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A Case Study of Serial-Flow Car Disassembly: Ergonomics, Productivity and Potential System Performance

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ABSTRACT

A recent European Union (EU) directive increases demands on car recycling. Thus, present craft-type disassembly systems need reconfiguration in order to be more efficient. A line-based system tested in the Netherlands was investigated regarding system performance and ergonomics. The system had reduced performance compared to the design specifications due to such factors as system losses, operator inexperience, and teamwork deficiencies. Operators' peak low back loads were lower than in Swedish craft-type systems. Direct, value-adding work comprised 30% of the work-day, compared to about 70% in the Swedish manufacturing industry. Alternative system configurations were simulated and discussed using a novel combination of flow and human simulations. For example, a smaller variation in cycle time implied higher output in number of cars per week and larger operator cumulative loading on the low back. In all models the cumulative load was high compared to the loads previously recorded in assembly work. © 2007 Wiley Periodicals, Inc.

1. INTRODUCTION

In the European Union over 15 million passenger cars were sold in 2004 according to European Automobile Manufacturers Association (ACEA, n.d.), up 1.7% from 2003. Around 8 million end-of-life vehicles (ELVs) are disposed of annually in the EU (ACEA, 2004) and this number is expected to increase.

An EU directive (2000/53/EU; European Parliament, 2000) requires that wastes from ELVs must be reduced to 15% of the total car weight by the year 2006 and to 5% by 2015.

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A major part of the present work was performed while the authors were employed at the National Institute for Working Life, Gothenburg, Sweden, now closed down.

The increasing numbers of ELVs and the increased demands on recovery rates create a challenge to obtain a cost effective and environmentally sustainable car recycling process with good working conditions.

Although product designers, manufacturers, car dismantlers, shredding industries, metal processors, and other decision makers should cooperate to obtain effective component and material recovery and recycling (van Schaik & Reuter, 2004), these different stakeholders appear to support different solutions to ELV handling. Although technologies for recycling shredder residue, so called post-shredding technologies, for increased recovery rates are being improved (General Motors, 2004; International Automobile Recycling Congress, 2005; shredding industry stakeholder, pers. comm.), they appear to be insufficient to meet the legislative demands (EGARA, 2003). Effective car dismantling, prior to shredding, for obtaining higher reuse and recycling rates could help to resolve this problem (Lambert & Gupta, 2005; Seliger, Hentschel, & Kriwet, 1997).

Today, Swedish car dismantling companies are all small and medium-sized enterprises with craft-type production (Kazmierczak, Winkel, & Westgaard, 2004). These companies currently focus mainly on the recovery of components for resale and the minimum removal of hazardous materials as required by law today (e.g., oil, gasoline). The work typically contains a large variety of tasks and is characterized by long cycles performed at parallel stations (Kazmierczak, Mathiassen, Forsman, & Winkel, 2005). If the legislative demands are to be met, more components and materials need to be dismantled, often without creating a corresponding added value. Thus, disassembly companies might be persuaded to consider changes in their business concept from “partial” disassembly of components for resale (e.g., engines, lights, whole seats), toward “complete” material disassembly (e.g., all interior plastics, PUR cushion foam, glass, etc.) for sale as “raw” materials for remanufacture.

For material stream production to become profitable, a large volume of ELVs is needed and thus rationalizations are anticipated. One potential solution might be a line system to create increased volumes of materials. The serial-flow line concept has been developed and is used by a Dutch disassembly company (Car Recycling System, n.d.), and it may be transferred to disassembly industries in other countries in the future.

A “rebirth” of serial-flow line assembly in Swedish manufacturing industry has triggered discussion and debate on its potential to improve productivity, product quality, and ergonomics in comparison to parallel assembly systems (Engström, Blomquist, & Holmström, 2004; Jonsson, Medbo, & Engström, 2004). A number of studies suggest that risk factors for musculoskeletal disorders may increase with the adoption of line-based production approaches (e.g., Fredriksson, Bildt, Hägg, & Kilbom, 2001; Neumann, Kihlberg, Medbo, & Mathiassen, 2002; Òlafsdóttir & Rafnsson 1998), while the output of lines can be lower (Jonsson et al., 2004; Neumann et al., 2006; Wild, 1975).

The aim of this investigation is to evaluate the system performance and ergonomics of a *present* implementation of the system. In conducting this evaluation we develop a simulation procedure for *predicting* system performance in terms of productivity and ergonomics.

