Quality improvement in manufacturing through human performance enhancement

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Introduction

The quality movement in product manufacturing and delivery of service has undergone change from its initial emphasis on quality through inspection, to the present-day emphasis on quality through the development of robust processes capable of performing consistently in developing products and services that meet and exceed user needs and expectations (Drury, 1997; Eklund, 1997). Since humans are known to increase process variability by being less reliable and less consistent compared to machines (Bullinger and Warnecke, 1983; Orpana and Lukka, 1990; Sata, 1986), it is frequently advocated that machines are preferable in situations characterized by design accuracy and tight tolerancing requirements. During the 1980s, it was believed that the demand for manufactured goods would be met by a small workforce operating in a modern automated environment employing advanced manufacturing technologies (O’Brien, 1991). Automatic identification systems (transponders, barcodes, radio frequency, speech input), automated storage and retrieval systems, conveyor and automated guided vehicle systems, machine assembly and test systems, robotics workstation, flexible manufacturing cells, and automated packaging are all examples of such advanced manufacturing technology. It is being realized, however, that an effective integration of modern manufacturing technologies and information, and therefore complete automation, is difficult to achieve, at least in the foreseeable future, without human input, for technical, economic and cybernetic reasons.

Hard automation does not lend itself to situations where products have to be changed frequently because of user needs, costs, or engineering improvements (Bessant and Haywood, 1985; Hartley, 1984). Furthermore, there is the need to provide flexibility as well as capability. Automated equipment often provides the flexibility but not the capability. Essential capability requirements include intelligence; ability to sense, see, touch, and feel; acquire knowledge and judgement to carry out complex tasks, and act according to the know-how of the skilled worker; perform tasks reliably to impart the necessary 3-D motions to the product; communicate with the operator by voice, written sentences, and other appropriate forms of communication; and learning on the job (Brady et al., 1984; Sheridan, 1995; Yamashita, 1987). Economic viability is also necessary if complete automation is to become feasible. It has been clearly demonstrated that the economic disincentives of the automated option are primarily due to low equipment reliability, high interest rates, and declining low wages (Brodner, 1986, 1990; Mital and George, 1989; Mital, 1991, 1982). From a cybernetics viewpoint also, complete automation is a sub-optimal solution for manufacturing organizations (Ashby, 1962; Brehmer, 1988; Mital et al., 1994).

It is evident that people will be necessary in manufacturing plants for a long time to come. Therefore, manufacturing organizations should aim at increasing the efficiency and effectiveness of an enterprise through the integration of technology and humans. Given that humans will remain an integral part of the industrial system, and given that it is difficult at the present time to exclusively rely on various tools of computer integrated manufacturing (CIM), such as computer aided design (CAD), computer aided manufacturing (CAM), computer aided process planning (CAPP), and computer aided quality (CAQ) systems, neglecting the human element will only result in sub-optimal system performance. To optimize...
manufacturing system performance, researchers have advocated many different approaches at different levels of analysis of system design, ranging from focus on the design of individual tasks, to macro ergonomics and participatory ergonomics at the organizational level. Thus, while improvement of a manual material handling task (Mital et al., 1997) is considered analysis at the micro level, supervisory control systems based on cognitive engineering principles (Norman, 1986; Rasmussen, 1992; Sheridan, 1994; Woods and Roth, 1988), sociotechnical systems theory-based optimization of social and technical systems (Gerwin and Kolodny, 1992; Taylor and Felten, 1993), and, more recently, computer supported cooperative work (Rosenbrock, 1985; Schmidt and Bannon, 1992; Sinclair, 1992), are examples of macro-level analysis of human-machine systems. Whatever the level of analysis of human-machine systems, the goal is still to optimize overall system performance through consideration of human performance at the design stage.

The focus of this paper is at the micro-level of analysis of system performance. Specifically, this paper is intended to show how quality improvements are possible through improvements in human performance. This is achieved through a collection of four case studies, presented in the next section, clearly demonstrating the relationship between quality and different variables affecting human performance.

The overall purpose of this paper is two-fold, and is based on the two different audiences this paper targets:

1. To demonstrate to a manufacturing engineering audience (including manufacturing engineers and managers, manufacturing system designers, shop floor personnel, and manufacturing researchers), the importance of ergonomics considerations in manufacturing systems design, and to alleviate fears in such an audience that a human in the system will always contribute to a lowering of product or process quality.

2. To demonstrate to ergonomists the need for them to temper their ergonomics recommendations by considering the impact of such recommendations on product manufacturing considerations such as product quality, choice of manufacturing processes and materials, and productivity.

Unless ergonomists can learn to evaluate the effect of their recommendations on production factors such as production volume, production rate, product design, etc., they will have little or no impact on engineering and system design.

