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A case study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry

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A case study is presented that evaluates the impact of partial automation strategies on productivity and ergonomics. A company partly automated its assembly and transportation functions while moving from a parallel-batch to a serial line-based production system. Data obtained from company records and key informants were combined with detailed video analysis, biomechanical modelling data and field observations of the system. The new line system was observed to have 51% higher production volumes with 21% less per product labour input and lower work-in-process levels than the old batch-cart system. Partial automation of assembly operations was seen to reduce the total repetitive assembly work at the system level by 34%. Automation of transportation reduced transport labour by 63%. The strategic decision to implement line-transportation was found to increase movement repetitiveness for operators at manual assembly stations, even though workstations were constructed with consideration to ergonomics. Average shoulder elevation at these stations increased 30% and average shoulder moment increased 14%. It is concluded that strategic decisions made by designers and managers early in the production system design phase have considerable impact on ergonomic conditions in the resulting system. Automation of transport and assembly both lead to increased productivity, but only elements related to the automatic line system also increased mechanical loads on operators and hence increased the risk for work-related disorders. Suggestions for integrating the consideration of ergonomics into production system design are made.

1. Introduction

Global market competition has placed manufacturing companies under pressure to improve their production systems. These improvements may target a number of performance parameters including production capacity, work in process (WIP), and cost efficiency. The ergonomic consequences of these improvement processes, in terms of exposure to risk factors for work-related musculoskeletal injuries, are rarely investigated. Nevertheless work related illness and injury have emerged as major social problems that can also compromise industrial competitiveness (Aaras 1994, Hendrick 1996) due to costs related to labour turnover, absenteeism, spoiled and defective goods, and reduced productivity (Andersson 1992). The European

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Agency for Safety and Health at Work (EASHW) reports that over 600 million working days are lost each year in Europe due to work-related ill-health (EASHW 2000). The EASHW also reports that estimates of the economic costs of work-related ill-health are up to 3.8% of the gross national product with 40–50% of this cost being attributable to work-related musculoskeletal disorders (WMSDs).

1.1. *Causal pathway of WMSDs*

Biomechanical and psychosocial factors at work have both been shown to influence the occurrence of work-related musculoskeletal disorders. Extensive reviews have particularly identified force demands on the body, repetition and working postures as being associated with WMSD type injuries for a number of body parts (Hagberg *et al.* 1995, Bernard 1997, Buckle and Deveraux 1999). The amplitude pattern of loading on body tissue over time is suggested to be a key element of injury risk (Westgaard and Winkel 1996, Winkel and Mathiassen 1994). Muscular efforts, even when as low as 2% of maximum capability on average, have been associated with injury when the total duration of exposure is long (Westgaard 1999).

Production operators' exposures to biomechanical risk factors are the consequence of the design of the production system (figure 1). The model presented in figure 1, extended from Westgaard and Winkel (1997), illustrates how strategic decisions made by senior managers can provide constraints to the design process that will ultimately determine working conditions, and hence risk factor exposures, for the operators of the production system. Westgaard and Winkel (1997) have explicitly identified cultural, social and corporate level forces as influencing these

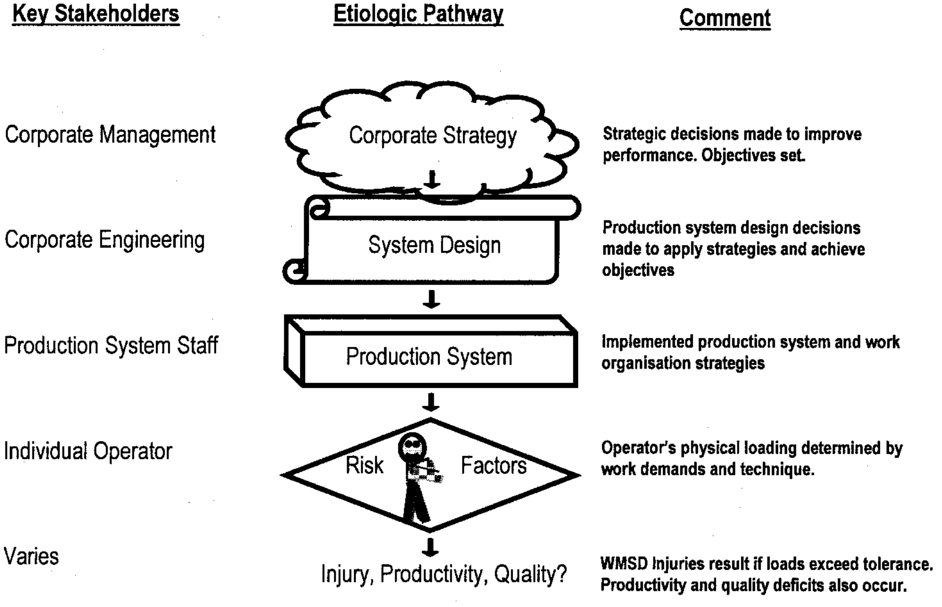

Figure 1. Theoretical model describing sources of injury (and related quality and productivity deficits) in production systems. WMSD Injuries (work related musculoskeletal disorders) are the consequence of a chain of events which start with corporate strategic decisions. This framework is embedded in social and economic contexts that will affect individual decisions at all levels of the organization.