2. MATERIAL AND METHODS

The serial-flow production system for car disassembly in the Netherlands (CRS) was studied over a 1-week period. The assessment strategy included both qualitative and

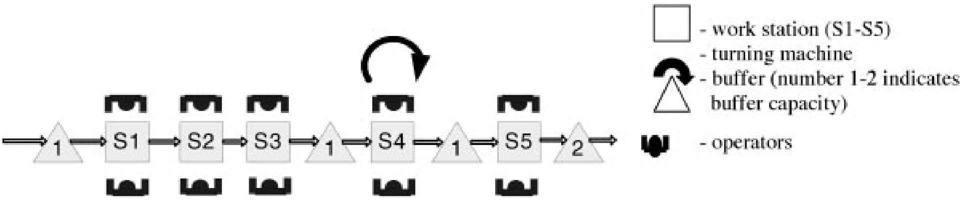


Figure 1 Layout of the investigated serial-flow disassembly system. S4 is shown in Figure 3.

quantitative data. Production data on the system input and output included total number of disassembled cars, car brand, and quantities of disassembled components and materials. This research work was done with the cooperation of a reference group (RG) of key dismantling representatives in Sweden. The RG acted as a "reality check" for validity of the collected data and also facilitated dissemination of the knowledge from researchers to industrial decision makers. The system developer reviewed an earlier draft of this article as a further validity check.

2.1. Case Production System

The investigated case production system was tuned for "complete" car disassembly, meaning disassembly of all components and materials from the car down to a pure metal body. The system used five stations and four buffers (Figure 1). At stations 1–3 (Figure 2) glass, rubber, and interior (foam, plastics) were removed. At station 4 the "turning machine" rotated cars upside down to facilitate engine and gearbox unfastening (Figure 3). At station 5 the engine and gearbox were removed (Figure 4). All the dismantled components

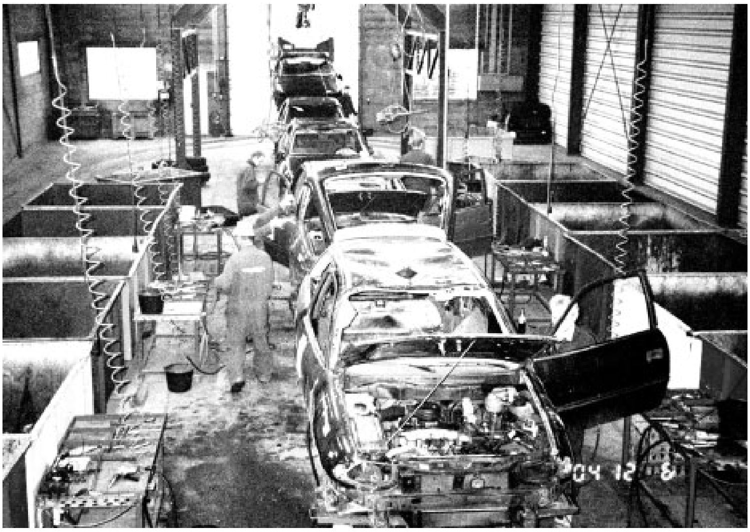


Figure 2 Stations 1–3 of the system where glass, rubber, and interior materials are removed. Containers for disassembled components and material are on each side of the line.

Figure 3 Station 4 of the system (see Figure 1) where cars are turned upside down for engine and gearbox unfastening.

and materials were collected in containers placed along the stations on both sides of the line (see Figure 2).

There were 10 male operators working in pairs at each station. Six operators had long experience in disassembly (4 months–14 years) and four operators were inexperienced (1 week of training) from a manpower company.

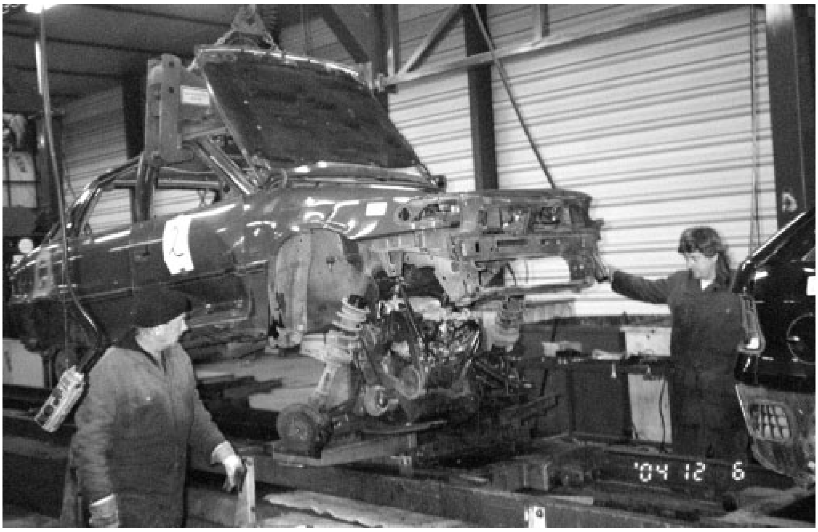


Figure 4 Station 5 of the system where the engine and gearbox are removed following release at station 4 (see Figure 3).

TABLE 1. Four Different Categorizations of Time in the Production System

	Time perspectives			
	Business terms	Engineering (flow simulation)	Engineering (video analysis)	Ergonomics (biomechanical model)[a]
Time category	Value-added	Utilized time	Direct work	Disassembly 1–8
	Non-value-added		Material & tool handling	Carry 1–4
			Transport	Transport
			Casual	Other
		Nonutilized time:	Waiting	Other
		1. Blocking		
		2. Starving		
		(not programmed into model)	Unplanned breaks	Breaks

Note. Notice that "utilized time" from the flow simulation includes both "value-added" and "non-value-added" time in a business perspective.