Case studies

There is a scarcity of literature on experimental investigations clearly demonstrating how different human performance variables (summarized in Figure 1), directly affect the quality of products and services. When the demands due to these variables exceed the physical, mental, and sensory abilities of an individual, it results in the deterioration of human performance and a resultant decline in quality (Figure 2). This section presents four case studies which attempt to relate how work conditions affect human performance, and hence output quality. These studies also suggest the ergonomic interventions needed in each case to improve the quality of product, or service, rendered.

Case study 1: ergonomic work conditions and product quality in auto assembly

This case study evaluated quality as affected by work conditions. The study was conducted in several phases in a Swedish car assembly plant (Ekklund, 1995). The assembly line studied was of the mini-line type consisting of eight shorter lines in a serial flow, with buffers in between. Each of these eight lines formed the basis for one department. Painted car bodies entered the first department and fully assembled cars left the eighth department, after which all cars were inspected in a separate (ninth) department, where final adjustment was also carried out.

The first phase of the study was aimed at developing an inventory of ergonomically demanding tasks. This inventory covered all eight departments where cars were assembled. Three major categories of tasks were identified:

1. physically demanding tasks;
2. tasks with design that made assembly difficult; and
3. psychologically demanding tasks.

Interviews were conducted with the most experienced workers. They were asked to identify at least five, and at most ten, tasks with ergonomic problems. Several of such problematic tasks were video recorded and were assessed by two experts: an ergonomist and a company physiotherapist.

The second phase consisted of analyzing quality statistics pertaining to all production departments except the first department. The statistics consisted of a number of recorded deficiencies from each department and the
A "quality deficiency rating" was calculated based on these statistics. The quality statistics from the first department were treated separately as the different aspects were measured by different group of persons using different criteria.

The third phase consisted of analyzing quality statistics of finished cars which passed through the final adjustment. A random sample of completed cars were selected, and disassembled. The number of deficiencies and the quality deficiency points were then recorded. The quality deficiencies were ranked on a scale of 1 to 50, where a score of 1 indicated an insignificant, superficial, deficiency, and a score of 50 indicated a very serious deficiency.

In the fourth phase, department internal quality statistics were acquired from the first department that was not included in the second phase. The data comprised the total number of recorded deficiencies and the deficiency types.

A total of 58 tasks with ergonomic problems based on one or more of the three categories mentioned earlier were identified. Of these, 43 tasks had problems in the form of physical demands. Product designs made the components difficult to assemble in 25 tasks, and ten other tasks were identified as psychologically demanding. Table 1 shows that the quality deficiency rating for tasks with ergonomic problems was 4.088 and that for tasks without ergonomic problems it was 4.154. The assembly time for the tasks with ergonomic problems was 25 per cent of the total assembly time. The relative risk for
quality deficiencies among the ergonomically demanding tasks was 2.95 \((4,088/0.25)/(4,154/0.75)\), indicating a noticeable over representation of quality deficiencies for ergonomically demanding tasks \((p < 0.05)\) from final adjustment statistics. The quality deficiency points from the random disassembly inspection also showed a statistically significant over representation for the ergonomically demanding tasks \((p < 0.05)\) and the relative risk for this category was 1.94. Table I also shows that the number of quality deficiencies for the ergonomically demanding tasks constituted 30 per cent of all quality deficiencies. With the relative risk being 1.85 they were also over represented \((p < 0.05)\).

Several workers in the final interview complained that tasks with ergonomics problems caused fatigue and pain in various parts of their body. The workers avoided exposing their bodies to more discomfort. They made less effort in performing the task correctly and were contented with slightly imperfect results. When they became tired or disturbed due to an ergonomic problem they tended to view that problem as being too difficult to solve in the time available. Rather than deal with it personally, the workers considered it better to pass on the uncompleted work to the adjusters.

In the assembly line where a group of assemblers worked on a stationary car, the task had to be completed by all the workers before the car moved to the next location. If any worker finished last he or she became the subject of heavy group pressure. To avoid such pressure the worker performed as fast as possible, and thereby took chances or deliberately passed on rectification tasks to the adjusters when problems occurred.

There were also organizational reasons for the observed quality deficiencies. Many workers pointed out that the reason for deliberately passing on uncompleted work to the adjusters was the perception of “fair play”. The assemblers had lower status and wages than the adjusters. The assemblers felt they were under pressure and that the adjuster had little or no work to do. The assemblers reacted to this situation by passing on more work to the adjusters. The workers also pointed out that some of the quality problems had existed for years, and that there was no response or even feedback whenever they reported such problems to the management. As a result, they lost the desire to make an effort in other areas and stopped trying to compensate for the fault.