processes. Production systems have been described as 'sociotechnical' systems with both equipment (technical) and human (social) subsystems. It has been suggested that the optimal design in both these domains requires simultaneous consideration, or 'joint optimization', in which different constraint domains are negotiated during design (e.g. Clegg 2000, Hendrick and Kleiner 2001, Ingelgård and Norrgren 2001).

If this were to be achieved in practice, it would be helpful to understand the relation between the technical sub-system and risk-related loads on human operators of the system. Each stage of the production system development process (figure 1) involves decisions that may affect system operators' biomechanical loading, and hence determine their WMSD risk. If a company is to control risk to system operators it must be able to recognize the injury potential in strategic and engineering decisions. Some connections have been identified between worker health and work production strategies such as 'Lean Manufacturing' (Landsbergis *et al.* 1999), or 'downsizing' (Vahtera *et al.* 1997). Engström *et al.* (1996) presented a number of cases of production using a parallel organization rather than conventional line, and showed that parallel production improved both productivity and working conditions. However, empirical data on linkages between specific strategies applied in production systems and their ergonomic consequences are sparse. Other negative consequences, such as quality deficits noted in figure 1, have also been linked to the presence of WMSD risk factors in the production system (e.g. Eklund 1995).

1.2. *Objectives of the investigation*

The aim of this paper was to conduct a field evaluation of the consequences of a production system re-design in terms of ergonomic and production performance characteristics. The increase in automation and the implementation of a line-based product flow observed as part of the re-design are consistent with common trends in the current industrial production strategy. The evaluation was addressed in the following series of enquiries:

(1) How did the change happen and what strategic, technical and work organizational design decisions were made during the change process?
(2) What changed in the production system and the organization of work as it was actually implemented?
(3) What were the consequences of these changes in terms of technical and ergonomic performance?

This paper focuses on the observed changes in the system, identifies the key strategic decisions implied by these changes, and examines their impact on productivity and operators' WMSD risk due to biomechanical loading of bodily tissues. Psychosocial aspects and WMSD symptom surveys were included in the larger study (Kihlberg *et al.*) but are not the focus of the analysis presented here. This investigation presents data linking ergonomics and production system design features, and thus contributes to the practical understanding required for the joint optimization of human and equipment elements in production systems.

2. Materials and methods

2.1. *The investigated case and project cooperation*

The site was a Swedish electronics assembly system producing AC/DC converters for mobile telephone transmission stations. The existing system used parallel assembly workstations with a 'batch-cart' production strategy in which operators would complete their assembly operation for one batch of product (between 4–160 items) and then manually transport the batch placed on a cartload to the next station and obtain a fresh cart of 'incoming' product. The company initiated this intervention to improve production performance. New strategies included automating assembly functions and adopting a line-based automated transportation system. The re-design was conducted with the stated goals to:

(1) increase annual production volume from approximately 115 000 to 140 000 units with capacity to expand further;
(2) decrease time to build each unit by 20%;
(3) decrease lead-time from 3.4 days to 24 hours;
(4) reduce the value of 'work in process' (WIP) by 30%;
(4) improve assembly quality so that visual inspection could be decreased by 80%.

The companies' design team was also charged with responsibility to suggest work organizational solutions, which would get and keep motivated personnel, increase the competence levels of the workforce, and organize job rotation to best distribute tasks with varying biomechanical demands between operators. Two project groups were established: The first was the technical design group focusing on production automation. The second was the work organization group charged with optimizing ergonomics and task distribution among operators in the new system.

In August 1998, the company contacted the research program COPE (Cooperative for Optimization of industrial production system regarding Productivity and Ergonomics; Winkel *et al.* 1999) to discuss a cooperation. The drive to redesign the production system came from the company. COPE was involved with the redesign project as participant-observers (Burns and Vicente 2000). Researchers attended meetings, provided advice and training to company groups, and observed the change process. A timeline for the project is presented in table 1. Initially, a three-day training course was provided for the work organization group in a number of technical and ergonomic assessment methods, including the

Start Date		Event
August	1998	Company contacts research group
October	1998	Contract signed for research project
November	1998	Training of company representatives in methods for assessment of exposure to mechanical and psycho-social risk factors
December	1998	Data collection: Video recording and questionnaires
Jan–March	1999	Analysis of activities and postures from video records
Jan–March	1999	Analysis of questionnaires and the interactive video method
May	1999	Presentation of the proposed work organization strategy to management
April/May	1999	Recruiting of personnel to the new line started
July	1999	Presentation of the implemented work organization by management
October	1999	The re-designed line begins operation
March	2000	The new plant owner of the production system takes over officially
September	2000	Data collection: video recordings of the new line, gathering of production data
September	2000	Data analysis started

Table 1. Important times for the evaluation of the production system redesign.