[a] See Table 4.

2.2. Methods

Multiple methods, each carrying its own perspective on how time is used in the system (see Table 1), were applied in this study.

2.2.1. Qualitative approaches. Document analysis of the business plan and design specifications provided information about the requirements for the system, its technical parameters, and intended output.

Interviews and discussions with the system developer (who does not own the case company) were conducted throughout the data collection phase in order to better understand the current system performance. A semistructured group interview with four experienced disassembly operators was carried out at the end of the data collection week. Table 2 presents the issues covered during the interviews.

2.2.2. Video recordings and activity analysis. Video analysis of activities at work was conducted to determine how working time was used (Engström & Medbo, 1997a). To obtain a wide range of work activities with good video quality, three or four different operators were analyzed on each of the five stations for one to three complete work cycles. The work activities included five categories: (1) direct work: value-adding activities including disassembly; (2) material/tool handling: including handling of car parts, materials,

TABLE 2. Issues Covered During the Interviews with System Developer and Operators

System developer	System operators
• Current system performance • Technology and work organization in the system • Suggestions for optimal performance	• Current system performance (measurement week vs. everyday conditions) • Limitations of dismantlers' work • Suggestions for system improvements • Facilitators to dismantlers' work

TABLE 3. The Five Input Factors and Their Two Levels That Were Used in the Flow Simulation Model I.

	Factor level	
Factor	I (observed)	II (designed)
A. Operator experience	4 at 60% & 6 at 100%	10 at 100%
B. Teamwork	no	yes
C. Cycle time		
Station 1–3	17 min/station transport 30 s, CV 0.2	10 min/station transport 30 s, CV 0.2
Station 4	7 min, transport 6 min, CV 0.02	6 min, transport 4 min, CV 0.02
Station 5	10.5 min, transport 30 s × 2, CV 0.2	9.5 min, transport 30 s × 2, CV 0.2
D. CV of cycle time		
Stations 1–3 and 5	0.4	0.2
Station 4	0.25	0.125
E. Distribution shape	normal	gamma

Note. Cycle CV at Level II is half of that at Level I. Transport times change only at Station 4 (Level II), due to faster equipment available on a newer system. Operators at Station 5 are responsible for transport IN and OUT; thus it is 30 s × 2.

and tools, as well as walking back to station after handling them; (3) casual: work-related communication, cleaning the workplace; (4) unplanned breaks: including nonorganized pauses and disturbances; (5) transport: waiting for the next car during line transport operation.

2.2.3. Flow simulation modeling. Due to the low system performance observed during the measurement week (see Results), flow simulations (Simul8 student version 9, 1993–2002) were used to investigate the potential performance of the system in a number of operative scenarios in terms of cars disassembled per week.

Based on the qualitative evaluation, five factors were chosen as having potential to improve performance without changing the essential five-station layout as observed (Table 3), and each of the factors was modeled at two levels:

- Level I: “low”; partly based on performance of the system during the observation week and on analysis of the video recordings;
- Level II: “high”; designed system based on data from the system developer and business plan for the system.

Model I: The five factors analyzed included the following:

A. *Operator experience*: a reduced work speed of 60% was estimated for inexperienced operators, of which there were 4 (of 10) operators in the measurement week.
B. *Teamwork*: there was assumed to be no teamwork in Level I—operators did not leave their assigned station. In Level II teamwork was simulated such that operators were able to move to the neighboring station once they were done with the current work tasks. Stations 4 and 5 were not included in the *teamwork* as these stations had prohibitively long walking distances.

C. *Cycle time*: operators' cycle times at different stations were modeled at Level I using the observed cycle times (measured from video recordings), and at Level II using the designed times and estimates that were much faster than observed.

D. *Coefficient of variation (CV) of cycle time*: high cycle time variation is known to reduce assembly line performance (Engström, Jonsson, & Medbo, 1996; Johnsson, 2005). Level I had high cycle time variation as estimated from video observations. Level II tested the effect of a lower CV at half (50%) of Level I.

E. *Distribution shape*: the shape of the distribution in operators' performance times was included to test the model's sensitivity to this assumption (Law & Kelton, 2000). This was set arbitrarily to Level I as a normal distribution, and Level II as a gamma distribution.

All design combinations ($2^5 = 32$) were simulated with 10 repetitions for each condition. Factorial analysis (Olausson, 1992) was used to test the effect of all factors on system output measured in number of cars per 40-h week as well as on system output measured in the utilized time (percent) defined as time spent working in all activities over the work shift.

