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

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ERGONOMICS AND PRODUCTIVITY CONSEQUENCES IN ADOPTING A LINE-BASED PRODUCTION SYSTEM

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Ergonomic and production system effectiveness are evaluated in a case of a production system re-design: from parallel flow dock-based, to serial flow line-based assembly. The line-based system displayed much tighter coupling of operators to the technical system and introduced system, balance and downtime losses. We observed reductions in: cycle times to 6% of previous, decision latitude, influence and control over work, perceived work load, and perception of available pauses. Layout and technology changes helped improve co-worker interaction and support, and reduce instances, but not magnitude, of peak spinal loading. It is concluded that serial flows can negatively affect psychosocial conditions and, if losses are high, reduce physical workload. An 'Action Group' has been formed in the company to adopt an evidence-based approach to the development of systems that are sustainable from both productivity and ergonomics perspectives.

INTRODUCTION

In this paper we use a case study in the redesign of motor assembly system, from a long-cycle dock system to a line-based system (Figure 1), to examine the relationship between system design, technical performance and work related musculoskeletal disorder (MSD) risk. Recent surveys indicate societal trends of increased work intensity – a MSD risk factor. This case's scenario appears to be a trend in Sweden of returning to line based production models after decades of more sociotechnically-based approaches. However evidence suggests that parallel flow systems can be more productive with better ergonomic potential than conventional line systems (Medbo 1999).

Integrating human factors into manufacturing system design remains an under-utilised mechanism for ergonomics intervention (Westgaard & Winkel 1997). While we focus on MSD risk factors, we adopt a systems perspective (Neumann 2001) including also performance and productivity variables of traditional interest to factory design teams. Joint optimisation of all of these factors may allow ergonomic problems to be solved in a profitable way (Winkel & Westgaard 1996). This study is part of a line of research that aims to understand the basis by which a production model is chosen and the consequences of this choice in the realized system.

Figure 1: OLD system dock workstation (left) & NEW line system (right)

METHODS

A longitudinal case study with most measures implemented pre and post system re-design was performed. We integrate qualitative and quantitative methods. Informal interviews and document analysis were conducted to understand both process and outcomes in the system redesign project. Production and economic data were obtained from company information systems and interviews. Questionnaires (n=81 pairs) were used to assess operators' perceptions of pain status, workload, stress, energy and psychosocial conditions. Portable data loggers were used to measure postures of wrists, arms, head, and back while working under normal conditions (n=8 pairs). Video recordings were made synchronously with data logging and analysed with respect to the time used for work activities including direct (value adding) and indirect work. Posture data were obtained for each activity category. In order to understand operators' movement between work areas a position logging system (originally from orienteering) was implemented. Biomechanical models were used to assess individual loading and production simulation models were used to understand system behaviour and working patterns.

Follow-up measures, planned jointly with the company, were made 6 months after the change. While detailed quantified posture and task information is not yet available, qualitative, modelling, questionnaire, and preliminary system performance data will be reviewed. System performance data will be re-examined 12 months after baseline to control for seasonal and run-in effects.

PRELIMINARY FINDINGS

OLD system. The OLD production system, designed with 18 'dock' stations, was studied having 12 Docks and a small 'learning line' in parallel for newer Operators. Operators worked alone at each dock to assemble each motor. Operators were required to finish 5 engines per day that increased to 5.5 shortly before measurement. Operators could stop working once this quota was reached. The system was designed, based on standard times, to allow 6.2 motors to be completed per shift per dock but this target was not enforced and not all operators were believed to be capable of this pace. Hand steered motorized carts allowed transport and lift-tilt position adjustment of motors. Parts were supplied to the dock using a 5-shelf 'kit' stocked with variant specific components by stock 'pickers'.

