Production system design elements influencing productivity and ergonomics

A case study of parallel and serial flow strategies

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Abstract

Purpose – The purpose of this paper is to investigate a strategic change from parallel cell-based assembly (old) to serial-line assembly (new) in a Swedish company with special reference to how production system design elements affect both productivity and ergonomics.

Design/methodology/approach – Multiple methods, including records and video analysis, questionnaires, interviews, biomechanical modelling, and flow simulation were applied.

Findings – The new system, unlike the old, showed the emergence of system and balance losses as well as vulnerability to disturbances and difficulty handling all product variants. Nevertheless, the new system as realised partially overcame productivity barriers in the operation and management of the old system. The new system had impaired ergonomics due to decreased physical variation and increased repetitiveness with cycle times that were 6 per cent of previous thus increasing repetitiveness, and significantly reducing perceived influence over work. Workstations' uneven exposure to physical tasks such as nut running created a potential problem for workload management.

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The adoption of teamwork in the new system contributed to significantly increased co-worker support – an ergonomic benefit.

Practical implications – Design decisions made early in the development process affect both ergonomics and productivity in the resulting system. While the time pattern of physical loading appeared to be controlled by flow and work organisation elements, the amplitude of loading was determined more by workstation layout. Psychosocial conditions appear to be affected by a combination of system elements including layout, flow, and work organisation elements. Strategic use of parallelisation elements in assembly, perhaps in hybrid forms from configurations observed here, appears to be a viable design option for improved performance by reducing the fragility and ergonomic problems of assembly lines.

Originality/value – The interacting design elements examined here pose potential "levers" of control by which productivity and ergonomics could be jointly optimised for improved total system performance.

Keywords Production planning, Productivity rates, Ergonomics, Cellular manufacturing, Assembly lines, Sweden

Paper type Research paper

Introduction

In 2004, the *International Journal of Operations & Production Management* presented a special issue (*IJOPM*, Vol. 24, No. 8) on "The end of good work" where Volvo's transition from parallelised long cycle work to serial line-based production was discussed for a number of sites. These cases appear now as a trend in Scandinavia to return to line-based production (Jürgens, 1997) after decades of using more sociotechnically-based approaches (Forslin, 1990; Engström *et al.*, 2004). This trend occurs despite evidence that parallel flow systems can be more effective than conventional line systems due to reductions in balancing and systems losses (Rosengren, 1981; Ellegård *et al.*, 1992a, b; Engström *et al.*, 1996; Nagamachi, 1996; Medbo, 1999). Interestingly, companies in other countries appear to be developing parallelised cellular manufacturing for just these productivity advantages (Johnson, 2005) as well as its suitability for many-variant, variable volume production scenarios (Medbo, 1999; Sengupta and Jacobs, 2004; Johnson, 2005). Medbo (2003b), has suggested that companies have not fully understood, and thus not fully capitalised on, the benefits of long-cycle parallel assembly approaches.

It is common for those advocating manufacturing strategies to claim, almost as an aside, that their strategy provides better ergonomics (Womack *et al.*, 1990). The operations management literature, however, contains little discussion of ergonomics (Dul, 2003) and the human effects of, for example, line production are left to the "ergonomics" literature to consider (Bao *et al.*, 1996, 1997; Ólafsdóttir and Rafnsson, 1998; Bildt *et al.*, 1999; Melin *et al.*, 1999; Fredriksson *et al.*, 2001). Similarly the human benefits of production strategies are also described in ergonomics journals (Engström *et al.*, 1995; Kadefors *et al.*, 1996) where they are unlikely to influence managerial discussions of, and decisions on, optimal production system design. Work-related illness is an ongoing problem globally and costs about 4 per cent of the world's gross national product with musculoskeletal disorders (MSDs) being the largest single contributor (WHO, 1999). MSDs, the ergonomics focus here, carry substantial direct and indirect costs for companies (Oxenburgh *et al.*, 2004). MSD risk is known to be associated with both physical and psychosocial risk factors in the workplace (Bernard, 1997; Kerr *et al.*, 2001; Buckle and Deveraux, 2002) some of which are also linked to product quality deficits (Eklund, 1995; Axelsson, 2000; Drury, 2000; Lin *et al.*, 2001). Capitalising on the potential benefits of good ergonomics in production systems may lie with system designers who are often ill-informed of the ergonomics consequences of their design decisions (Perrow, 1983; Neumann, 2004).

In previous work, it has been demonstrated how strategic elements, chosen early in the production system design phase, have consequences for both productivity and ergonomics in the resulting system (Neumann *et al.*, 2002). This example notwithstanding, the sources of MSD risk factors in terms of specific production system design elements and operation practices remain poorly understood. In this paper, we use a case of manufacturing strategy change, from parallel-assembly to serial line-assembly work, to further probe these relations. In so doing, we follow Kuipers *et al.*' (2004) "beyond the lean-sociotechnical systems debate" in favour of a more nuanced examination of the design elements that appear to pose potential levers of control for designing production environments that are both efficient and sustainable (Docherty *et al.*, 2002). The aim of this paper is to identify specific production system design elements and their consequences for both productivity and ergonomics in a case of production strategy change.