VIDAR (Kadefors and Forsman 2000) and PSIDAR (Johansson Hanse and Forsman 2001) participative video assessment methods. The goal of the researchers was that the work organization group should use information gathered by themselves to answer to their responsibilities towards the company. The work organization group used VIDAR and PSIDAR as well as a questionnaire and their in-house ergonomic checklist approach to assess working conditions in the system. Once the redesigned system had been implemented the research team proceeded to compare the new and old systems.

2.2. *Data collection strategy*

2.2.1. *General considerations*

Problems existed in quantifying specific indicators of company objectives. Changes, for example, in the companies' engineering time study methods, made quantified comparisons based on company data impossible. In such cases, qualitative assessments were made.

Different production operators staffed the new system, preventing individually paired comparisons, a problem that has been observed in similar studies and is part of the challenge of research in real production systems (Johansson *et al.* 1993). Large within and between individual variability, demand large subject pools for statistical power (Mathiassen *et al.* 2002) which is not feasible in most research contexts. In this study, only 1 operator-workstation pair was available for detailed analysis from the old system, although 4–6 subjects were available in the new system and over 100 subjects were available for general questionnaires (Kihlberg *et al.*). The small sample used here allows us to suggest trends but not to make statistical comparisons. While measurement error remains a concern in this study, the same measurement system assumptions, and matched manual assembly workstations, were used for both system assessments so as to limit possible bias. In order to escape the effects of inter-individual variability we have attempted to use production level indicators and biomechanical modelling procedures based on standardized anthropometrics in order to gain insights into the consequences of strategic design elements. We have applied qualitative and quantitative methods to ensure that the indicators reported here are consistent with observations made both in the field and during slow motion video observation.

2.2.2. *Production system level assessment*

Operators' work activities were examined in detail using a video-based activity analysis system with a time precision equal to one frame or 0.04 seconds (Engström and Medbo 1997). Up to 2 hours of videotape of key stations in each system were analysed depending on the frequency of relevant transportation activities. This information was then combined with production records and interview information to assess the technical performance of each system. Key indicators included: *production volume* over nine-week periods, *labour input* (in working hours per product), the amount of *'Work in Process'* (WIP), the extent of *quality work* required including checking and repairing activities, total time spent on *transportation activities* and *machine supervision* activities, *delivery dependability* or the extent to which shipments to the customer were made on time, and *lead time* as the time between receiving an order and delivering product. System features, such as *number of operators, number of workstations*, and the *number of manual component assembly workstations,* number of *manually assembled components* and labour inputs for *manual assembly time*, were determined for each system. Qualitative descriptors were used when quantified comparisons were not possible.

2.2.3. *Detailed workstation assessment*

Matched manual assembly workstations, which had essentially the same work functions, were chosen to explore the technical and ergonomic consequences of the implemented changes at the workstation level. Ten product cycles were video analysed to generate averages for the variables of interest. One subject was available from the batch-cart system and five subjects were available for the line-based system where median values were determined across operators. The limited sample size precluded the use of statistical comparisons. Video recordings were analysed to identify the duration of exposure to risk-related work postures. These included *back flexion* greater then 30°, *neck flexion* greater then 30°, and *arm elevation* of more than 30° from the vertical. Production performance indicators included: amount of time spent in *component get* (acquisition), *component put* (insertion to the circuit board), and *product transportation* activities, as well as forced *waiting time* caused by blockages or shortages in the running system, and *utilization time* when the operator is engaged in work tasks.