NEW system. The NEW line system used a serial flow of 18 stations and reduced station cycle time to 6% of the 'dock' cycle time. Automated Guided Vehicles (AGVs) provided motor transport and eliminated short walks between assembly cycles. Parts were supplied directly to the line in large crates. Operators retrieved parts directly from the crates occasionally adopting awkward postures. The AGV contained a computer monitor providing part numbers for the particular variant to the operator. *The product itself* was largely unchanged between OLD and NEW systems requiring about the same component mounting work. There were however many product variants requiring different components that, for lower volume variants, were positioned further away from the operators' workstation resulting in load carrying.

Motivation for the re-design. Reasons for the change, examined through company documents and interviews, included overcoming current capacity limitations and was summarized in the project directive: *"A line will mean it is easier to come to clear the expected 70,000 rate, that we decrease learning time, simplify material supply, make it easier to make other changes (because we skip changing 18 places), have a more social workplace with fewer work injuries and, above all reach a reduced product price".* In apparent contradiction the corporation's own standard on work organisation stated: *"serial flows with short cycle times generate waiting times that are not experienced as pauses but as disturbances in the work rhythm. This also generates accelerated work with poor ergonomics as a consequence."* These waiting times were observed in the new system, with utilization times in the NEW system as low as 67% as seen in simulation modelling (Figure 2). Balance losses were not modelled but are also a relevant factor. These results were predicted by the corporate standard: *"leaving the concept of the traditional line means that the system losses are reduced since the time dependence between fitters/operators is reduced"* and *"parallel flows reduce the need of buffers and reduce balance losses."*

The Work Organization. The 5 motor quotas in the OLD system limited production to 81% of planned capacity (89% at 5.5 quota) and reduced the impact of other

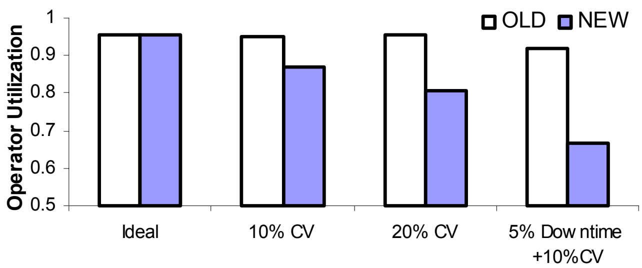

Figure 2: Sensitivity of NEW line and OLD dock systems' operator utilization rates to variability in operators' cycle time (10% & 20% coefficient of variation) and to machine downtime (5% downtime) based on flow simulation models.

losses seen in Figure 2. The OLD system appeared to invite faster work paces to accumulate rest time for operators who could reach the quota. The NEW system had a team structure in which operators rotated every break within the 4-6 stations of the team's area. Operators stayed on-line for the full shift. Waiting patterns in the NEW system, which may not be fully restful, was determined by system loss patterns. Neither system collected information on operators' work pace or work pattern related loading.

System performance. Planned comparisons of system performance are presented in table 1. Data is not presented for the NEW system as the effects due to design strategy were confounded by ongoing run-in activity and simultaneous increases in customer demands that placed unrepresentative pressures on the NEW system. Qualitatively we can report increasing output with similar staffing levels, despite the line system's losses. Labour was saved in 'kit picking' but added with line-'runners' who move along the line as needed. Investment in the AGV system increased capital costs. Extra resources were required to maintain quality levels during the run-in period. More detailed assessment of performance indicators, especially economic factors connected to MSDs, is currently underway.

Biomechanical loading. Affordability of lift-assists was seen as an ergonomic advantage of the NEW system and three were installed. These could not reach more distant component variants however, which then required manual handling and some carrying. Although all stations no longer handled heavy parts, the system-wide peak spinal loading was about the same in both systems with 470N shear loading and L4/L5 compression over 2600N. Nevertheless operators reported lower back loading on the Borg RPE-10 scale ($P<0.01$) on the new system. More detailed profiling of postures and load accumulation, now underway, must also account for system functioning and loss patterns. Duration of exposure to powered hand tools, for example, could be expected to rise as direct labour efficiency is increased in the new system. The company collects no systematic data with regards to operators' exposure to biomechanical load.