Production systems under study

This case, in an engine manufacturing system at Volvo Powertrain in Skövde Sweden, examines assembly of the same product in both parallel-cell (old) and serial-line (new) production approaches (both shown in Figure 1). In this paper, we focus on the final assembly stage in which the production strategy was changed. The two systems are described here.

The old system originally used 18 parallel workstation "cells" operating in three shifts, at which a single operator worked alone to assemble an entire motor. When we conducted our measurements, six of the parallel stations had been converted to a "mini-line" used to train new operators on the assembly sequence. The system was designed for a completion rate of 6.2 motors per cell and shift based on 115 per cent

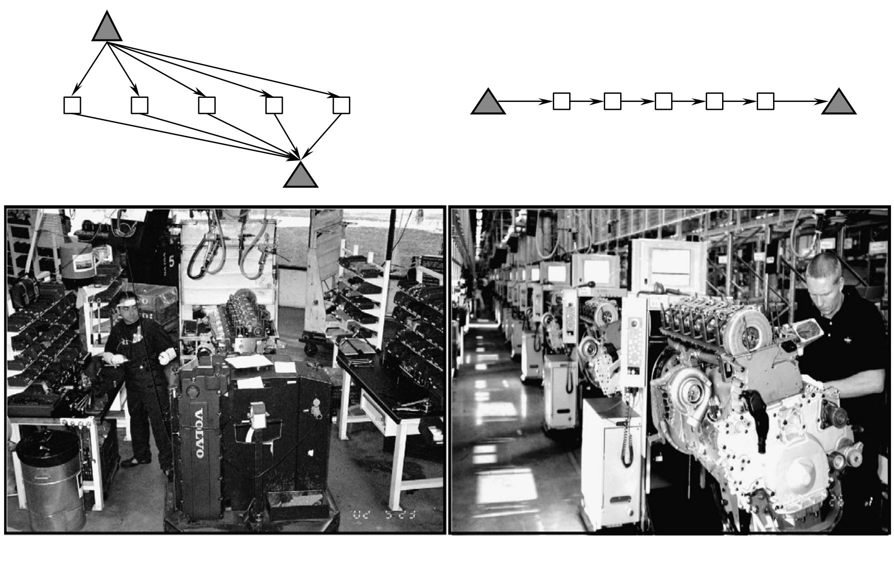


Figure 1.
Flow schematics and workstation pictures for the old cell-based, parallel flow assembly system (left) and the new serial-flow line system (right). Schematics are abridged to illustrate flow principle with five stations (squares) between two buffers (triangles)

pace on a predetermined motion time system (PMTS). Managers believed that not all operators were capable of this pace. At the time of measurement, cell operators had a daily quota of 5.5 motors and could stop working (but not leave the plant) once the quota was reached. Hand-steered carts allowed transport and lift-tilt positioning of motors. Parts were supplied to the workstation using a "kit". Order picking for each kit was a separate sub-system. When each engine was completed the operator would manually guide the finished motor to the quality control area and select, (often the easiest) from amongst available variants, a new motor and kit from the "in-buffer".

The new system replaced the parallel final assembly with a serial flow of 18 stations, for all product variants, designed at an equivalent PMTS rate of 13.9 motors per hour. Automated guided vehicles (AGVs) transported motors through the system thus eliminating short walks between assembly cycles. Parts were supplied directly to the line in large crates about 2 m from the line. The AGV included a computer monitor that provided operators with part numbers and assembly sequence information for each particular variant and specified torque requirements during assembly. While each workstation required a single operator, operators were grouped into "teams" of 5-6 and rotated between stations in their team's area at each break. Teams themselves would rotate amongst areas periodically. Team leaders or "runners" were used to help smooth flow disturbances.

Methodology

The Time Point of Measurement in dynamic systems is an important issue. The old system had been in operation for almost ten years before measurement and was running under "normal" conditions at the time of evaluation. The new system was built in the summer of 2002 and had been scheduled to reach full production within three days. This was not achieved and follow-up measures were delayed, by agreement of the joint researcher-company steering group, until six months after start-up to reach more realistic performance. Production data from matching months of March and April were used for both systems to control for known seasonal variations in production.

The assessment strategy included both qualitative and quantitative data intended to provide a rich web of information to illuminate the design issues related to flow, layout, material supply, and work organisation elements for matching amounts of assembly work.

Qualitative methods included interviews, discussions and meetings with company stakeholders in order to understand each system's structure, work organisation, and operational characteristics (reported in part above). Documents such as corporate standards and project directives were also examined. All project findings and articles, including this paper, were reviewed by and discussed with company personnel to ensure their accuracy, to enhance our interpretation, and to maintain confidentiality of sensitive company information.

Records/performance data analysis at the system level was evaluated quantitatively using data from the company's own information systems and records. Key indicators included production volume, direct and indirect labour costs, maintenance costs, capital costs, sickness absence (SA) rates, and quality deficits. Most of this data was only available at the level of the entire department, part of which had no flow strategy change.