Model II: Model I in simulation showed unexpected performance impairments due to "teamwork" (see Results). To examine factors related to this effect, a second simulation model (Model II) was created. The additional input factors that we tested were

F. *Teamwork type*: Level I: limited teamwork, which corresponded to Level II in the previous simulation (Model I) (see Table 3). Level II was now designed so the operators could move freely to help coworkers at any of the stations 1–3;

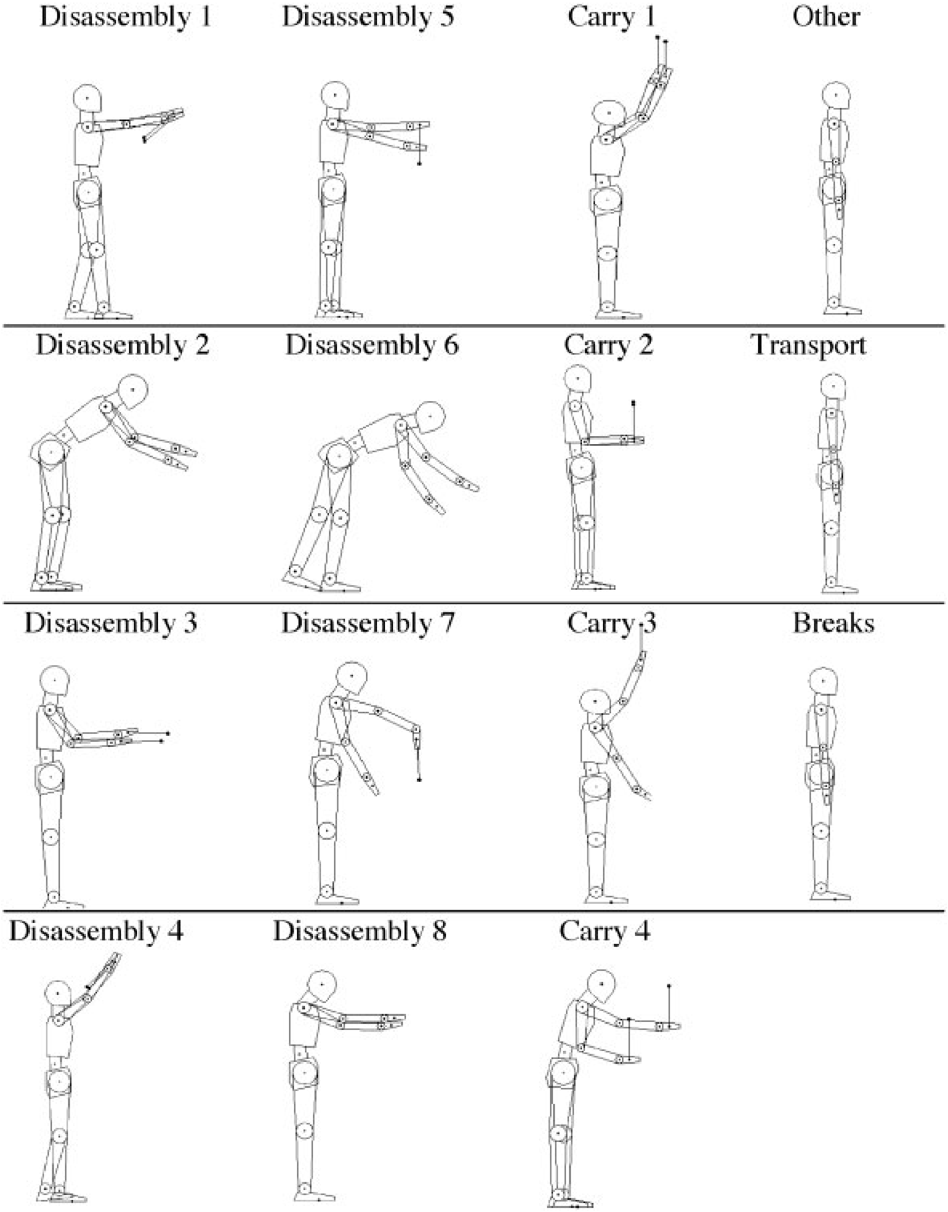
G. *Walk time*: Level I: walking time estimated to 15 s between neighboring stations, Level II: 7.5 s.

The other three factors, operator experience, cycle time, and coefficient of variation of cycle time, were kept the same as in the previous simulation (see Table 3).

2.2.4. Peak load. Operators' exposure to peak spinal loads was quantified using the Watbak biomechanical model (Ergowatch, University of Waterloo, Canada; Neumann, Wells, & Norman, 1999). Situations judged by an experienced researcher to be most critical to the back were selected from the video recordings of each of the nine operators and assessed using the biomechanical model of the lumbar spine to give the spinal compression force, the reaction shear force, and the moment at the L4/L5 joint (Norman et al., 1998) (see Figure 5).

