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Integrate Ergonomics into Production System Design

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For a more in-depth look on this subject, please see:

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Integrate Ergonomics into Production System Design

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ABSTRACT

A case study is presented evaluating the productivity and ergonomic consequences of strategies implemented in a re-design of an electronics assembly system. The company applied partial automation strategies for assembly and transportation functions, moving from a parallel-batch to a serial line-based production system. Through simultaneous consideration of technical and ergonomic indicators we aimed to identify linkages between design decisions, productivity, and ergonomics. Data obtained from company records and key company informants were combined with detailed video analysis, biomechanical modelling and field observations of the system. Implementation of the strategy to partly automate assembly operations was seen to reduce labour inputs for component assembly work without directly affecting ergonomic conditions. The automation of transportation strategy reduced both labour inputs and work in progress. This strategy also resulted in considerable reductions in work-task variability, and hence increases in repetitiveness for operators at manual assembly workstations. The manual assembly station examined had some increase in shoulder load amplitudes and a larger increase in the time-density of work (reduced porosity). Work activities were focused almost exclusively on stereotyped 'get and put' actions which increased in average frequency from one every 8.3 seconds to one every 7.4 seconds. Workstation design was constrained by initial decisions to adopt automation technologies and also affected by later problems in the automation of assembly. Ergonomic conditions varied across individuals and stations in the system. The adopted work organisation plan resulted in uneven distribution of risk factors across operators in the production system. It is concluded that strategic decisions made early in the design of the production system have considerable impact on ergonomic conditions in the production system. Optimal design for sustainable and efficient production require simultaneous and integrated consideration of technological and operator functions in the manufacturing system.

1.0 INTRODUCTION

While risk factors related to work-related musculoskeletal disorders (WMSDs)are known (Hagberg et al., 1998; Benard 1997; Buckle and Deveraux, 1999), it is less clear how production system design decisions may foster injury potential. Figure 1 presents a theoretical framework in which operators are exposed to WMSD risk factors as a result of the designed production system and work organisation. Pressure to increase worker productivity by increasing the time-density of work may result in the elimination of needed recovery periods and raise the workers' accumulated loading. In some cases the improvement of the workstation design, and consequent reduction in peak loading, has actually facilitated the increasing time-density of work and thereby increased injury risk. This has been called the 'ergonomic pitfall' (Winkel & Westgaard 1996). Similarly, implementing strategies to specialise workers' tasks by narrowing the range of duties may concentrate biomechanical loading onto particular anatomical structures. More varied work would distribute this loading across the body. These are two examples in which decisions in the design of the production system can have ergonomic consequences for the operator. Our research investigates the relationship between production system design decisions and the resulting technical and ergonomic performance of the implemented system. Key dimensions of exposure to mechanical injury risk factors include the amplitude of the load, the pattern of loading, as well as the total duration of loading experienced by the operator (Winkel & Mathiassen 1994).