Biomechanical modelling. A two-dimensional static link segment model (Norman *et al.* 1998) was used to estimate shoulder moment (torque) for each essential action in the manual assembly workstations examined. Non-assembly activities, such as waiting and talking, and other system-related stoppages were not included. Thus, the comparison focused on the two workstations as designed, and resulted in 'full speed' estimates that represent realistic maximal loading patterns for these two stations. The duration of activities was determined from the video analysis and used to determine a time weighted average shoulder moment and the *cumulative load per product*. The *average shoulder load as a percentage of female capability* was determined using benchmark population data in the model software. The largest single instant of loading was taken as the *peak shoulder moment*. Other model-generated indicators included the *average arm elevation*, percentage time with the *arm elevated beyond 30°,* in *product transportation activities* or in *component get and put activities.*

3. Results

3.1. *Implemented physical changes to system*

The redesign of the production system included the addition of robotic assembly stations, a line-based conveyor system that replaced the product carts, a dedicated wave soldering machine, and both in-circuit testing and automatic circuit board cutting machines. Schematic flow diagrams of the two systems are presented in figure 2. The new system had fewer buffers and thus reduced WIP. There was no apparent change in space utilization between the batch and the line systems. The 'post-assembly' testing and packing operations remained unchanged in the new design. The most substantial changes affecting addition or removal of manual work in the system are summarized in table 2. The final product itself did not change.

3.2. *Work organization strategy changes*

At the macro level, the ownership of the production system changed five months after production was commenced at the new line. The system redesign process,

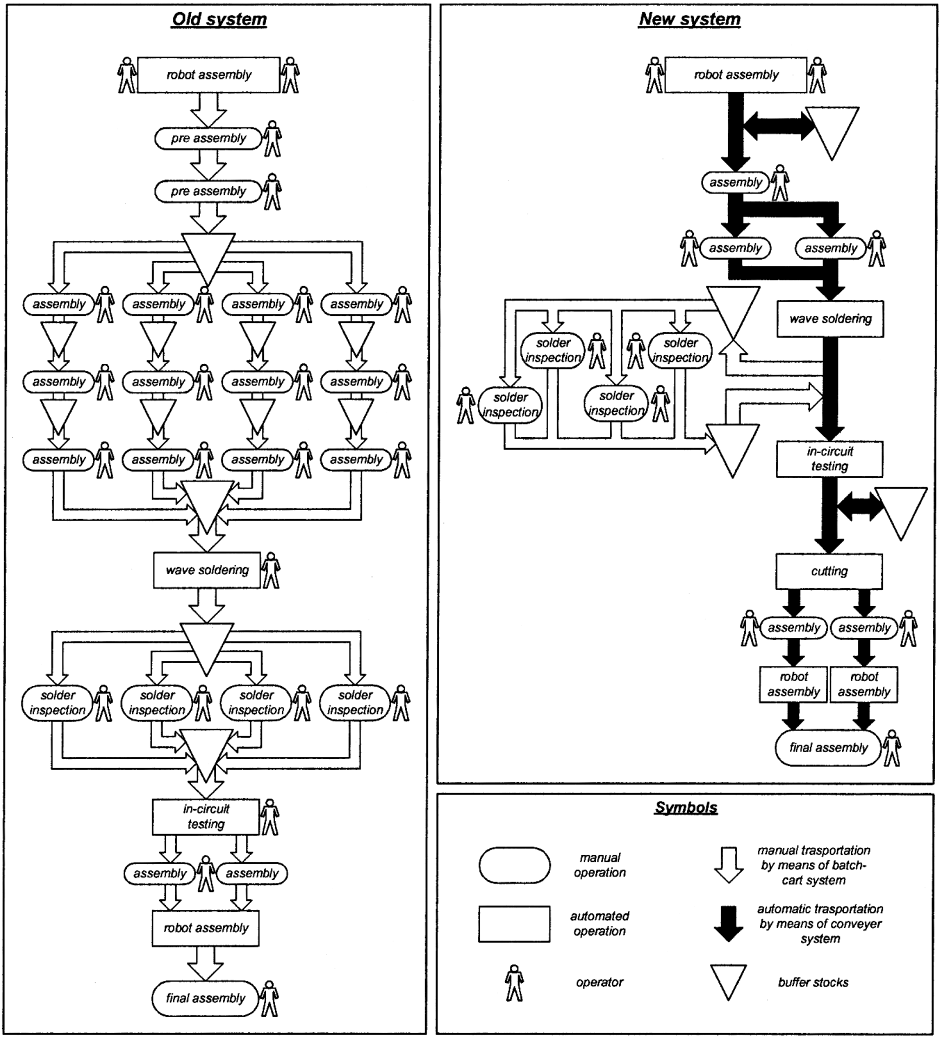

Figure 2. Flow diagram depicting the material flows, workstation arrangement and buffer locations in the old (batch-cart) and new (line-conveyor) systems.