Questionnaires. Pair-wise comparisons of operators experienced in both dock and line systems ($n=54$) indicate significant ($p<0.05$) reductions in 'decision latitude', 'influence and control of work', and 'physical exertion' scales and increases in 'social support' and 'relationships with fellow workers' scales in the NEW system compared to OLD. While a trend ($p<0.11$) of reduced general 'physical discomfort' was observed, the 'Nordic' symptom instrument indicated increases in shoulder pain (3-month history). In this sub-sample of operators, 71% reported fewer pauses in the new system (6% said more) - consistent with the quoted corporate standard. Most operators also reported reduced work variation (68% vs. 19%), and reduced stimulation (63% vs. 16%) in the NEW system. These results are consistent with a shorter cycle, pace-controlled system with in which operators are close enough to talk to each other.

Table 1: System Performance Comparisons (Data normalised to the Total per motor costs in the OLD system, n/a indicates data not yet available)

Indicator	OLD	NEW
PRODUCTION- Volumes (normal to Old)	**100**	n/a
Standard Cycle Time (normal to Old)	**100**	6
Throughput time (normal to OLD)	**100**	n/a
STAFFING – Total Operators (% OLD)	**100**	102
Middle section (% OLD Total)	18	18
Picking (% OLD Total)	11	0
Docks/Line (% OLD Total)	34	46
USA Motor line (% OLD Total)	0	7
Other (% Old Total)	37	30
ECONOMICS*– Total Costs (norm/motor)	**100**	n/a
Direct Labour Costs (%OLD Total)	50	n/a
Indirect Costs (%OLD Total (%OT))	50	n/a
Ind. Costs – Labor (%OT)	42	n/a
Ind. Costs – Capital (%OT)	4	n/a
Ind. Costs – Maintenance (%OT)	1	n/a
Ind. Costs – Other (%OT)	3	n/a

DISCUSSION

This is a case study and therefore represents a particular instance and time-point of these two production strategies. Table 2 presents an overview of specific system design elements and their apparent consequences for system effectiveness and ergonomics. These results are consistent with previous case studies (eg Neumann 2001) and generally show internal consistency across qualitative and quantitative domains. Of the many measurement issues affecting this study the interpretation and stability of company data systems posed a particular challenge. The dynamic nature of the production system itself, where coefficient of variations in monthly production indicators ranged from 10-25% or more during this run-in period pose interpretational challenges. To overcome this variability we applied a broad range of measures to triangulate on the ergonomic and

Table 2: Analysis of some of the consequences of key design elements on system effectiveness and ergonomics.

Design Element Change	System Effectiveness		Ergonomics	
	Benefit	**Deficit**	**Benefit**	**Deficit**
Parallel to serial flow	Facilitated change in work organisation	Sensitive to system, balance, and downtime losses	Production disturbances may provide break opportunities	Reduces possibility of spontaneous breaks, reduced job control
Reduced cycle time	Easy to learn station More control of operator time		Easier to tell if work pace matches system	Reduced physical movement variation
Changed system & workstation layouts		Adding components for new variants difficult due to space constraints	Increased opportunity for interaction, not all stations handle heavy parts	Lift assists can't reach all heavy parts
Change from Kitting to Line Picking	Picking of kits eliminated (positions eliminated)	Operators must walk further to some parts	Lift assists (3) available for picking heaviest parts	Lifting parts from bins still cause high loading.
Manual to automated guided vehicles (AGVs)	No manual steering work On screen checklists for variants	High capital & upkeep costs, prone to breakdowns (losses)	Adjustments can reduce biomechanical loading	Reduces physical variation, Contributes to reduced job control
Work Organisation change (solo to team-work, eliminate quota)	Operators remain 'on-line' for full shift.	'Runners' needed to assist with line disturbances (positions added)	'Team' structure may foster co-worker support	Work pace steered by system, Reduced job control

productivity consequences of production system design choices (Table 2). This analysis sets the stage to identify system elements that could be strengthened or modified to improve both ergonomics and effectiveness simultaneously.