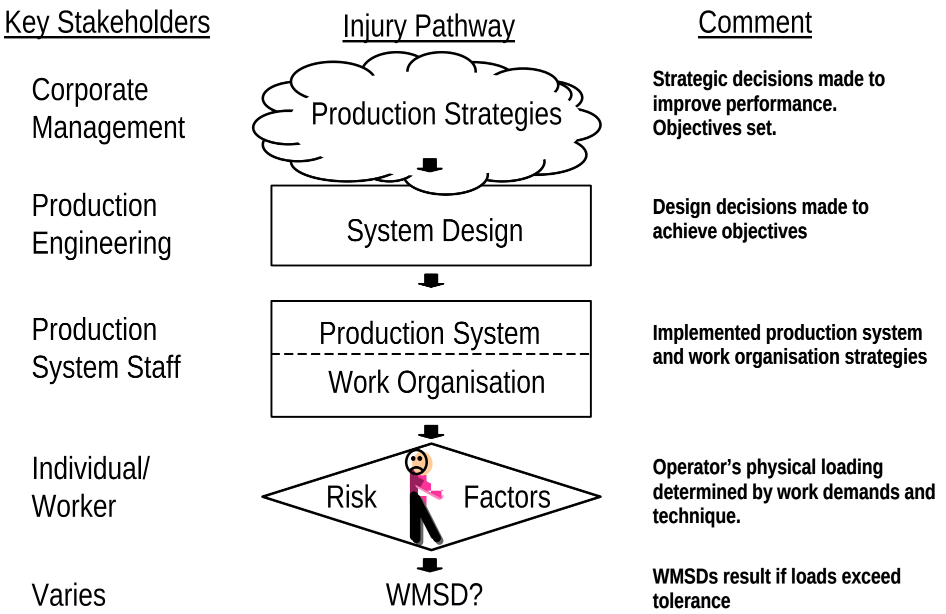

Figure 1: Theoretical framework for the investigation of design related sources of factors that increase the risk of work-related musculoskeletal disorders (WMSDs) in the production system.

2.0 METHODS

An electronics company, producing AC/DC converters for the telecommunications industry, decided to increase productivity by automating parts of their production process. This automation was intended to improve the technical performance of the system. The company was concerned about ergonomic conditions in the new system and engaged the research team through the COPE program (Co-operative for Optimisation of Industrial Production Systems regarding Productivity and Ergonomics; Winkel et al., 1999). The company formed two groups: a technical design group responsible for technical aspects of the system, and a work organisation group who focussed on workstation design and work organisation strategies for the new system. The COPE researchers assisted the company in making it's own ergonomics assessments for it's work-organisation team from the design group. This team then produced a proposal for the work organisation in the new system. The research team evaluated the ergonomic and technical consequences of the production system re-design using detailed video analysis of transport and assembly activities from positions across the system. Production information was also obtained to describe the system performance. Additionally interviews with company personnel helped provide qualitative information on both system performance and working conditions. Comparisons were made at the level of the production system including data normalised to the per product level and also expressed as a function of operator working hours.

A detailed analysis of ergonomic and production performance at a specific manual assembly workstation, performing comparable operations in both the old and the new system, was conducted. Video analyses of core job tasks were conducted using a detailed video analysis system (Engström & Medbo 1997). One subject was available for video analysis in the old batch system and five subjects were available from the new line-based system. Biomechanical modelling techniques were also applied to these workstations in order to quantify physical demands of the two systems.. This allowed the assessment of some of the specific ergonomic consequences of the strategies applied in the new system. Limited sample sizes available for comparisons of physical workload indicators precluded statistical comparisons. Instead, multiple methods, supported with qualitative data from company personnel and the multidisciplinary research team, were used in order to 'triangulate' and confirm key-findings.

3.0 RESULTS

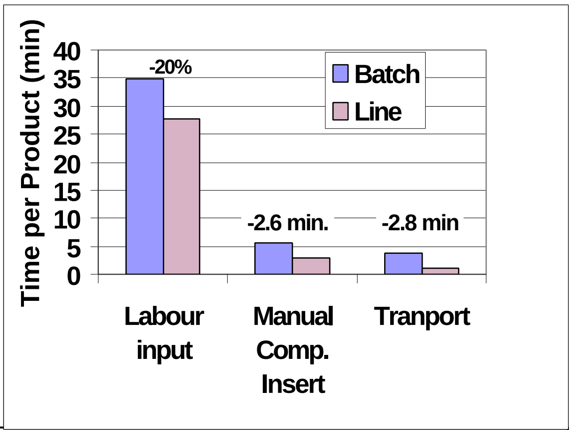

Figure 2: Labour inputs for the whole product (obtained form company records), and for manual component insertion and transportation (obtained from video analysis)activities for both systems.

The implemented re-design included strategies of automation of assembly, adoption of an automatic line transport strategy, construction of adjustable workstation designs, and adoption of a new work organisation strategy. The resulting system increased output and reduced labour inputs (Table 1, Figure 2). The amount of quality checking work and re-work, required to reach a final quality level for delivered products of 100%, was reported to be unchanged between the old and the new system. The automation strategies used resulted in elimination of some manual assembly work and smaller increases in other manual work such as loading cases onto the new conveyor system and monitoring automatic machines. Utilisation of manual assembly operators was observed to decrease due to forced waiting during line stoppages (Table 1). The line system had no buffering between manual assembly stations and thus a reduced amount of work-in-progress (WIP).