Manual work eliminated	Manual work added
• Component placement (moved to robots)	• Cleaning after board cutting
• Manual soldering (process change)	• Loading cases onto conveyor
• End trimming of component pins (to robot)	• Machine monitoring and maintenance
• Framing of boards (process change)	
• Transport of product (to conveyor system)	
• Product load-unload operations (automated)	

Table 2. Summary of the changes in manual work observed as a result of the adoption of the new Line-based production system.

however, continued without major interruption. The old system had a day shift with 33 operators who worked together with two swing shifts (morning and afternoon) with 13 workers each. *The planned work organization strategy* was developed from exposure predictions based on the results from the work organization group's own ergonomic assessments. This resulted in the categorization of all workstations into three levels similar to those used in Swedish ordinances (Swedish National Board of Occupational Safety and Health 1998). The team used this information to set the intended work organization plan based on a two-shift system. The operators were to be divided into four groups of 4–5 operators each. Each group would be responsible for a set of tasks including each of the three ergonomic 'levels'. The intent of the rotation schedule was to move operators between these tasks, partly so as to increase variability of mechanical workload and thereby lessen the risk-related exposures on any one body part, and partly in order to distribute risks equally among operators. After 2–3 days the groups would shift to be responsible for another set of work tasks.

The manager of the new line, who had not been engaged in developing the work organization plan, rejected the proposed organizational strategy. Instead he established a core group of workers, supplemented by temporary workers from an employment agency to accommodate fluctuations in production. An increase in production volume forced the company to introduce a three-shift 24-hour system. Operators worked one shift at a workstation and changed to another station during the next shift. There was no formal rotation strategy. Several workers though, such as Material Handler/Stockperson and Robot attendants, did not rotate with the other workers and instead specialized at their roles. According to management, the use of temporary workers provided production flexibility and allowed for staff reductions as subsequent automation was expected to reduce the need for operators. The new line manager indicated that the cost of cross-training temporary operators, required for the proposed work organization system, was not warranted given the nature of their employment.

3.3. *System level consequences*

The results of the system comparisons are presented in table 3. Production volume increased, as did the variability of production. System lead-time was observed to decrease substantially. This appeared to be related to changes in the reporting system more than in the production system itself. Decreases in labour input per product were seen to result from automation of both assembly and transportation. The new system also created some increased labour costs due to increases in robot and machine supervision work and decreased operator utilization. Compared to the batch-cart system, the new line system was considerably more expensive to build and was reported to require roughly the same amount of quality work such as checking and re-work.

Peak loading to spinal or shoulder tissues was low for most work in the new line system with the exception of some material handling activities. The storage of some parts close to ground level resulted in about 90° of forward flexion and spinal compression levels as high as 4500 N for a large male. In these actions, spinal joint shear could exceed 1200 N.

3.4. *Work station level consequences*

Table 4 summarizes the results of the manual assembly station comparison. Components located on the table surface in the batch system were elevated to two

Performance indicator	Source	Batch system	Line system	Percentage difference
System perspective				
Production Volume (9 week period)	Docs^1	19600	29551	51
Production variability (%CV^2 of month average)	Docs^1	6%	16%	167
Labour input (operator hours 9 week period)	Docs^1	11 366	13 725	21
Work in Process	Interview		Decreased	—
Quality Work	Interview		Unchanged	—
Delivery Dependability (% shipped on time)	Interview	100%	100%	0
Lead Time (hours to deliver batch order)	Docs^1	76.8	22	–71
# operators employed	Docs^1	59	60	2
Total # workstations available	Docs^1	28	16	–43
# Manual assembly workstations	Docs^1	16	6	–63
Product perspective				
Labour input (operator min./product)	Docs^1	34.8	27.8	–20
Total # components (#/product)	Docs^1	60	60	0
Manual Assembly (# components/product)	Docs^1	48	26	–46
Robot Assembly (#components/product)	Docs^1	12	34	183
Manual Component Assembly time (min./prod.)^3	Video	5.5	2.9	–47
Machine Supervision time	Interview		Increased	
Operator Transport activities (min/product)	Video	3.9	1.1	–72
Workforce perspective				
Manual Component Assembly time (% of total work hours)^3	Video	15.8	10.4	–34
Robot supervision time (% of total work hours)	Interview		Increased	—
Transportation time (% of total work hours)	Video	11.2	4.1	–63
Quality Work (amount of total work)	Interview		Unchanged	—

[1] 'Docs' indicates internal company records as the information source

[2] %CV is the percent coefficient of variation based on monthly data

[3] Manual component assembly time includes the sum of all workstation times up to the wave soldering operation at which point all components have been added to the product.

Table 3. Comparison of performance indicators between the old 'Batch' system and the new 'Line' system from the perspectives of the entire system, of the product, and from the workforce.