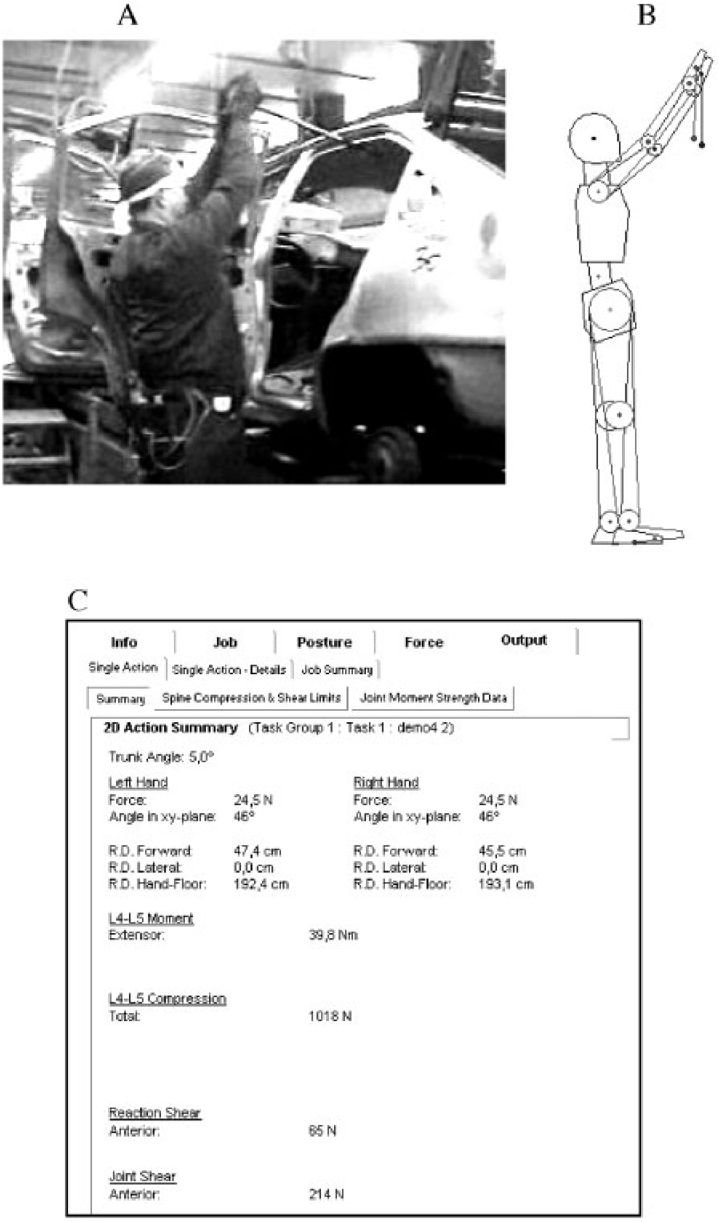
2.2.5. Cumulative load and simulation. To understand how different system configurations (and their consequent demands for increased performance) affect cumulative load on operators, we combined biomechanical analysis with the flow simulation assessment of system outputs (Neumann & Kazmierczak, 2005). This analysis was conducted for a single workstation (station 1), which included a variety of activities. One work cycle of 23.5 min with one representative operator was chosen for this analysis. The first step was to calculate the loading based on a posture for each relevant loading action and the average time spent performing each action, for this operator (summarized in Table 4). Postures were obtained from the recorded videos and then applied to the human manikin using Watbak software (cf. Norman et al., 1998). Figure 5 presents an example of

TABLE 4. An Illustration of All Loading Actions in One Work Cycle for One Operator.



disassembly posture ("disassembly 4") captured from the video and the corresponding manikin illustration with obtained loadings.

Cumulative load for each action was calculated by multiplying each action's load amplitude (e.g., spinal compression in newtons) by its duration. To combine the biomechanical data with flow simulation, we time averaged loading corresponding to "utilized time" (work) and "nonutilized time," which is waiting due to blocking and starving. Finally,



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2D Action Summary  (Task Group 1 : Task 1 : demo4 2)

Trunk Angle: 5,0°

Left Hand                            Right Hand
Force:              24,5 N           Force:              24,5 N
Angle in xy-plane:  46°              Angle in xy-plane:  46°

R.D. Forward:       47,4 cm          R.D. Forward:       45,5 cm
R.D. Lateral:       0,0 cm           R.D. Lateral:       0,0 cm
R.D. Hand-Floor:    192,4 cm         R.D. Hand-Floor:    193,1 cm

L4-L5 Moment
Extensor:                     39,8 Nm


L4-L5 Compression
Total:                        1018 N



Reaction Shear
Anterior:                     65 N

Joint Shear
Anterior:                     214 N
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Figure 5 An example of one disassembly posture obtained from the video (a) and transferred to human manikin (b) with the loading output (c) (the information on the hands is not used in the analyses).

time-weighted average (across actions) was calculated for utilized working time reported by the flow simulations. The biomechanical loading during nonworking time was, in turn, also applied over the shift according to the "waiting time" (nonutilized time, in percent) from the model output.

3. RESULTS

3.1. Interviews and Observations

In the documents describing the system, target production capacity was stated to be 10,000 cars/year (200 cars/week). However, during the data collection week, the output was 82 cars, about 40% of the designed capacity. The average throughput time for a product was 2 h 37min (range 1 h 23 min to 4 h).