Video analysis was used to quantify the amount of operator time utilised in different activities, an indicator with both productivity and ergonomic implications (Engström and Medbo, 1997) for 20 cycles and 11 operators in the old system and for 195 cycles across 18 stations with seven operators (of the original 11 studied) in the new system. Direct work, sometimes called value adding work (Liker, 2004), included any assembly work and acquisition of components or tools that could be completed without the operators having to move from their assembly position. Indirect work included getting components, materials and tools when this required moving away from the product. Other work included activities such as paper or computer record keeping, quality control work, and motor transportation. Waiting was caused by disturbances such as system or balance losses. In order to check the time costs related to kitting (order picking) in the old system, 17 cycles from seven operators of this part of the material supply system were also analysed.

Flow simulation modelling was conducted as an illustration of the principle, that operator variability causes system losses in lines (Wild, 1975; Engström *et al.*, 1996; Johnson, 2005), which supports the empirical observations from this case. Station utilisation rates (an efficiency indicator) were examined for coefficients of variation (CV) of 0, 10, and 20 per cent from the mean cycle time performance as well as for a condition with equipment downtime (5 per cent downtime at 10 per cent CV). Since, many sources of variability were ignored in this illustration of principle, statistical analysis was not attempted.

Biomechanical modelling (WATBAK, University of Waterloo, Canada) was used to quantify operators' exposure to peak spinal loads. Worst-case scenarios were identified and analysed in both systems. Analysis of video was also used to determine number of repetitions of activities, such as nut running, which imply biomechanical loading and vibration exposure.

Questionnaires were distributed to all available operators in both old and new systems, with a response rate of 82 and 93 per cent, respectively. The sample of operators with experience in both systems included 49 males and five females with an average age of 30 years (range 21-44 years) with 4.5 years (2-23 years) employment with the company. Question instruments included perceived physical workload assessed using Borg's RP-10 scale (Borg, 1990), tested with paired *t*-tests. Pain and discomfort symptoms were assessed using a modified version of the Nordic questionnaire (Kuorinka *et al.*, 1987) and tested with the McNemra non-parametric test for paired samples. Psychosocial factors, known risk factors for MSD, were measured using existing questionnaire instruments (Karasek, 1979; Karasek and Theorell, 1990; Rubenowitz, 1997), and tested with paired *t*-tests. Additional questions regarding operators' perceptions of the system change were also included and tested with one-sample *t*-tests.

Results

We present here the results of the old and new system comparison for each evaluation method providing an overview of system performance. The observed design change included modifications to product flow (from parallel to serial), material supply (from kit to line supply) and workstation layout, implementation of new carriers (AGVs), and changes to the work organisation. A summary of our findings, related to each design element, is presented in Table I which is subsequently discussed in detail.

Design element change	Advantages	Disadvantages
Parallel to serial flow	Facilitated change in work organisation	Fragile with system and balance losses
	Production disturbances may provide physiological rest	Production disturbances not perceived as pauses
		Reduced job control
Cycle time reduction	Easier to learn 1 cycle	Reduced physical variey (increased repetitiveness)
	Easier to tell if work pace matches system	
Changed system and workstation layouts	Increased opportunity for interaction (improved co-worker support)	Difficult to add new components (space limitations)
	Not all stations handle heavy parts (e.g. reduced spinal load)	Lift assists cannot reach all part variants
		Space shortage results in awkward reach to small parts
Kitting to line picking	Order picking eliminated (positions eliminated)	Operators must walk more to get parts
	Lift assists available for heaviest parts	Lifting parts from large crates causes high loading
Manual to AGVs	On screen checklists and logging	High capital and maintenance costs
	Adjustments (if used) can reduce physical load-counts for both carrier systems	Contributes to reduced job control
	No manual cart steering work	Reduced physical variation
		AGVs interacted with layout to raise height of tools
Work organisation (solo to team-work + eliminate quota)	Operators remain "on-line" for full shift	"Runners" need to assist with line flow (positions added)
	Team work fosters co-worker support	Work pace steered by system – reduced job control
	Eliminate incentive to rush	Reduced work content

Notes: The dotted line between some elements indicates the tighter coupling of these particular elements. These elements pose potential "levers of control" by which ergonomics and productivity are determined by designers simultaneously

Table I. A summary results presenting advantages and disadvantages, in terms of both ergonomics and productivity, observed with key design elements in this case

The personnel allocation within the systems is presented in Table II. It shows the elimination of the kit-picking job, the addition of variant-specific assembly and line-support positions, and a net increase of one operator in the new system. Staffing levels showed some day-to-day variability.

Staffing	Old	New
Total operators	46	47
Picking	6	0
Cells/line	19	26
USA motor line	0	4
Other (number/shift)	21	17

Table II. Staffing levels (usual number of operators per shift) in the new and old system

Reasons for the change from old to new were summarised in the project directive (VPT, 2001):

> 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.

Senior managers emphasised the need to increase production volume as having played a key role in the decision to change production strategy. Generally the old parallel system as realised was perceived to be inefficient, difficult to manage, provided poor control and support to maintain operators' working pace, and had not resulted in particularly good ergonomics as indicated by sickness and absence records. The line system was seen to have more possibility to develop component-specific lift assists for improved ergonomics.