Indicator	Data source	Batch system (stn 3)	Line system (stn 2)	Percentage difference
Workstation perspective				
Observed cycle time (s/product)	Video	141.1	121.5	−14
# component inserted	Docs[1]	17	16	−6
Component get time (s/cycle)	Video	51.8	47.1	−9
Component put time (s/cycle)	Video	24.4	30.2	24
Product transport time (s/cycle)	Video	23.1	7.8	−66
Operator perspective				
Forced waiting (% time)	Video	0	19.2	***
Utilisation (% time at work tasks)	Video	98.5	76.1	−23
Component get & put time (% time)	Video	53.9	63.6	18
Neck Flexion > 30° time (% time)	Video	83.9	42.5	−49
Shoulder elevation > 30° (% time)	Video	23.3	24.2	4

[1] 'Docs' indicates internal company records

Table 4. Summary results comparison for batch and line-based assembly systems at matched workstations performing approximately the same amount of component insertion. Indicators are presented from the product perspective in seconds per product cycle, and from the operator perspective in percentage of working time.

Biomechanical model of assembly work				
Indicator	Data Source	Batch System (stn 3)	Line System (stn 2)	Percentage difference
Cycle time used in model	Video	135.1	83.2	−38
Cumulative Shoulder moment (Nms/product)	Model	533	372	−30
Average shoulder moment (Nm)	Model	3.94	4.48	14
Average shoulder load as % female capability (%)	Model	11.4	14.6	28
Peak shoulder moment (Nm)	Model	5.5	6.3	15
Average shoulder elevation (degrees)	Model	31.0	40.4	30
Shoulder elevation > 30° (% time)	Model	44.3	55.6	26
Product Transport Activities (% time)	Model	17.5	7.1	−59
Component get and put activities	Model	56.4	92.9	65

Table 5. Summary of biomechanical model results comparing matched manual component assembly workstations from the old batch system to the new line system.

racks immediately above the new conveyor system. Although the new station had adjustable table heights that allowed both standing and sitting, this feature was not used frequently during the four days of field observation. The conveyor system itself eliminated the periodic standing and walking associated with replacing the cartload of products when each batch was complete. This manual transport was replaced with a button pushing action similar to the component-place action. Operator utilization decreased 23% due to the increased forced waiting in the new line system.

The biomechanical model results, which are based on assembly-related tasks only, are summarized in table 5. These calculations indicated decreased cycle time, increased time in shoulder elevation, increased average shoulder loading, and a substantial increase in stereotyped 'get' and 'put' activities.

4. Discussion

The implemented line system had a higher production volume and lower per product labour inputs than the old batch-cart system. The major strategic production decisions made by the technical design group included the automation of assembly and the automation of transport into a line system. The design of workstations, which was part of the work organization groups' focus, appeared to be constrained by binding decisions made by the technical group. The key ergonomic risks identified in this workplace include arm work with low biomechanical variability, short cycle times, and prolonged duration at some stations. In this case, the time-density of work, and thus work-related biomechanical loads, is probably of greater concern than the actual size of the relatively small loads (e.g. Westgaard 1999). The time-density of work is analogous to the concept of duty cycle (percentage active time within work-cycles), which is emerging as a potentially useful ergonomic indicator (Veiersted *et al.* 1993, Moore 1999). While one should always be cautious when generalizing from case studies, the case presented here appears consistent with Johansson *et al.* (1993) who suggest that isolating or delaying human factors considerations can compromise the success of capital investment in new technology. These results are also consistent with the interview investigations of the change process in which operators reported stress due to the work-pace of the new system and expressed concern about their long-term health (Kihlberg *et al.*). This use of mixed, qualitative and quantitative, methods increases our confidence in the numerical results presented here.

4.1. *The work organization strategy*

The proposed task rotation plan of the work organization group would have shifted operators strategically through positions with varying load patterns. Such a strategy may be useful in reducing risk if there is sufficient latitude, or variety, in the biomechanical loading patterns of available tasks. The group had carefully chosen task patterns to provide a variation in workload for all operators and could have alleviated problems for operators engaged in particularly load-intensive workstations. The decision not to implement this strategy was related to changes in the company's hiring strategy. It was believed that not all of the temporary workers would be able to perform all work tasks. The use of temporary workers, perhaps combined with the increase in technical complexity at some workstations, appears to have inhibited the willingness, or the capability, to invest in educating operators to be multi-skilled. This limited the effectiveness of the work rotation strategy by concentrating the physical exposures of sub-sets of workstations, in particular manual assembly stations with low-variation shoulder exposure, on particular operators. Thus, decisions made by the line-management determined the individual operator's exposure pattern to WMSD risk factors.

Peak loading, observed in only a few tasks here, poses a problem for rotation schemes that can expose all workers to a problematic task (Frazer *et al.* 1999). Risk related to peak spinal loading experienced by the stocking specialist, for example, is not necessarily shared by workers who do not rotate into this role. While these high peaks pose potential risk to the back (e.g. Norman *et al.* 1998), they are not an integral element of the production strategies used here and could be corrected using, for example, a continuous improvement approach. Peak loads aside, having assemblers take turns supplying parts would increase task variability in the relatively time-intensive assembly work and would serve to reduce their repetitive motion exposures.

