the Bureau had felt compelled to set stringent training standards for. Oxygen was activated manually, by either pulling a cord or turning a knob, each device had a mouthpiece with bite lugs and a flange that fit between lips and teeth, a nose clamp was affixed to the mouthpiece by means of a cord, and goggles were stowed inside the case. The notion that a unit "can be activated quickly, even by an untrained and/or excited person" was put to the test at a cooperating coal company. A group of surface workers (who are not required to carry SCSR) was brought into a training room where the device's function was explained in detail. Each person was then asked to don the apparatus while being videotaped. Only the company pilot was able to figure out the SCSR well enough to isolate his lungs, though he did not get the wearing straps tied nor goggles in place. No one else in the group of 14 was able to activate the device. Researchers concluded there are few built-in cues to help people activate SCSR, nor did it appear that the interface was characterized particularly well by the "integrity, reliability, efficiency, and usability" Dekker and van den Bergen (1996: 301) considered essential for an ergonomically correct product.

Barrier: Claims are often not put to real-world tests. Without end user testing in the design phase, one's knowledge base limits his/her perception. The tendency is to see only confirmatory evidence.

The UoK study team noted that SCSR were the result of engineering research and development that had taken years. Nowhere, however, could they find evidence that ergonomic or cognitive studies had been conducted to determine what human design features the devices should have (Vaught *et al.* 1996). After the apparatus had tested out as reliable in field trials, been shown to function well mechanically, and to have a fairly long shelf life, they were placed in the mines. From that point workers must accommodate the SCSR in order to use them effectively. Training would have to be a large part of that accommodation, but the training research focused narrowly upon donning proficiency rather than on overall usability.

Barrier: If a product is working according to specifications, any subsequent failures are likely to be blamed on the human user.

Lack of capability is clear in an account given to the UoK researchers by a safety instructor who had 96 trained workers don their SCSR and travel through theatrical smoke at a mine. His observations: (1) workers had to be helped to don their devices; (2) about one-quarter of the miners forgot to put on their nose clamps; (3) roughly a dozen individuals omitted their goggles; (4) nine people did not get their oxygen turned on; (5) several workers became entangled in the wearing straps; and (6) at least two miners failed to insert their mouthpieces correctly. Focusing upon this problem the study team, over the next 5 years, developed a rationalized donning sequence that could be used with all SCSR then on the market. Next, the researchers designed an evaluation method that would allow them to observe donning attempts and chart each miner's performance. Then, they constructed low cost training apparatus and tested them against the more expensive models offered by equipment manufacturers. Finally, the study team employed their innovations in the field, training miners to proficiency and plotting their forgetting curves. One group of coal miners was trained to proficiency (able to perform five perfect sequences in a row) so that samples could be evaluated through the following year. Of those evaluated after 90 days, only 30% had retained enough knowledge to get their lungs isolated and the SCSR secured. It was apparent that there was little or nothing intuitive about the design of SCSR that will prompt a trained person's memory. Current guidelines are such that these miners had 9 months to go before they would be retrained.

Barrier: A patchwork pattern of training and usability instructions developed when problems are encountered is not a substitute for anticipation of design problems prior to implementation.

Although they were committed to finding training solutions for the use of an apparatus that requires practice to master, under a standard that mandates little practice, researchers did encounter other usability issues. In interviews with 46 workers who used SCSR while escaping underground mine fires, the study team found 29 who reported having had breathing difficulties. Twenty-seven miners, though in smoke, removed their mouthpieces to breathe. As one individual stated, "I know there's a lot of CO ... but I can't breathe. If I can't breathe in this thing [SCSR], I'm just going to collapse anyway" (Brnich *et al.* 1992). Potential breathing problems became greater when a second generation SCSR was introduced in the early 1990s. During the requirements phase it was decided that if these devices were made only twice the size and weight of a filter self-rescuer, they could be worn rather than carried or stored as the larger units had been. These size and weight specifications were met partly by crowding the metabolic limits for oxygen delivery. Where the first SCSR provided excess oxygen under certain conditions, the person-wearable SCSR (PWSCSR) measured it out more carefully. It can be imagined that if a miner decided s/he was not getting enough oxygen from a first generation apparatus, the problem would be magnified by a device designed to deliver a lesser quantity per minute.

Barrier: A product may meet physiological requirements, yet fail to meet psychological ones. This must be recognized and attended to, or the device may not be successful.

A second usability problem related to the size and weight issue was wearability. It had been assumed by those establishing requirements that a device only twice the size and weight of a filter self-rescuer could replace the FSR on a miner's belt without undue complications. This reasoning might seem valid unless one applies the concept to more familiar objects replacing one's glasses with a pair twice the size and weight; or, exchanging the car in one's driveway for one twice the size and weight. In both instances, it might be expected there would be problems with mobility and physical impairment, among others. Such seems to have been the case at a mine where accident data collected over 10 years were reviewed by company personnel. They reported a dramatic increase in accidents due to fatigue and balance after introduction of the person-wearable units. In an investigation conducted by researchers at this mine, a sample of 51 workers was asked their opinions about wearing the PWSCSR. The miners' answers to a set of objective statements about the PWSCSR and FSR suggest the following: (1) they felt pain and soreness after wearing the PWSCSR all shift; (2) they did not feel pain and soreness after wearing the FSR all shift; (3) they did not think wearing either device posed a danger of injury; (4) the weight of their belts, however, has at some time caused a fall due to loss of balance; and (5) given a choice, they would switch back to wearing the FSR even though it offers less protection.