In apparent contradiction to the decision to move to a line, the corporation's own standard on work organisation stated (Backman, 2003, p. 2):

> 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 predicted waiting times were indeed observed in the new system in both the video analysis results and the flow simulation results (see below). The corporate standard also discussed the benefits of alternatives to line production (Backman, 2003, p. 3):

> 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 for buffers and reduce balance losses.

System characteristics. Production volume, a primary change objective, increased by 12 per cent in the new system. Cycle times were 6 per cent of those in the old system moving from over 1.2 hours to under five minutes. Extra resources were required to maintain quality levels during the run-in period – a common feature of system change. We were not able to obtain comparable quality data for the two systems. Training time was reported as improved in the new system since it took about a day to learn each station. The time taken to learn all assembly tasks in the new system, required for team rotation between areas, remained roughly the same as the old at about one month.

Economic performance is presented in Table III. Investment in the AGV system increased capital costs. The start-up of this high-tech system was reported to be responsible for the increases in maintenance and "other" costs – which combine to over 15 per cent of total costs in the new system (Table III). Labour costs per motor, adjusted for annual increases, showed a 3 per cent increase in this comparison.

Video analysis results are shown graphically in Figure 2 where total product assembly times are normalised to the old system (at 100 per cent). If the old order picking (kitting) activities, part of the material supply sub-system, were also included in the analysis then the total operator time per motor in the old (+ kitting) system increased to 124 per cent (of old shown), still slightly lower than the 128 per cent (of old) assembly time in the new system. In the kitting system of old, 40 per cent of time was spent acquiring components while 60 per cent of time was indirect and other work. The performance of the kitting sub-system itself was not further examined. Cycle time variability was 15 per cent (CV) in the old system. "Spot" checking of 88 cycles on six stations on the new system revealed a within-station cycle-time CV of 13 per cent (range between stations 5-17 per cent) and a CV of 24 per cent if calculated across all cycles and stations together.

Flow simulation results are presented graphically in Figure 3. Results demonstrate the sensitivity of linear flow to system losses caused by variability in

New vs Old	Cost item	Old total (per cent)	New total (per cent)
Percentage of change			
+32	Total assembly costs	100	100
+3[a]	Direct labour costs (/motor)	50	41
+54	Other costs (/motor)	50	59
+21	Indirect labour cost	42.2	38.5
+81	Maintenance costs	3.8	5.2
+206	Capital costs	4.2	9.7
+2,455	Misc. "other"	0.3	5.5

Note: [a]Labour cost difference is adjusted for a 5 per cent increase in labor rate

Table III. Comparison of economic performance results including cost breakdowns for each system (left) and the per cent of difference between the systems (right)

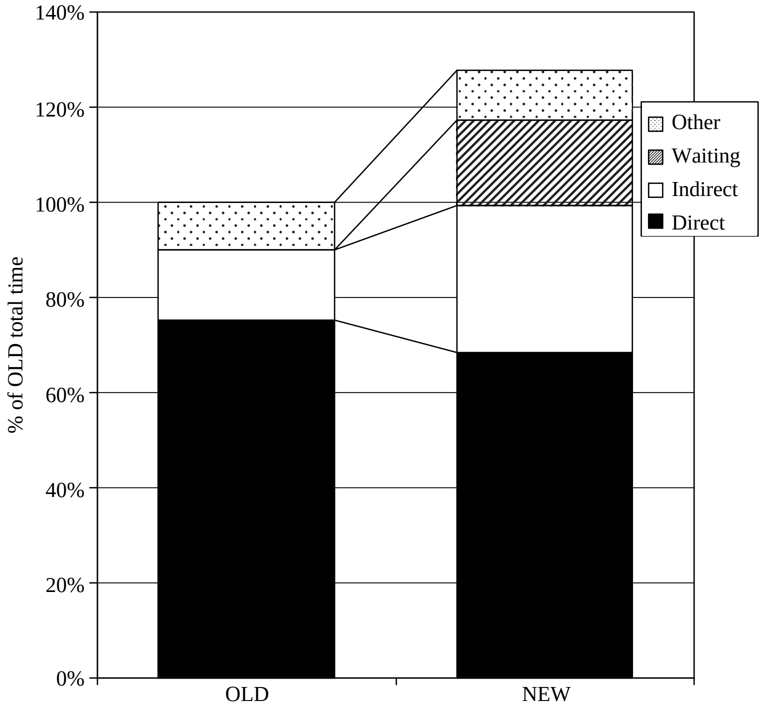


Figure 2. Results of video-based activity analysis for time spent during motor assembly in old and new systems. Old system time does not include waiting after quota has been reached. Note the emergence of waiting time caused mostly by system and balance losses in serial flow and increased indirect work related to the increases in walking to get parts

operators' cycle time – at variability levels similar to those observed in this study. The serial flow system model was also more vulnerable to equipment downtime.