As the 'temporary' workers become more familiar with the system or as political will in the company shifts, a new work organization system could be implemented to systematically increase variability in operators' daily work exposure patterns.

4.2. *The strategy of the automatic line system*

Automation of transportation and adoption of a serial line system removed transportation-related activities, including the transfer of product to and from carts and machinery, and the elimination of operators' periodic standing and pushing of carts to the next operation. Framing activities were also eliminated by positioning soldering machinery in line with the conveyor, resulting in further reductions in task variability for manual assembly operations (table 4). Reduced work-cycle time, due in this case to the elimination of non-assembly work, is associated with increased injury risk (Bernard 1997). In addition to faster repetitions and more similar work actions ('get and put') we observed small increases in amplitude due to elevated components (table 5), and decreased opportunity for muscular recovery formerly present during transportation activities (table 3). The intensification of manual assembly work seen here is consistent with other studies of partial automation (Coury *et al.* 2000) and poses a potential ergonomic hazard when exposure duration is long (Bernard 1997, Buckle and Deveraux 1999). This strategy provides an example of a production-ergonomics trade-off in which productivity is improved at the cost of increased WMSD risk. The adoption of a serialized line system also reduced opportunities for interaction amongst operators. Increases in WMSD symptoms have been previously associated with the adoption of line-based production systems (Fredriksson *et al.* 2001, Ólafsdóttir and Rafnsson 1998).

The reduction in buffers in the new system would help reduce work in process (WIP) but introduces an element of machine pacing to the work—a potential ergonomic hazard (Rodgers 1996). Reductions in WIP will reduce the company's investment in on-hand stock. Low WIP would reduce throughput time, which in this case was massively affected by the simultaneously implemented information system change. On the other hand, the absence of buffers will tend to increase losses due to starving, the unavailability of upstream products or parts, or blocking, which is an inability to clear the workstation because there is no space in the next station (Wild 1995). This forced waiting, linked to decreased operator utilization, was observed in the line system. Blocking and starving related stoppages are less common in parallel production systems (Medbo 1999) and were not seen here in the batch-cart system. Veiersted (1994) demonstrated that the potential opportunity to recover muscles during a forced waiting caused by machine stoppages might not be utilized by all operators. When interviewed, operators in this system commented on the increased stress associated with technical problems and stoppages in the system (Kihlberg *et al.*). Thus, the elimination of buffers can have negative consequences both for ergonomics and productivity.

4.3. *The automation of assembly strategy*

The automation of component assembly accounts for a large part of the reduction in labour input, although more operator time was needed to monitor and feed the assembly machines. Ergonomically, this monitoring work, performed by specialists, was quite varied but involved regular awkward bending and reaching into the robot to retrieve misplaced components. While the reduction in assembly work removed monotonic reaching and placing movements at the workforce level, this manual assembly remains concentrated on specific workstations. The uneven distribution of ergonomic risk factors in the system highlights the important role of the work organization strategy in determining an individual operator's biomechanical loading profile.

In this case study, technical problems with automating the assembly of some components were identified late in the re-design project. Manual assembly of these parts was therefore required. These additional parts were accommodated into the workstation design by adding a second, elevated, row of components (figure 3). For the operators this resulted in increased numbers of component insertion actions per board over the original design. The increased frequency of repetitions, combined with the higher demands of reaching elevated components, resulted in the increased shoulder loads seen in the biomechanical model. Both time-density of work and load amplitude appear to have been increased by these indirect effects of the partially successful automation attempt. This illustrates how decisions in the technical subsystem can have unanticipated downstream consequences on ergonomics. The automation of stereotyped tasks has the potential to increase productivity without direct negative affects to ergonomic working conditions, depending on the nature of the remaining manual work and the distribution of these work tasks among system operators.

4.4. *Manual assembly workstation design*

The manual assembly workstation design (see figure 3) was conducted within constraints provided by the automation of assembly and transportation functions. These included work rates, the conveyor pathway itself, and the late addition components that could not be automated. The reduction in neck flexion postures observed in video analysis and increased average shoulder elevation seen in the biomechanical model, were consistent with the shift of an operator's attention from the tabletop up to the elevated component racks used in the new system to avoid the conveyor pathway. Shoulder loads in the biomechanical model, considered