This study clearly demonstrates that ergonomics problems lead to the deterioration of worker performance, which ultimately leads to quality deficiencies. Poor work design, a product which was difficult to assemble, and organizational shortcomings were the reasons for such performance and quality problems. Using the results from this study, the plant management now has initiated a participatory change project. Work tasks with ergonomics and quality problems are given higher priority of change.

### Case study 2: ergonomic workplace and quality of inspection in manufacture

This case study analyzed the manufacture of consistently high quality products (Klatte et al., 1997). It strengthens the argument that a process capable of producing quality products should take into account not only machine-specific parameters, but also factors related to work design and work organization. In instances where even the best efforts to control product quality result only in partially capable processes, inspection of the outgoing products will eliminate those with faults. This study is an examination of the effect of machine- and material-specific factors, and the effect of work design measures on the quality capability of industrial processes in the production of inside door panels in the pressing department of the Wolfsburg auto works in Germany.

Preliminary examination revealed that the main problem of variance in quality of the inside door panel was due to possible differences between the two types of metal sheets that are processed, and the setting parameters of the drawing press. The sheet metal came from two coil suppliers, A and B. The three levels of settings for the pressure exerted by the sheet metal retainer on the drawing press (minimum, medium, and maximum setting), were intended to cover the whole range of settings of the drawing press. The assessment of the process capability of the stamping process was based

<table>
<thead>
<tr>
<th>Phase</th>
<th>Assembly time proportion (%)</th>
<th>Tasks with ergonomic problems</th>
<th>Tasks without ergonomic problems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Assembly time proportion (%)</td>
<td>Quality deficiency ratings</td>
<td>4,088(50)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative risk</td>
<td>2.95</td>
</tr>
<tr>
<td></td>
<td>Assembly time proportion (%)</td>
<td>Quality deficiency points</td>
<td>221(39)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative risk</td>
<td>1.94</td>
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<tr>
<td></td>
<td>Assembly time proportion (%)</td>
<td>Number of quality deficiencies</td>
<td>342(30)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative risk</td>
<td>1.85</td>
</tr>
</tbody>
</table>

Note: Numbers in parentheses are percentages.
on a sample comprising 60 inside door panels, 24 of which were examined for surface quality, and all 60 for dimensional accuracy. The compliance of the door panels with the required dimensions, was, in each case, examined at 13 measurement points distributed throughout the entire contour of the door.

The results showed that surface quality of the inside door panels was influenced by both the press setting and the coil supplier (\( p < 0.05 \)). More surface faults occurred with the parts produced from supplier B coil than with those from the coil from supplier A. This could be due to the differences in the characteristic values for the material, as well as in thickness of the steel sheet. Also, increasing pressure level of the drawing-press retainer resulted in improvement of surface quality.

Examination of the inside door panels for dimensional accuracy revealed significant differences (\( p < 0.05 \)) between the three press settings at four out of 13 locations. Significant differences between the coil suppliers were observed at five of the 13 measurement points (\( p < 0.05 \)). The press line produced a process capability index \( C_p \) greater than 1.33 for all measurement points except at point 2, for which the \( C_p \) was 1.07. Therefore, the process was considered as only partially capable in the case of measurement point 2.

Production processes which are partially capable necessitate inspection of outgoing parts for quality. At Wolfsburg, the workers carried out a cycle-related, visual, 100 per cent inspection of the surface quality. The workers at the end of the press line manually removed the finished inside door panel from the conveyor belt and placed it in transportation containers. Both front and rear sides of the panel were inspected for surface quality by turning the door panels. As the production rate of the installation was 12 parts per minute, a cycle time of 20 seconds resulted for the handling and examination of the part when four workers were employed. Within that period it was only possible to turn and inspect the entire inside door panel. The examination was performed at the conveyor belt while the parts were in motion. The overall levels of illumination and contrast were relatively poor. The examination, thus, was of low reliability due to these factors.

On account of the fact that detection performance is better during a cycle independent procedure (McFarling and Heimstra, 1975), and since the level of illumination has a significant impact on the reliability in industrial quality testing (Ferguson et al., 1974), the inspection was sought to be improved by optimizing the illumination, and switching to a cycle-independent examination. It was decided to replace the 100 per cent inspection at the conveyor belt with a sample testing at a special inspection workplace close to the conveyor belt. This was expected to facilitate cycle-independent examination of a stationary object under conditions of optimal illumination, and extension of cycle time for inspection of the individual panels. Such an ergonomic redesign of the workplace lead to an improvement in quality while reducing the cycle time for inspection.