Health records. SA records showed this system to have sick-leave rates consistently double that of the stated company target. Total SA rates, which include general sickness as well as MSDs, declined slightly from 9 to 8.3 per cent in the comparison period. Men's SA decreased from 7 to 5 per cent. Women, who provided less than 20 per cent of total working hours, had SA rates increase from 16 to over 22 per cent. It was not possible to specifically identify MSDs or to distinguish between long and short-term SA from the company records. Pain in the last three months was reported by over 50 per cent of operators in the new system for the neck, shoulder, hand-wrist, and lower back. Pain reporting rates are summarised in Table IV and differences, although substantial (over 25 per cent change) for shoulder, neck and feet, were not statistically significant.

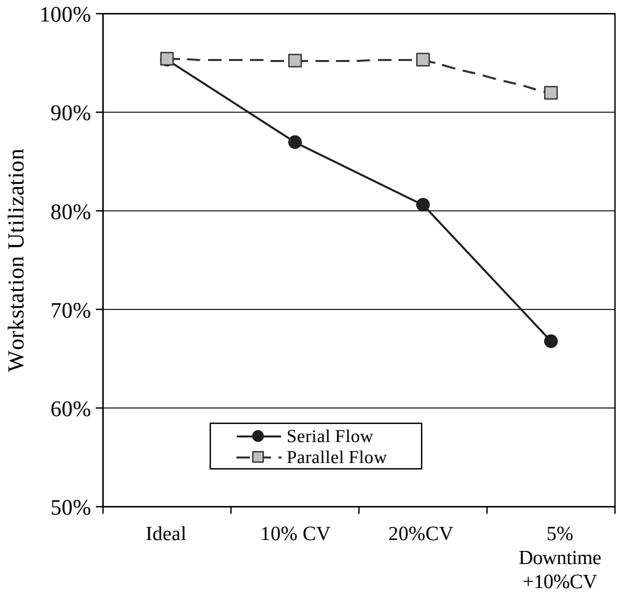


Figure 3.
Flow simulation demonstrates the sensitivity of each flow approach to system losses as a function of cycle time variability (modelled here using a cycle-time CV of 0 , 10 and 20 per cent) and additional disturbances such as downtime. Note that mean cycle time is the same for all models and balance losses are excluded

Table IV.
Percent of operators reporting the experience of pain in previous three months for each body part ($n = 54$ pairs)

Body part	Percentage in old	Operators reporting pain Percentage in new	Percentage of difference
Neck	54.7	54.7	0
Shoulder	47.2	60.4	+28
Elbow	30.2	22.6	−25
Hand-wrist	61.5	62.3	+1
Upper back	29.4	26.9	−9
Lower back	78.8	71.7	−9
Knees	23.1	20.8	−10
Feet	32.1	41.5	+29

Psychosocial indices are summarised in Table V. They indicate significant ($p < 0.05$) reductions in decision latitude and influence over work. Co-worker support and teamwork climate indices, however, showed significant ($p < 0.05$) improvements. When specifically asked to compare the old vs new systems, operators perceived the new system to have fewer pauses, (76 per cent said "fewer" 6 per cent said "more"; $p < 0.001$) and reported a faster working pace, (56 per cent vs 25 per cent "slower"; $p < 0.05$). The new system was reported to offer less autonomy at work (81 per cent vs 4 per cent "more"; $p < 0.001$), less stimulation (67 per cent vs 11 per cent "more"; $p < 0.001$), and lower variation at work (70 per cent vs 17 per cent "greater"; $p < 0.001$). Fellowship, in contrast, was rated better in the new system (61 per cent vs 4 per cent "worse"; $p < 0.001$). Perceived physical exertion rates showed a pattern similar to the pain reporting, ranging from 5.3 to 6.5 ("hard" to "very hard") on the Borg scale, and tended to be lower in the new system but were only significantly reduced for the back ($p < 0.003$).

Biomechanical loading was observed to be unbalanced between stations in the new system. Figure 4 shows the daily total nut-running actions for each station, used as a

Psychosocial index (scale range)	Old	New	Percentage of difference	*P*
Karasek and Theorell (1990)instrument:				
Psychological Demands (1-4)	2.84	2.90	+2	0.47
Decision Latitude (1-4)*	2.31*	2.14*	−7*	0.02*
Co-worker support (1-4)	2.83*	2.95*	+4*	0.03*
Rubenowitz (1997)instrument				
Influence over work (1-5)*	2.76*	2.48*	−10*	0.04*
Management climate (1-5)	3.22	3.30	+2	0.55
Stimulation from work (1-5)	2.58	2.49	−3	0.40
Teamwork climate (1-5)*	3.65*	3.83*	+5*	0.01*
Workload (1-5)	3.06	3.21	+5	0.15

Note: $^{*}p < 0.05$ on paired *t*-test

Table V. Psychosocial index variables from questionnaire instruments ($n = 54$ pairs)