Assembling motors is largely a job of getting components and bolting them on. An important aspect for MSD risk will be how concentrated these activities become for operators. If efficiency gains are sought by maximising operators' nut-running time, for example, then MSD risk will increase. If, on the other hand, current losses could be filled with productive work that does not increase critical biomechanical exposures then both good ergonomics and good productivity could be achieved. This is the challenge for the company's 'Action Group', recently established at this site. This multi-stakeholder group is to make 'evidence based' improvements to 1) current systems, 2) future system designs, and 3) the product by which both human factors and other productivity goals can be met in a sustainable production system. We will operate in an action research mode offering tools and using information feedback, including the analysis presented here, while monitoring both process and outcome factors during the development project. The objective is to see if productivity can be improved in a sustainable way by working smarter - not just harder.

CONCLUSIONS & RECOMENDATIONS

While physical load amplitudes were controlled by workstation layout factors, system-flow & work organisation strategies controlled individuals' exposure time patterns. Adoption of the line system bypassed work organisational barriers in the OLD dock system (the quota) that limited productivity and rewarded operators who rushed with longer rest periods. Instead system and other losses in the NEW line system created many small waiting periods during the day and resulted in reductions in productivity, work autonomy, and decision latitude. The current case shows both systems to be sub-optimal when ergonomics and productivity are considered jointly. Companies should adopt tools and processes to generate and evaluate evidence of both human and technical factors in designing production systems. We suggest that hybrid systems with parallel elements and team-based work may provide new opportunities for innovation. Follow-up monitoring is necessary to track system stabilisation and aid the ongoing joint optimisation of ergonomics and productivity in this manufacturing system.

ACKNOWLEDGEMENTS

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CASE STUDY:

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Arbetslivsinstitutet WEST National Institute for Working Life

VOLVO Powertrain – Skövde Plant

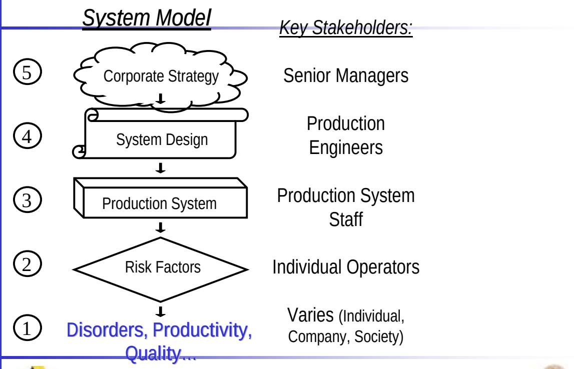
D12 Final Assembly

- Production System re-design
- Good-bye DOCKS…
  …Hello LINE!
- new AGVs
- New work organization

A RESEARCH OPPORTUNITY!

OLD	NEW
’DOCK’ Station	’LINE’ System

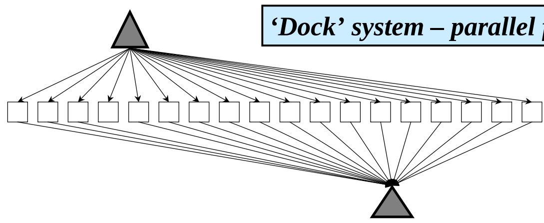
‘Causal Cascade’



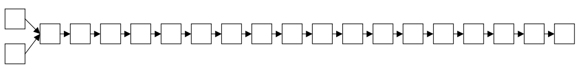
Methods & Triangulation

- Qualitative Assessments – informal dialogue
- Questionnaires (psychosocial, pain, psychophysical, work organisation)
- Document Analysis (Economic, production, quality, strategy)
- Video Recordings
- Direct Posture Measurement (Lund loggers)
- Flow Simulation (Automod)
- Biomechanical Modelling (Watbak)
- Economic Modelling (M. Oxenburgh)