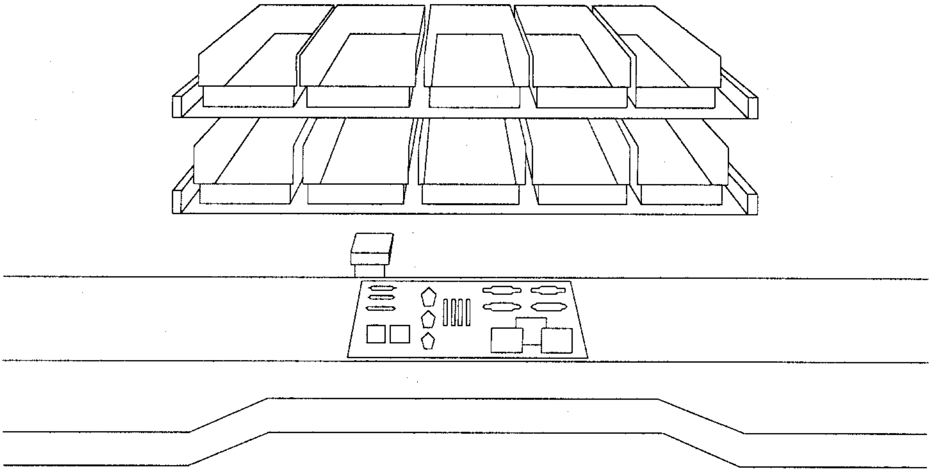

Figure 3. Layout of the second manual assembly station on the new automated line system. Elevated racks were required to make room for the conveyor system and to accommodate parts not fitted for automatic assembly back to the manual assembly process.

relative to female population strength capabilities as a time weighted average, exceeded 14% of maximum when calculated during uninterrupted work. Jonsson (1982), studying muscle activation patterns, has suggested that average (or median) muscular loads should not exceed 10% of maximum capacity. Higher average tissue loading, observed here in the line system, has also been associated with elevated WMSD risk (Norman *et al.* 1998). The ergonomic assessments indicate that shoulder WMSD risk has increased on the new workstation. In the broader study of this population, Kihlberg *et al.* found that 59% of operators reported neck/shoulder stress or disorders related to working at the manual assembly station studied here - the highest rate of any workstation in the system.

The line system workstations were designed, at considerable expense, to accommodate both sitting and standing. We did not observe many operators utilizing this feature. While sit-stand workstations offer variation for the back and leg musculature, they do not necessarily change the repetitive demands for essential job tasks of 'getting' components and 'putting' them onto the circuit board (Winkel and Oxenburgh 1990). Workstation layout decisions will not affect risk related to time-intensity or reduced task variability. Thus, the risk for the body part of primary concern, in this case the shoulder, would be unchanged.

4.5. *General discussion*

This paper provides empirical evidence suggesting negative ergonomic consequences of production system design decisions guided by technical considerations. Thus, the study supports the need for joint optimization of human and technical aspects in production system design, as identified by sociotechnical theory (Clegg 2000, Hendrick and Kleiner 2001, Ingelgård and Norrgren 2001). The findings are also consistent with existing calls to incorporate human factors into decision-making at the earliest phases of the design process (Burns and Vicente 2000). In order to achieve this, it is necessary to understand the linkages between technical aspects of the system and the loads on biological tissues of system operators. The relationships found in this study illustrate some of these linkages. The design process observed in this case, combined with the absence of specific ergonomic performance criteria for designers, allowed for a decision making chain that inadvertently increased risk for system operators. We make, in the next section, both specific and procedural recommendations for minimizing risk while optimizing productivity in production system design.

5. Conclusions

The automation of repetitive assembly work reduced system-level operator exposure to manual assembly work, and thus system-level WMSD risk. It also increased productivity. However, the remaining manual assembly work increased in intensity and monotony due to the automation of transportation functions, which simultaneously increased both productivity and WMSD risk. The early selection of technological solutions reduced biomechanical exposure latitude and could not be overcome by adjustments to the workstation layout. Production system designers and senior decision-makers have decisive influences on the ergonomic quality of their production systems.

5.1. *Implications and recommendations*

The following comments, directed at practitioners, appear warranted based on the results from this case study and on available literature.

Designers should consider both work removed and work remaining when planning automation. While automation of repetitive monotonous work (seen here in assembly automation) can reduce exposure at the system level, it will not necessarily improve the remaining manual workstations. Automating tasks that provide load variation will concentrate operators' biomechanical load onto particular body tissues. Muscular recovery time should be strategically designed into jobs, preferably by including varying tasks in the operators' jobs.

At the organizational level, production system designers have substantial responsibility for ergonomic conditions in their systems. Companies should establish accountability chains within their organizations to generate feedback and learning. Managers should demand specific ergonomic performance indicators, at the operator risk factor level, to provide feedback early in the design process. Production system designers should actively identify and develop strategies that simultaneously enhance both ergonomics and productivity in the system. Operators and technology should be considered jointly from the earliest stages of production system design. Ergonomic thinking in design stages can improve safety and productivity simultaneously with little additional cost.

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