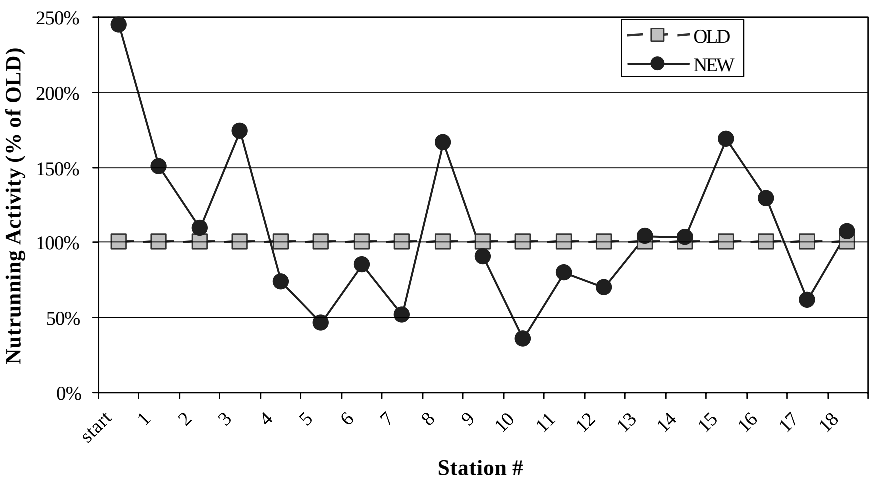


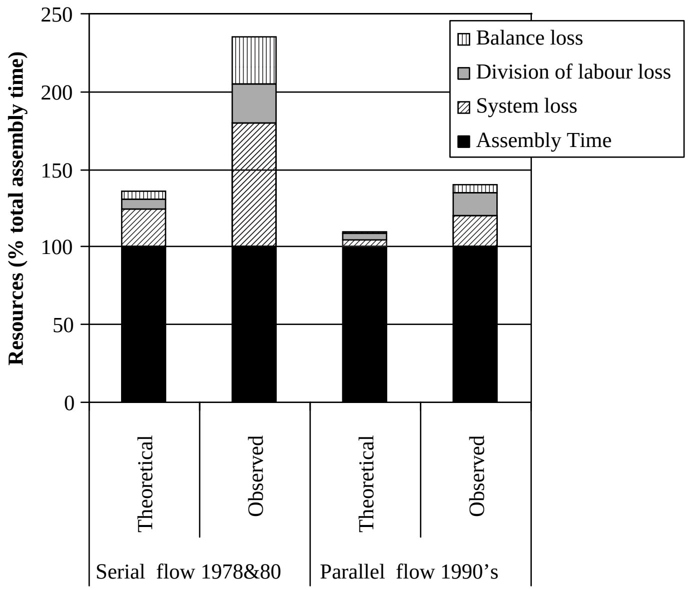
Figure 4. Nut-running, used here as a surrogate for vibration exposure and arm/hand loading, was seen to vary widely across stations in the new system (solid line) and were stable in the old system (dotted line). Data is based on video analysis and production volumes as designed

surrogate for both mechanical and vibration loading to the upper limb. The system-wide (across all stations) peak spinal loading was about the same in both systems with 470N shear loading and L4/L5 compression over 2600N experienced while retrieving parts from close to floor level. Unlike the old system this only occurred on some stations and some cycles in the new system.

Discussion

Instead of a simple confrontation between line and parallel production strategies as being "Bad" or "Good" work in a binary fashion we observe a more complex picture of advantages and disadvantages to both ergonomics and productivity in the systems studied here. While both systems had room for improvement, previous data from automotive assembly operations as shown in Figure 5, suggests that the parallel production has greater inherent potential – potential that is not always realised in practice (Engström and Medbo, 1995). Since, strategic production choices are not made in isolation but consist instead of "a bundle of interconnected measures" (Brassler and Schneider, 2001), it becomes important to consider the chosen design elements in a system more carefully. These elements (Table I), if understood by the designer, pose levers of control by which a system's productivity potential might be realised without compromising performance through poor operator ergonomics. In striving for such an understanding we present a discussion based on the "design elements" observed in this specific case study in terms of both their productivity and ergonomics implications.

Flow strategy. The company appears to have implemented a new technical system to overcome productivity limitations caused by the work organisation, particularly the quota, and material supply sub-system of the old system. Facing an overriding demand to increase output, management opted for a radical change in flow strategy.



Source: (From Engström and Medbo, 1995)

Figure 5.
Losses and resource consumption as calculated under optimal conditions (theoretical) and as observed in the Swedish car production systems having serial flow (observed in the 1970s and 1980s) and parallel flow (observed in the 1990s at Volvo's Udevalla plant). The losses are given in per cent as a fraction of total value added time (no losses in pure assembly). Note that the resource consumption of the parallel flow is almost the same as the theoretically lowest resource consumption of a flow line system