Table 1: Key indicators comparing old batch and new line systems at the system level and workstation level for comparable manual assembly stations.

	Batch System	Line System	%Difference
SYSTEM LEVEL			
Production Volume (9 week period)	19600	29551	51%
Labour input (operator min. / product)	34.8	27.8	-20%
ASSEMBLY STATION LEVEL			
Utilisation (% time at work tasks)	98.5	76.1	-23%
Average shoulder elevation (deg.) [1]	31.0	40.4	30%
Average shoulder moment (Nm) [1]	3.94	4.48	14%
% time in 'get & put' activity[1]	56.3	92.9	65%

[1]Data from biomechanical model calculated for undisturbed production

The examination of manual assembly work showed that, although both stations had about the same number of components to insert per product, the new line-based workstation had less task variety. Work tasks consisted almost exclusively of repeated reaching for and inserting ("get & put") of components (figure 3), exceeding 90% of time during undisturbed production. The old system also included the activities of transporting product and mounting the product into a frame for the soldering operation. The product cycle time on the new system was faster resulting in an average 'get & put' repetition once every 7.4 seconds compared to once every 8.3 seconds over the shift in the old system. Increases in the percent time with arms elevated, and increased average shoulder load were also observed in the biomechanical modelling analysis. The new system had parts elevated above the working table and the amount of time operators' spent in inclined head postures was observed to decrease on these stations. The workstation design provided sit-stand capability but was not frequently used during the 4 days of field observation. Biomechanical modelling of the manual assembly stations indicated an increase in average arm elevation angle (Table 1) and also increased shoulder

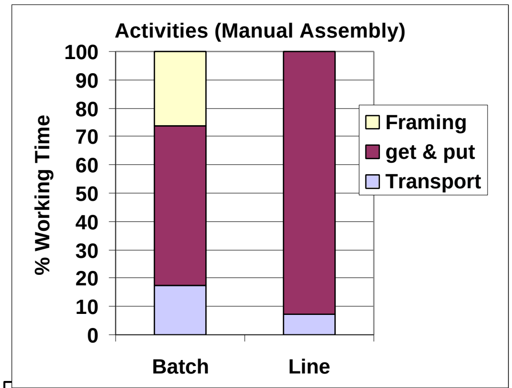

Figure 3: Activity analysis for comparable manual assembly workstations in the two production systems (from video analysis).

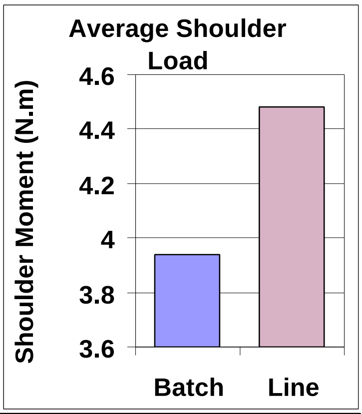

Figure 4: Average operator shoulder load for operators at comparable manual assembly workstations (from biomechanical model).

loading (figure 4).

The work organisation strategy, developed by the work organisation team to distribute loading among the operators, was not implemented. Management personnel, who had not been involved in designing the work organisation strategy, felt the plan was unworkable since part of the staff on the new system came from an outside ‘temporary’ employment agency and were unfamiliar with the system. Instead particular operators staffed more complex and variable jobs, such as robot supervision, without rotation. Operators who rotated every shift in an informal pattern filled the remaining positions. The jobs among which rotation occurred tended to be the low variability manual assembly and inspection work with frequent stereotyped upper arm movements.

4.0 DISCUSSION

4.1 Automation Strategies in the Production System

Both automation strategies used in the case study improved labour efficiency in terms of worker minutes used per product. The strategy to automate assembly was observed to reduce the total exposure of system operators to repetitive monotonous assembly work although the remaining component insertion work remained concentrated onto three workstations. Problems in the automation of some component insertion operations resulted in increased shoulder loads on the remaining manual station that had to pick up the work that could not be automated. Automation of the transport system in contrast eliminated work that had provided muscular variability for operators. The result was a concentration of muscular activities on stereotyped and rapid ‘get & put’ movements at the manual assembly workstation. Intensification of worker effort has been observed in other cases of automation improvements (Coury et al., 2000). Even though loads observed here were of low amplitude injury risk remains as these loads occur for extended periods involving the same body tissues. Exposure amplitudes as low as 2% of maximum capability are of potential concern if the force demands are sustained over a long time period (Westgaard, 1999). Further ergonomic concern relates to the reduction in variability and potential loss of recovery time, or micro-pauses, reductions of which have been associated with WMSDs (eg. Stoy & Aspen 1999, Veiersted et al.1993). Electromyographic testing would be required to support this possible injury pathway. These findings illustrate how decisions during the development of the production system can determine the subsequent risk factor exposure of operators in the functioning system (figure 1).