Barrier: Sometimes design tradeoffs are made arbitrarily without controlled studies based on proven principles. This may lead to unintended consequences, such as having workers who are adequately protected but uncomfortable or visa versa.

6. CONCLUSIONS

In general, the ignoring of human factors in the design phase constitutes an organizational blind spot. This blind spot has usually been recognized after the fact in partially failed attempts to "reinvent" organizations. A recent example is the result of re-engineering efforts here and abroad: "the basic assumption is that if you get the engineering right the human factor will fall into place. ... As a result, the re-engineering movement has encountered exactly the same problems and failures experienced by older style classical management principles" (Morgan 1997: 22). The integration of ergonomics into system and product design is not accomplished by just putting an ergonomist on the project but requires a change in the cultural thinking of the designers and the organization. The *use parameters* document needs to be considered as important as the *product specification* and *product requirements* documents. An organization's social framework must be structured to accept ergonomics as part of the design criteria. That would increase the amount of interest design engineers need to have in ergonomics. Further, the design team should be educated about how to recognize and apply ergonomic principles during all development stages. This would help reduce the barriers to ergonomics integration. Methods used to assess ergonomic design criteria can be found in Chapanis (1996) and Ainsworth (1992). Chapanis (1996: 294) addressed the difficulties and rewards of ergonomics integration, but clarified that "even the best efforts of human factors professionals and system designers cannot guarantee that a system will be successful because of the many factors over which they have no control." The way to move toward control over the system is to recognize that barriers do exist and the organizational structure may be part of the problem. Then, begin a culture change by using sound ergonomics and design principles to predict product usability and safety.

REFERENCES

BRNICH, M.J., VAUGHT, C. and MALLETT, L., 1992, SCSR proficiency requires hands-on practice. *Coal*, July, 52–4.

BROBERG, O., 1997, Integrating ergonomics into the product development process. *International Journal of Industrial Ergonomics*, 19, 317–27.

CHAPANIS, A., 1996, *Human Factors in Systems Engineering* (New York: Wiley).

DEKKER, E.F. and VAN DEN BERGEN, E.A., 1996, Human Factors in E&P facility design, a participatory approach. In *Proceedings of the International Conference on Health, Safety & Environment*, Society of Petroleum Engineers (SPE), #35792, New Orleans, LA, 297–302.

KIRWAN, B, and AINSWORTH, L.K., 1992, *A Guide to Task Analysis* (London: Taylor & Francis).

MORGAN, G., 1997, *Images of Organization* (Thousand Oaks: Sage).

PARKER, D.J., McCAA, G.S. and DENNY, E.H., 1934, *Self-contained Oxygen Breathing Apparatus: A Handbook for Miners* (Washington, DC: US Department of the Interior, Bureau of Mines).

PERRY, E.N. and WAGNER, P.A., 1973, One-hour self-rescue breathing apparatus. *American Institute of Aeronautics and Astronautics*, paper no. 73-1358.

STEIN, R.L., 1978, New respiratory equipment for the mining industry. *Industrial Hygiene for Mining and Tunneling*, November, 59–71.

VAUGHT, C., COLE, H.P. and WIEHAGEN, W.J., 1996, A program to enhance the self-contained self-rescuer donning proficiency of underground coal miners. OMB-No. 0990-0015.

International Encyclopedia of Ergonomics and Human Factors

Edited by
Waldemar Karwowski

VOLUME II

TAYLOR & FRANCIS
Founded 1798

London and New York

Date 12/5/01

ROUTING AND TRANSMITTAL SLIP

TO: (Name, office symbol, room number, building, Agency/Post)	Initials	Date
1. GEORGE BOCKOSH, OD		
2. ROB TUCHMAN, OD		
3.		
4.		
5.		

X	Action		File		Note and Return
	Approval		For Clearance		Per Conversation
	As Requested		For Correction		Prepare Reply
	Circulate		For Your Information		See Me
	Comment		Investigation		Initial
	Coordination		Justify		

RE: PUBLICATION DISTRIBUTION

ATTACHED ARE 3 COPIES OF THE FOLLOWING PUBLICATION:

DATABASE RECORD NO.: 11

TITLE OF PAPER: Work design: barriers facing the integration of ergonomics into system design

PUBLISHED IN: International Encyclopedia of Ergonomics and Human Factors

AUTHOR(S): Lisa J. Steiner and Charles Vaught

REPORTED IN MONTHLY REPORT: 10 (month) 2001 (year)

FILLED IN PUBL. AVAILABILITY DATE IN PUBL. DATABASE: 11/6/2001 (mo./day/year)

SUBMITTED ORIGINAL TO DIANE FELICE FOR POSTING IN CISS: 11/6/2001 (mo./day/year)

DO NOT use this form as a RECORD of approvals, concurrences, disposals, clearances, and similar actions

FROM: (Name, org. symbol, Agency/Post)	Room No. — Bldg.
Joy Lamars	226 — 152
	Phone No. 412-386-6472 Fax No. 412-386-6764

5041-102

OPTIONAL FORM 41 (Rev. 7-76)
Prescribed by GSA
FPMR (41 CFR) 101-11.206