‘Dock’ system – parallel flow



Line system – serial flow

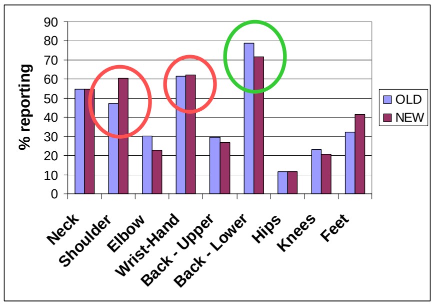


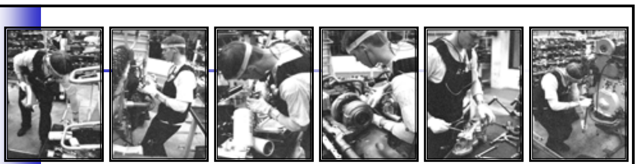
Document Analysis

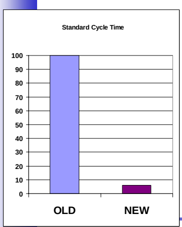
"leaving the concept of the traditional line means that the system losses are reduced since the time dependence between fitters/operators is reduced" and *"parallel flows reduce the need of buffers and reduce balance losses."*

- Volvo Corporate Standard

Pain Reporting







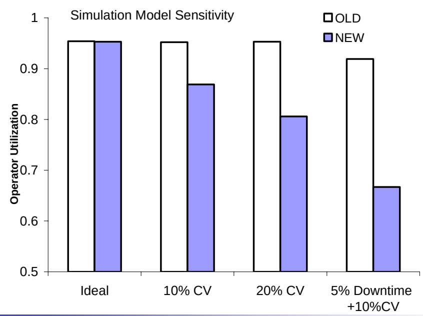
Cycle Time Down to 6%

Knowledge inside the company…

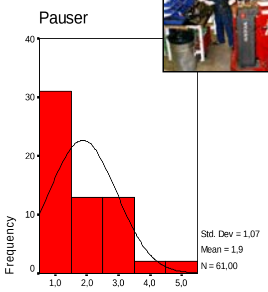
"serial flows with short cycle times generate waiting times that are not experienced as pauses but as disturbances in the work rhythm. This also generates accelerated work with poor ergonomics as a consequence."

- Volvo Corporate Standard

FLOW SIMULATION MODEL – Sensitivity to operator variance & disturbance

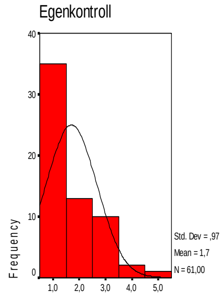


Fewer Pauses & Reduced control over work-pace



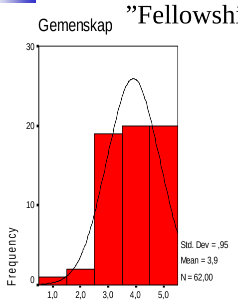
-LESS—SAME—MORE-

Line Flow linked to Decreased Control/Autonomy



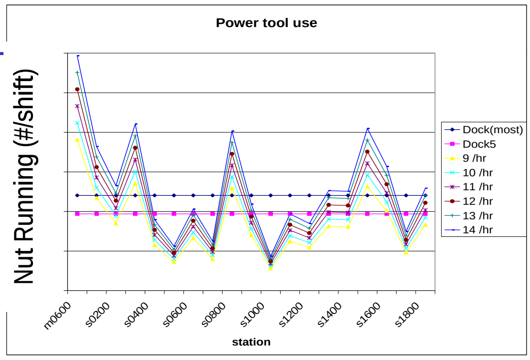
-LESS—SAME—MORE-

Layout & Teamwork Increased Social Support



”Fellowship”

-LESS—SAME—MORE-



Conclusions

- Layout controls exposure amplitude, flow strategy controls exposure pattern
- Serial flow associated with:
  - Increased repetitiveness (less variability)
  - Increased Output
  - Decreased efficiency (System losses)
  - Decreased control & perceived pauses
- Layout and Work Organisation increased co-worker support

Recommendations

- Both Systems were suboptimal - Hybrid systems using team-work and parallel flow elements have good innovation potential

Ergonomics

Productivity

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

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