Based on the researchers' observations and the interviews, the following factors reduced performance of the investigated system and posed opportunities for improvement:

- The experienced operators first examined a car briefly and then disassembled it, whereas inexperienced operators tried to act more directly by applying force;
- Personnel unfamiliar with "complete" dismantling typically perform only partial dismantling of only some components and materials that are sold at subsidized premiums in the Netherlands (http://www.arn.nl);
- Downsized configuration: 10 operators instead of 12 and five stations utilized instead of six (the original design included the sixth station that was neither observed nor simulated in this study); a loss of 80 labor h/week;
- Lack of personnel due to sickness (reduced number of operators); two operators were absent in total for a whole workday, which implies a loss of 8 labor hours;
- Undeveloped teamwork; operators waiting for each other;
- Lack of production engineering and management on the floor; no steering, no feedback about the performed work; lenient working hours and long breaks (lack of strict start and stop times);
- System and balance losses: "normal" losses from the serial-flow production due to cycle time variability (e.g., Engström et al., 1996; Wild 1975);
- Large proportion of work included material and tool handling, partially due to the workplace design—narrow aisle between the line and material containers and thus frequent opening and shutting cars' door ("material")—and partially due to "human" factors—misplacing materials, leaving tools at other workstations, longer walking than needed;
- Researcher disturbances: 2 h × nine operators per week plus short interruptions, which implies a loss of about 20 labor h/week.

Interviews and discussions with the system developer supported our observations about the system's reduced performance. In his opinion, the most important suggestion to improve system performance was to provide stronger production management. This would facilitate optimizing of work organization, logistics at the line, and supply of incoming products and leaving materials. As the system developer said: "Production management is also about workers: with a real production leadership you can motivate and train people." He did not consider prior education as necessary: "It is training on the job and feedback from the management on right tools and working techniques that are important." The system developer described the change in disassembly approach: "We are not dismantling cars, we are producing material streams," and thus the following conditions must be met: "You need three things—materials' volume, continuity, and purity—in order to succeed."

The group interview with the system operators also supported researchers' observations on the system's reduced performance. The main reasons were claimed to be of both

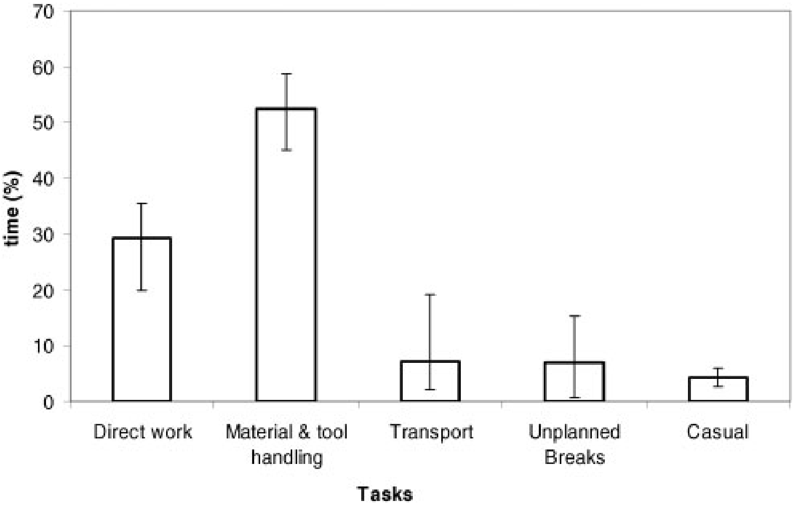

Figure 6 Mean relative duration of all five activity categories during the whole working day, obtained from video activity analysis ($n = 5$). Bars show range across individuals.

a "human" and organizational nature. Similar to the system developer, the operators emphasized lack of management and structured organization on the floor. They mentioned such problems as the inexperienced operators unfamiliar with disassembly work, poor communication, and impaired teamwork between the "core" Dutch operators and the inexperienced "new" ones from another country. The inexperienced operators had only 1 week of training in the system before the study period whereas, as operators reported, "You need 3–4 weeks to learn all the stations." The system has potential for good performance, as mentioned by the interviewees: "If you take 10 experienced people—it works great." The ELV itself was also noted to play a role: "Every car is different." Some models are easy to disassemble; old cars are usually rusted and thus harder to disassemble. The operators named factors that could facilitate their work, which were mostly of a technical nature, such as a faster "turning machine," more new tools (old ones break), and flaps to stand on the line in a safer posture while disassembling in the back end of a car.

3.2. Activity Analysis From Video Recordings

Figure 6 shows duration of activities across all stations in the disassembly work. Direct work comprised about 30% of the total working time. The largest proportion of time was devoted to material and tool handling—over 50%.

3.3. Simulated System

Results of flow simulation (Model I) for output in total number of cars are presented in Table 5. C*ycle time* had the largest effect on the system output, increasing the number of cars per week by almost 58. Unexpectedly, *teamwork* had a negative effect on the output. Factor E (*distribution shape*) had no significant effect on output and was pooled for subsequent analyses.

TABLE 5. Results of the Simulation Testing the Impacts of Five Factors and their interactions in Terms of Cars per Week.