Table 2: Summary of the production and ergonomic benefits and deficits resulting from the two automation strategies implemented in the re-designed production system.

	Production		Ergonomic	
Strategy	**Benefit**	**Deficit**	**Benefit**	**Deficit**
Assembly Automation	Reduced manual assembly work		Overall decrease in monotonous work (system)	
		Increased machine support work	Increased variable work	Some awkward bending and reaching
Side Effect (problem reaching automation targets)		Return of work to manual assembly		Increased shoulder loading (parts on elevated rack)
Automatic Line Transport System	Reduced manual transportation work			Reduced task variability
	Reduced handling of product in preparation for assembly		Some reduction in handling activities	Increased arm elevation & average shoulder moment
Side Effect: (Disturbances in unbuffered system)	Reduced WIP	Decreased operator utilisation (due to forced waiting)	Forced waiting may provide recovery time for some, but not all, individuals.	

4.2 Workstation Design

The design of the workstations was considered after technical system decisions had been made. Even though ergonomic considerations were explicitly considered during workstation design, the work organisation group was not able to overcome constraints created by the previously chosen technical strategies. In both cases of automation, negative ergonomic consequences were observed to result from interactions between the automation and the physical workstation design. In the case of the line system, which created some spatial constraints for component stocks, an elevated rack was used to hold component bins above the line level. A second elevated rack had to be added as difficulties reaching automation objectives resulted in shifting extra components to the manual stations (Figure 2). While the provision of sit-stand capability at the workstation might increase variety in whole body posture it would not reduce the essential ‘get & put’ demands the job placed on the shoulder. The worsening ergonomic conditions on this workstation can be interpreted as unintended side effects of the partial automation strategies applied. Procedurally, this increase in injury risk is the consequence of placing ergonomic design criteria beneath strategic decisions relating to the design of the technical sub-system which are made at higher levels of the model presented in Figure 1.