While some production increase was achieved, system, product variant/balance, and other losses inherent in the new system reduced expected output during the re-measurement period. Use of "running" operators, and ongoing work to develop the new team organisation, may reduce the impact of these losses but can carry their own costs. The heightened sensitivity of serial flows to downtime, shown in simulation, also has implications for losses related to slower operators, beginners, elderly workers, or those returning to work after injury. The systems losses observed in the new system here, both in video and simulation analysis, are consistent with previous studies of linear flow systems (Rosengren, 1981; Engström *et al.*, 1996; Johnson, 2005) and in theoretical work (Wild, 1975) (Table I). That these losses are experienced as annoying waiting time, rather than more ergonomically advantageous pauses, was predicted by the company's own standard and observed in the questionnaire. The pattern of stoppages on the line modified the pattern of physical loading experienced by the operator, and also led to an uneven, or unbalanced, distribution of loading across different workstations with a commensurate uneven distribution of MSD risk (Figure 4). The line strategy successfully took control of work-pace away from the operators as observed by decreases in work autonomy indexes and thus an expected increase in risk of disorders. Line systems have long been criticised for reducing operators' control of their work (Ellegård *et al.*, 1992a; Eijnatten *et al.*, 1993) and have been associated with reduced commitment and job depression (Parker, 2003). As early as 1914, Henry Ford was forced to respond to the 370 per cent operator turnover caused by poor working conditions on the production line by raising wages drastically to $5 per day (Raff and Summers, 2003).

Cycle time. The new system had reduced cycle times with increased repetitiveness and potentially increased MSD risk (Bernard, 1997; Buckle and Deveraux, 1999). Biomechanically, the hazard of a given cycle-time will depend on what work is performed inside the cycle – long cycle times can also have monotonous work but represent a greater potential for task variation as well as a psychological aspect of being responsible for the whole product rather than just a few components. The company perceived the reduced cycle time in the new system as an advantage as it reduced training time needed for a new employee to become productive – although total training time to learn the whole system did not change.

Layout and kitting. A discussion of system layout is difficult to separate from the flow and material supply strategies. The shift from kitting to line-stocking appeared as a major strategy change. Bozer and McGinnis (1992) have presented a detailed model by which the drawbacks and benefits of kitting can be quantified. Engström and Medbo (1992) have discussed the importance of establishing a component kit that creates implicit, or embedded, instructions on the assembly sequence supporting efficient assembly and fast learning (Medbo, 2003a). Groups in both Sweden (Medbo, 1999) and Japan (Nagamachi, 1996) have demonstrated kit-based whole product assembly by inexperienced operators at paces well above "standard" PMTS times. The argument against using kits hinges both on the efficiency of the kitting process, and the need for double handling. The old system in this case had potential for improved layout of both the kit and, as indicated by "indirect" work in video analysis, the kitting sub-system. In the new system, large crates of components along the line replaced the kits. As a result, operators walked considerable distances between product and racking to acquire components for each product variant with increased load carrying as an ergonomics consequence. The time cost for such configurations, observed here as "indirect" work, has also been observed previously (Medbo, 2003a; Edberg *et al.*, 2005). Line picking has also been found to give more quality problems compared to kitting systems (Medbo, 1999).

Layout and lift assists (LAs). Since, LAs tend to be component specific there was not room for all possible assists in the old cells. The layout and solitary work organisation of the old system prevented the sharing of LAs and purchasing assists for all stations was seen as too expensive. While lift assist can potentially reduce spinal loads, we add a caution that they can also increase shoulder loading as these muscles are used to stabilise the lift-system in a now longer transfer action (Frazer *et al.*, 1999). Alternative layout of parallel workstations in, for example, a star configuration would permit sharing of equipment between stations.

AGV technology. The adoption of high-tech AGVs eliminated some operator walking for motor transport, increased the system's capital cost, and the cost of buffering in the system. While AGVs can act as a "marker" for high-tech production – a potential marketing benefit (Engström *et al.*, 1998), they are less flexible than hand-steered carts where routing can change spontaneously when needed. Run-in costs of the AGV system were higher than expected and still observable at the six-month comparison point. The AGVs may have added an element of machine pacing, contributing to reduced job control and possibly increasing muscular demands (Arndt, 1987).

We observed that power tools, suspended above the engine, had to be elevated by 10-20 cm in order to avoid them hitting the AGV's monitor during transport. This caused higher reaching consistent with the observed increases in shoulder pain and presents an example of how problematic interactions between design elements can emerge in implementation of new technology. Finally we point out that the AGV system – or an alternative – could also support parallelised production with regards to assembly sequence, learning, working pace, and hand-off of partially completed motors to the next shifts, according to the particular needs of the system (Medbo, 2003b).

Work organisation. In the old system the quota, combined with a "whole engine" rule where operators would only start a new motor if they could finish it within the shift, reduced output considerably from designed levels. This old work organisation also provided an incentive for operators to hurry so as to reach quota sooner and then relax, an effect observed in other studies (Johansson *et al.*, 1993) and possibly a sign of a problem in the control system's support of work pace in the longer cycles.