Factor or interaction	Description	Effect (number of cars per week)
C	cycle time	57.6
A	operator experience	38
D	CV of cycle time	16.9
AC	operator experience—cycle time interaction	9.2
B	teamwork	−6.9
AD	operator experience—CV of cycle time interaction	5.1
CD	cycle time—CV of cycle time interaction	4.5
AB	operator experience—teamwork interaction	3
BD	teamwork—CV of cycle time interaction	−2.4
BC	teamwork—cycle time interaction	−1.7
BE	teamwork—distribution shape interaction	1.15
AE	operator experience—distribution shape interaction	−1.14
DE	CV of cycle time—distribution shape interaction	0.8
E	distribution shape	−0.25
CE	cycle time—distribution shape interaction	0.1

Note. Factors E and CE had no significant ($p < .05$; factor analysis) effects on system output.

The four factors A, B, C, and D, all with significant output effects at $p < .001$ (ANOVA), were further analyzed to compare outputs (number of cars/week) from different combinations of factors (Table 6). The highest simulated output (183; case 12) was obtained with 10 experienced operators working two at each station, without teamwork across the stations, working with reduced cycle time variability.

Table 7 presents the results from a factorial analysis on the output in terms of percent utilization rates in Model I. *Coefficient of variation of cycle time* had the largest effect on utilization rates by 9.4%. *Operator experience* had the second largest effect. *Teamwork* decreased operator utilization.

Table 8 presents the results from factorial analysis of the "alternative teamwork" on system output (Model II) and only the effects of the main factors are included. As seen in the table, *teamwork*, in form of boundless work across stations 1–3, (F) had no effect; however *walk time* (G) had a positive effect on output.

3.4. Biomechanical Results and Integration With Flow Simulations

3.4.1. Peak lumbar load parameters. On average, peak compression force for nine operators was 2780 N (range 1618–4213 N), reaction shear force 415 N (240–734 N), and L4-L5 peak moment 154 Nm (89–238 Nm).

3.4.2. Integration of human modeling and flow simulation. The average loading during "utilized" and "nonutilized" time, used to interpret simulation results, is presented in Table 9. Figure 7a shows the cumulative loading (compression force) over the shift across the 16 simulation cases outlined in Table 6. Figure 7b shows the corresponding data for the lumbar moment.

TABLE 6. Comparison of Different Combinations of the Four Significant Factors in Terms of Output: Average Number of Cars and Average (Across All Operators) Utilization Rates

A. Operator experience	B. Teamwork	C. Cycle time	D. CV of cycle time	Simulation case	Average number of cars	SD	Average utilization rate	SD utilization rate	Compression load/car (MN s)
4 at 60% & 6 at 100%	no	I	I	1	68.9	1.97	62.4	11.8	0.31
4 at 60% & 6 at 100%	no	I	II	2	79.7	1.25	71.6	13.4	0.28
4 at 60% & 6 at 100%	no	II	I	3	115.5	2.82	62.1	11	0.18
4 at 60% & 6 at 100%	no	II	II	4	134.7	1.56	71.6	12.3	0.16
4 at 60% & 6 at 100%	yes	I	I	5	64.2	2.67	59.7	13.8	0.32
4 at 60% & 6 at 100%	yes	I	II	6	69.5	3.65	64.8	13.9	0.31
4 at 60% & 6 at 100%	yes	II	I	7	106.8	3.91	59.7	12.9	0.2
4 at 60% & 6 at 100%	yes	II	II	8	118.6	4.37	65.3	13	0.18
10 at 100%	no	I	I	9	91.7	2.12	66.4	2.7	0.25
10 at 100%	no	I	II	10	109.8	1.57	79.4	2.1	0.22
10 at 100%	no	II	I	11	154.1	2.87	66.5	2.8	0.15
10 at 100%	no	II	II	12	183.2	1.87	78.6	2.6	0.13
10 at 100%	yes	I	I	13	90.2	2.84	67.1	6.9	0.25
10 at 100%	yes	I	II	14	105.6	2.91	77.3	6.7	0.22
10 at 100%	yes	II	I	15	151	4.08	67	6.9	0.15
10 at 100%	yes	II	II	16	176.6	3.62	77.5	6.6	0.13

Note. Levels I and II are observed and designed, respectively. Level I describes longer cycle times and larger coefficients of variation (CV).

TABLE 7. Results of the Simulation Testing the Impacts of Factors and Their Interactions on Utilization Rate

Factor or interaction	Description	Effect (utilization rate)
D	CV of cycle time	9.4
A	operator experience	7.8
B	teamwork	−2.5
AB	operator experience—teamwork interaction	2.1
AD	operator experience—CV of cycle time interaction	2.0
BD	teamwork—CV of cycle time interaction	−1.6
DE	CV of cycle time—distribution shape interaction	1.0
E	distribution shape	−0.8
AE	operator experience—distribution shape interaction	−0.6
BE	teamwork—distribution shape interaction	0.5
CE	cycle time—distribution shape interaction	0.2
BC	teamwork—cycle time interaction	0.2
CD	cycle time—CV of cycle time interaction	0.1
C	cycle time	−0.06
America	operator experience—cycle time interaction	−0.04

Note. Factors above the line represent significant contributions ($p < .05$; factor analysis).