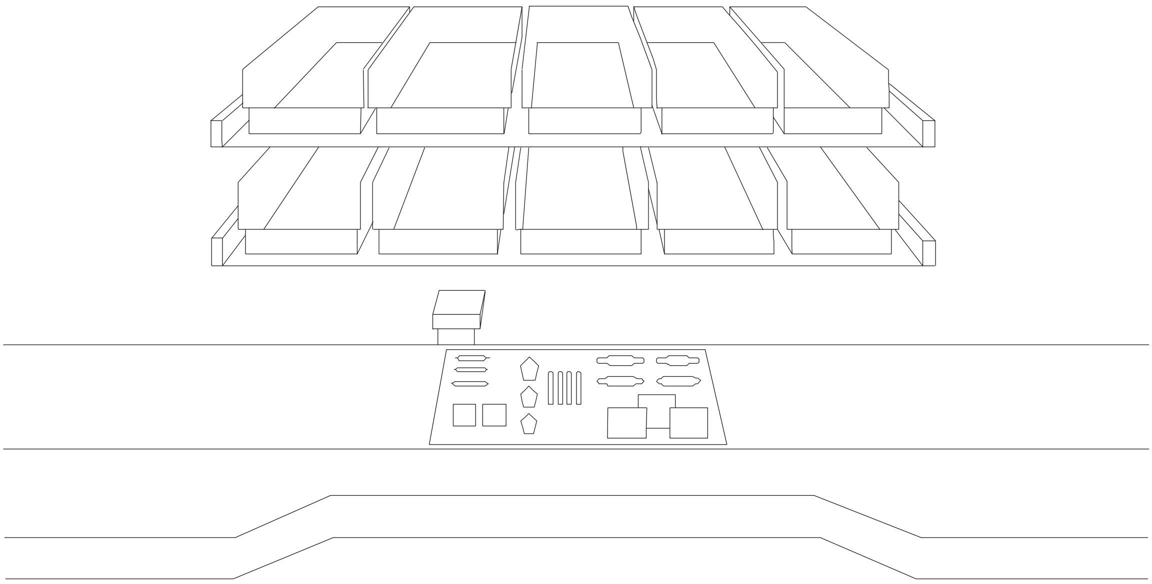

Figure 2: Layout of manual assembly station on the new automated line system. Elevated racks were required to make room for the conveyor system and to accommodate parts shifted from automatic assembly back to the manual assembly process.

4.3 Work Organisation

Given a series of workstations with varying exposures, the work organisational strategy will determine operators' ultimate exposure pattern to these risk factors. In the case studied we observed the development of a team-based rotation strategy which was suggested by the work organisation group. Managers who had not been involved in the planning process subsequently rejected this strategy. Part of the reason for this appears to be the use of temporary workers, which made the multiskilling of workers appear less cost effective as future automation efforts would lead to the elimination of these operators. From a biomechanical perspective, it is improbable that rotation among work tasks with similar demands will provide substantial reductions in overall loading. Nevertheless, rotation strategies remain a potential approach to limit the duration of exposure of operators to workstations that have particularly intensive time-loading patterns.

4.4 General Discussion

These results establish coherent chains of consequence, which link strategic production decisions to the exposure of operators to known injury risk factors as illustrated in Figure 1. Understanding this causal chain of increasing injury risk is necessary to develop effective intervention strategies. If the primary sources of the risk factors are embedded in the production strategies used when designing the system, then it is unlikely that subsequent reactive improvement effects will have substantial impact. Ergonomic quality in the production system is determined by managers and engineers who choose and then implement particular manufacturing strategies.

While caution should be used when generalising from case study data, it is probable that the relationships observed over the course of this re-design process will exist in other projects. The positioning of workstation design decisions subsequent to technical sub-system decisions, for example, has been noted as a potential problem. Johansson et al. (1993) have suggested that "…paying insufficient attention to human resource issues until after the technology has been selected and implemented creates a risk of problems that are so severe that the capital investment in new technology may be completely negated". Designers should note that the ergonomics consequences of automation strategies depends on the nature of the work that is being automated as well as what work tasks remain for the operators. The work organisation strategy can be used to increase task variety and thus distribute work-loads across more body tissues. Integrated consideration of a production systems technologies and it's operator interfaces is necessary to achieve optimal designs.

5.0 CONCLUSIONS

Production system designers and senior decision-makers have clear impacts on, and hence responsibility for, the ergonomics of their production systems. The automation strategies implemented here increased both productivity and potential risk of musculoskeletal disorders of the upper limb. Early selection of technological solutions provided constraints that could not be overcome in the ergonomic consideration of the workstation layout.

6.0 RECOMMENDATIONS

Designers and managers should recognise the possible ergonomic implications of decisions made during production system design. Automation efforts should focus on stereotyped repetitive work while maintaining work variability for operators. Feedback on, and accountability for, ergonomic conditions in production systems should be established within the design process. Simultaneous and integrated consideration of operators and operations, from the earliest stages of the design process, should be applied to develop manufacturing systems that are both productive and sustainable.

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Integrate Ergonomics Into Production System Design

Evaluating the ergonomic and productivity consequences of a partial automation strategy.

Patrick Neumann
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Workplace Injuries - Scope of Problem

- 1996 USA: $60 Billion Comp Costs (GAO 1997)
- Work Days Lost
  - 125 Mil. (USA)
  - 600 Mil. (EU) (ill health)
- 4% Gross World Product in ill health (WHO:ILO 1998)
  - ~40% Musculoskeletal Disorders

Why Ergonomics?