According to a recent experimental study (Mital et al., 1998), comparing manual inspection with hybrid inspection in a general manufacturing scenario, it was concluded that hybrid inspection led to superior performance compared to manual inspection, as indicated by improved accuracy and improved speed of inspection. Manual inspection activities are entirely carried out by a human inspector, whereas hybrid inspection is semi-automated and the inspectors are assisted by equipment such as vision systems, coordinate measuring machines, etc. (Kopardekar et al., 1995). It can be expected that by employing hybrid inspection using special imaging and measurement equipment to measure surface quality and dimensional accuracy, further enhancement in inspection performance and the resultant quality of outgoing door panels can be achieved at Wolfsburg auto works.

**Case 3: workplace illumination and product quality in circuit board manufacturing**

This case study illustrates the ergonomic improvements undertaken at the circuit board manufacturing unit of IBM located at Austin where automatic machines were used for insertion of components into circuit boards (Helander and Burri, 1995). Besides process monitoring, machine operators also performed visual inspection and quality control of the inserted components. On interviewing the operators it was found that the illumination level was inadequate for visual inspection. While some of the areas had an illumination level of approximately 1,000 lux, several work areas were as low as 120 lux. As 1,000 lux was generally considered a minimal requirement for visual inspection of small parts, the illumination level was increased to 1,000 lux throughout.

The increased illumination was achieved by implementing the following changes:

- Fluorescent tubes were installed.
- Lights, which had been turned off to conserve energy, were switched on.

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Light fixtures were lowered from the ceiling.
Windows were installed in the wall for outside light.

The outside windows were beneficial for several reasons. Besides improving the illumination level, they also created an aesthetic and friendly environment. The outside view also served as a landmark for operators to orient themselves in the plant, and created better awareness of the time of day, which is specially important for shift work. Because of this, outside windows are required by law in several European countries.

The detection rate of faulty items improved with the increased illumination, even in areas for routine handling of products and supplies, and as a result, the process yield also improved dramatically. Operator productivity and process yield improved by 23 per cent and 18 per cent, respectively, while the injury rate reduced by 19 per cent. The beneficial effects of the improved illumination were acknowledged by the operators.

In a field study, it is often difficult to quantify the effect of ergonomic improvements on quality, as opposed to other engineering changes, and this case study suffers from a lack of control of several such variables which could have contributed to the quality improvements. However, at the end of the study, 26 managers and engineers were interviewed. They all agreed that approximately half the quality improvements could be due to ergonomic changes while the other half were attributed to other engineering and production changes.

The manufacturing management was extremely positive about the ergonomic improvements and reported that several other manufacturing areas also claimed benefits from the ergonomic redesigns since it improved the quality of the product coming to their area.

Case study 4: ergonomic changes and quality improvement in flashlight and lantern plant
This case study involved the riveting operation at a flashlight and lantern plant and showed how ergonomic modifications resulted in better productivity and quality of system functioning (Pulat, 1992). An expensive machine was designed and custom built to automate the label-riveting operation on flashlight tubes. The task involved the placing of oval-shaped plastic labels of size 1in. major axis length and 0.25in. minor axis length on a rotating table of 1ft diameter with very close fit requirements. Labels were picked up from the table by a suction mechanism and positioned on a tube which was delivered to the riveting station by a conveyor mechanism. The label was then automatically riveted to the tube at both ends.

The plant was experiencing many rejects from this operation and most of the rejects had the label missing. It could be that either the suction mechanism did not work properly, or the worker could not keep up with the speed of the rotating table. Visual observations led to the conclusion that the problem was due to the operator. It was found that it was very difficult for the operator to keep up with the speed of the rotating table. Three adjustments helped change what was an expensive operation into a profitable one:
1. The angular speed of the turntable was reduced.
2. The job was assigned to an operator who possessed better finger dexterity.
3. The vendor was contracted to deliver labels packaged in proper alignment, reducing many finger movements for orientation.

After these changes, the operation achieved a significant reduction in the reject rate and almost a 50 per cent increase in output.

Conclusions
This paper illustrates, through four case studies, how ergonomic work conditions affect human performance and quality. Presently, quality improvements are primarily sought by improved process techniques and materials. However, a holistic approach toward quality assurance requires that due consideration be given to improving operator efficiency. Paucity of experimental investigations in clearly demonstrating the link between ergonomics and quality suggests that more systematic research needs to be performed to investigate how quality is affected by ergonomic variables such as work area, job design, equipment design, man/machine design, personal interaction, organizational structure, and work environment. Eventually, quality products can only be created by making a process possible by optimizing all the variables related to production such as workers, material, and machines. Further, experimental investigations demonstrating clear linkages between ergonomics, quality, and cost are needed. Variables that affect human performance, variables that affect quality, and variables that affect cost must be considered systematically in such investigations.
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References