Teamwork was originally a central element of sociotechnical innovation (Eijnatten *et al.*, 1993) and was intrinsic to the long-cycle parallelised assembly approach developed at the much discussed Volvo Uddevalla site (Ellegård *et al.*, 1992b; Engström *et al.*, 1995). The layout can also interact with work organisation. Workstation configuration in the old system reinforced the solitary work organisation approach. The new system, with its teamwork approach, retained a layout that was essentially oriented to individual work although communication between stations was facilitated. The use of teamwork in the new system is consistent with the positive results in co-worker support, team climate, and fellowship scales, implying a reduction in MSD risk (Karasek and Theorell, 1990; Bongers *et al.*, 1993). Job rotation inside the team was used to enlarge the shorter cycle work activities – an example of how work organisation can modify the physical loading pattern established by the flow strategy. Rotation may moderate the effects of repeated loading from particular stations – provided that it brings the operator to other stations allowing recovery of the used muscle groups. However, rotation may also expose all workers to risk-generating peak loads thus increasing average risk for the whole workforce (Frazer *et al.*, 2003). Furthermore, if rotation does not bring the operator to a station allowing recovery of the (over-) used muscle groups, then it cannot be expected to reduce MSD risk. Moving administrative work to the shop floor and engaging front line employees in development work generally could also provide physical and mental variation while contributing to companies' competitiveness (Gustavsen *et al.*, 1996; Huzzard, 2003).

General discussion. Production systems are dynamic and subject to continual change and improvement: both old and new systems had potential for improved performance. The old system reportedly had higher productivity earlier in its life cycle. It is not possible to say if the long run-in period required for the new system is typical for lines in general or if this differs for parallelised assembly, which permits phasing in new production seamlessly into existing production. The higher competence of old assembly workers, who understood the whole product, should have helped reduce run-in problems. We would expect that, if the new system were to improve efficiency, physical repetition would increase and physiological recovery time decrease leading to overall increases in MSD risk. On the other hand, reports from the company suggest that reduction in disturbances can be beneficial as operators reach a psychological sense of "flow" in their repetitive work.

Rather than a "testing" of design archetypes' superiority, this case sheds light on the productivity and ergonomics consequences of production system design elements (Table I). This analysis demonstrates how ergonomics and performance in the realised system are the product of many interacting decisions in the design process. While the analysis here is consistent with previous case study research (Neumann *et al.*, 2002) we see a need for replication of such analyses in other cases and extension of discussion on how "joint optimisation" might be achieved in practice through, for example, the tactical use of counter-measures to minimise disadvantages of a specific strategy. The observed interaction of system elements, such as between "layout" and "material supply" highlights the need for coordination amongst design groups throughout the development process. Separate consideration of human and technical factors, or sub-systems, is unlikely to lead to system solutions that are globally optimal (Burns and Vicente, 2000; Neumann *et al.*, 2002) and retrofitting to overcome problems from early design decisions can be prohibitively expensive. We observed that the company did not have leading indicators of ergonomics integrated in the management information system – making it difficult for them to judge risk in their systems and provide feedback to design teams. The role of product design in contributing to ergonomics and losses is not explored here but remains a possible area for improvement. Nor is the role of leadership roles, which may be quite different in these systems, explicitly explored. While the productivity advantages of parallel flows have been demonstrated (Wild, 1975; Rosengren, 1981; Engström *et al.*, 1996; Nagamachi, 1996; Jonsson *et al.*, 2004; Johnson, 2005), this case illustrates how these advantages are not always realised in practice and is consistent with the observations in *IJOPM*'s 2004 special issue on the topic (*IJOPM*; Vol. 24, No. 8). The joint optimisation of social and technical elements in production systems remains an operations management challenge. This paper contributes to this effort by examining production system design elements in both ergonomics and productivity terms – an approach that remains uncommon in both OM and ergonomics research fields.

Conclusions

Both old and new systems examined here had advantages and disadvantages. This case suggests that parallelised flow, as a design element, appears to have potential for improved performance in both ergonomics and productivity terms. This potential was not realised in this case and was compromised by other system elements including the work organisation and operational control systems as well as limits in the kitting system. The new system showed increased risk of MSDs due to increased repetitiveness and physical monotony, as well as poorer psychosocial conditions with elements of machine pacing, and high loading levels on particular stations. The emergence of system and balance losses was observed in the new serial system and may have reduced work intensity. The use of team structures in the new system improved co-worker support, which implies a risk reduction. Reported pain levels in both systems remain high. While workstation layout determines operators' physical load amplitudes, the flow strategy and work organisation influence the pattern of physical loading. Psychosocial factors appear to be influenced by a combination of flow strategy, work organisation and, to a lesser extent, layout. This case also illustrates the importance of combining complementary production system elements that will simultaneously determine both the effectiveness as well as the ergonomic conditions in the realised production system.

Recommendations to practitioners

Based on the results of this study and the related literature, we provide the following advice for managers:

- Hybrid system designs, using elements of teamwork and strategically implemented parallel flows, may yield improvements to both ergonomics and productivity.
- Establish indicators and goals for ergonomic performance evaluation that include explicit physical loading and psychosocial criteria.
- Design teams should be held accountable for meeting ergonomic goals jointly with productivity goals. Pay special attention to possible interactions between design elements.
- Interaction between system elements can be critical for reaching expected performance. Work organisation and incentive system elements, for example, should be specifically designed to support the type of layout/flow system chosen.

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