- Less Injury and Pain
- Better Quality & Productivity (org. performance)
- Compliance and Due Diligence (legal)
- Corporate citizenship & Industrial Rel. (Intangibles)

Wherever you have Manual work…
…you have ergonomics

Theoretical Framework

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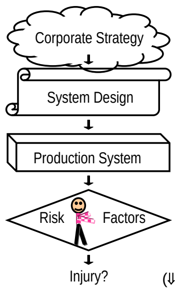

(⇓ quality & productivity)

Exploratory Longitudinal Case Study

An Electronics assembly system was re-designed

Before: *'Batch-transport' System*

After: *'Line-conveyor' System*

Exploratory Pre-Post Case

- QUANTITATIVE:
  - Production information
  - Video Analysis of Stations (limited sample sizes)
  - Biomechanical Modelling & detailed video of key stn
- QUALITATIVE
  - Key Informants
  - Observations from field, video, photos
  - Questionnaires & Interviews conducted

Exploratory Pre-Post Case

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  - Production information
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- QUALITATIVE
  - Key Informants
  - Observations from field, video, photos
  - Questionnaires & Interviews conducted

☛ Focus on mechanical loading and production performance

Strategic Change Process: 2 groups

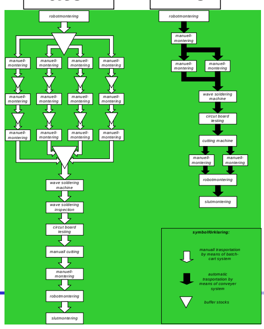
TECHNICAL GROUP:

1. Automation of Assembly
2. Automation of Transport to Line System

WORK ORGANISATION GROUP:

1. Ergonomic Design of Workstations
2. Work Organisation - to improve working conditions

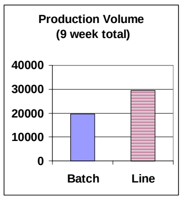
System Level Results: Work Changes

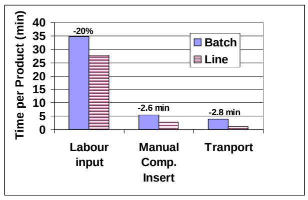


- Manual Work Eliminated:
  - Assembly
  - Framing
  - Transport
- Work Added
  - Robot supervision
  - Forced waiting

☛ **Less potential for co-worker interaction & support (⇑ risk) ?**

System Level Results: Productivity





- Increased output
- Increased production variability
- No change in Quality Work

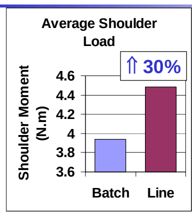
- less labour input
- less manual assembly
- less manual transport
- more expensive workstations

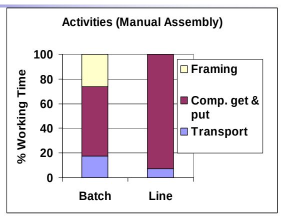
Workstation Level Results

⇑ insert rate from 1 every 8.3 sec to 1 every 7.6 sec

- Adjustable workstation (sit-stand capability)

Workstation Level Results: Ergonomics





- Cycle time ⇓ 38%
- Arm elevation ⇑ 26%

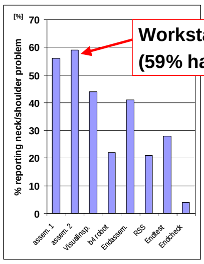
- Decreased task variability
- time in get-put moves >90%

☛ Ergonomic Indicators based on undisturbed production suggest increased intensification for shoulder tissues

•Neumann et al. 2001, ICPR Prague, CZ

Workstation Level Results: Shoulder Pain

- 4 worst stations have same handling activities



Workstation studied
(59% have Shoulder problem)

(~1 year Post change)

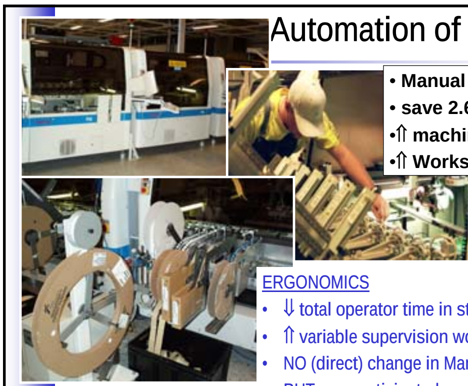
OPERATOR REPORTS:

•New system was very stressful due to work speed and technical problems in the system.

• Operators reported concern about their long term health (burnout & sick leaves)

Produktionsergonomi, Malmö Högskola

Automation of Assembly



• Manual work ⇓
• save 2.6 min / board
•⇑ machine supervision
•⇑ Workstation cost

ERGONOMICS
- ⇓ total operator time in stereotyped tasks
- ⇑ variable supervision work (reaching?)
- NO (direct) change in Manual Assembly
- BUT... unanticipated consequences ...

Produktionsergonomi, Malmö Högskola

Strategy: Automation of Assembly

Failed to automate some components
⇒ moved to manual station
⇒ Added to second (higher) rack

⇑ shoulder moment (⇓ neck load?)
⇑ number & distance of movements per product
⇑ average load & % time in rep. Movements

Be prepared for unanticipated consequences in automation strategies 'downstream'

Produktionsergonomi, Malmö Högskola

Line Automation Strategy

Batch Transport System:
1) Assembly
2) moving parts & product

Line System:
1) Assembly
(Moving is done by conveyor)

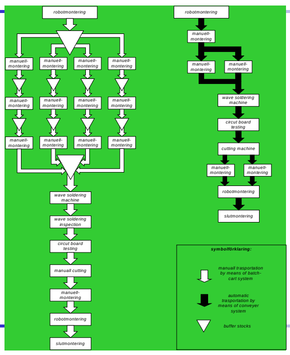
• More value added work, faster cycles
• Less task variety & muscular recovery: load intensification

Produktionsergonomi, Malmö Högskola

Line Strategy

Batch

Line



•Serial layout & automatic transport
- ⇓ W.I.P.
- ⇑ Disturbances & Losses
- ⇓ cycle times (no framing)
- Difficult to expand

• Machine Pacing (⇑ risk)
• ⇑ Frustration from disturb.
• manual assembly showed time-intensification

Produktionsergonomi, Malmö Högskola

Workstation Design Strategy

Constraints from tech. team:
• Conveyor pathway & space
• Line rate & tasks
• Number of parts (increased)

• 1st rack elevates parts above transport system (⇑ load)
• 2nd rack added for failed automation parts (⇑ load)

• Adjustable 'Ergonomic' workstation (sit-stand capability):
- expensive & not used much
- does not change essential shoulder demands

Produktionsergonomi, Malmö Högskola

•Neumann et al. 2001, ICPR Prague, CZ

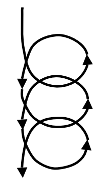
Strategy: Work Organisation

- USED: Partial rotation, unstructured
- Some operators had 'specialised' jobs (hi variability)
- Work Org. team planned rotation to balance load
- New manager rejected Work Org Strategy
  - Temporary operators being used
    - Could be eliminated with further automation
    - Didn't warrant investing in multiskilling (?)

⇒ Operators' workload unevenly distributed

Case Study Illustrates Linkages to Injury

Decision Pathway?



Injury Pathway	Comment
Corporate Strategy	**1) Improve Performance with Automation 2) Consider Ergonomics separately**
System Design	**1) Technology choices for line system 2) Workstation design constrained by tech.**
Production System	**1) Increased rate, machine pacing elements 2) Fewer tasks, less interaction potential**
Risk Factors	**1) Reduced Work Variability (⇑ intensity) 2) Increased shoulder loading**
Injury?	***59% report neck/shoulder pain or stress***

Case Study Conclusions

1. Productivity and Ergonomic objectives coincided in automating repetitive assembly work (*workforce level*) but…
2. Unanticipated problems in automation constrained *workstation* design with negative ergonomic consequences
3. Productivity and ergonomics were in conflict in the automation of transport work
4. Strategic decision makers and engineers set early constraints for operator physical loading

Message to Practitioners

- PROCESS
  - integrate ergonomic considerations
  - consider ergonomics at operator and system levels
  - establish indicators of physical load
- STRATEGY
  - Consider BOTH work remaining and work automated (remove repetitive work retain variable work)
  - Look out for load-intensification on specific body tissues (short cycle, line systems, no rotation)

Productivity - Ergonomics Relationships

Ergonomics

Productivity	Better	No Change	Worse
Better	Go!	OK	$ + pain
No change	OK		X
Worse	**Hidden Gains?**	X	X