4. DISCUSSION

The investigated car recycling system had reduced performance compared with the designed specifications. The simulation model suggested a number of options to improve the performance. Procedures to estimate possible ergonomic implications reveal that cumulative loads on the low back were high compared to the loads in assembly work (Norman et al., 1998).

4.1. Current Performance and Ergonomics

Direct disassembly work comprised only 30% of the total working time. This is about the same level as direct work in "craft-type" disassembly in Sweden (Kazmierczak et al.,

TABLE 8. Results of the Simulation (Model II) Testing the Impacts of the Five Factors in Terms of Cars per Week

Factor or interaction	Description	Effect (number of cars per week)
C	cycle time	51.8
A	operator experience	31.8
D	CV of cycle time	16.8
G	walk time	6.7
F	teamwork type	−0.4

Note. Only main effects are presented. Factors above the line represent significant contributions ($p < .05$; factor analysis).

TABLE 9. Time-Weighted Average Loads on the Lumbar Back During Work and Nonwork Activities

Activity	Moment (Nm)	Compression (N)	Shear (N)
A. Utilized time: work activities (incl. transport)	38.2	1011	78
B. Nonutilized time: nonwork activities (breaks)	14.5	633.8	41.2
Ratio B/A	38%	63%	53%

2005) and is much lower than in assembly work, where direct work accounts for about 70% of the total working time (Bao, Mathiassen, & Winkel, 1996; Engström & Medbo, 2003; Neumann, 2004). Consistent with Kazmierczak et al. (2005), value-adding, direct work, although comprising a small proportion of the day, may represent exposures that

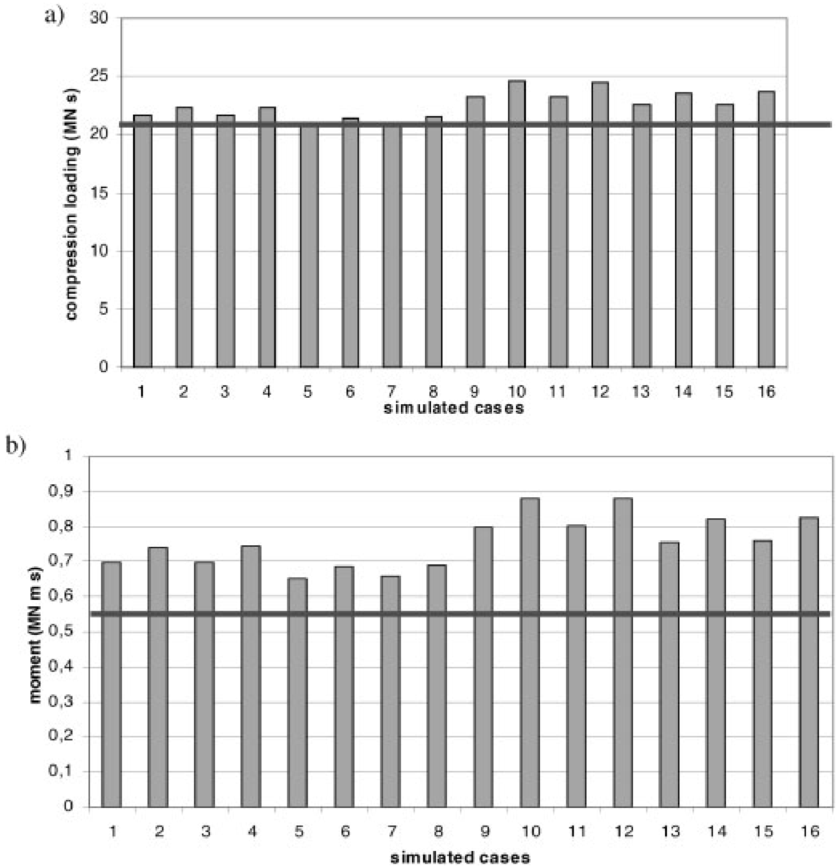

Figure 7 Cumulative (a) compression loading (MN s) and (b) moment (MNm s) for the whole shift for the 16 simulation cases (see Table 6). The horizontal line represents the level of cumulative compression loading (21 MN s) and moment (0.55 MNm s) for the “cases” (operators reporting low back pain) in a large automotive facility (Norman et al., 1998).

are associated with higher risk for musculoskeletal disorders compared to the exposures in non-value-adding work. Thus, increasing proportions of direct work due to rationalizations may increase risk.

Reaching direct work proportions similar to assembly (reducing cycle times and variability) may be difficult due to the complexity and nature of disassembly work, as discussed by Lambert and Gupta (2005). The complexity is influenced by a variety of car models, age, and their conditions, which in turn has effects on variation in disassembly times, frequency of tool changes, and biomechanical loads. The large proportion of work in the observed system included material and tool handling. This was partially due to workplace design that forced workers to open/close the car door repeatedly, or to take time to remove the doors to clear the way for material transport. Developing an optimal technique for door handling/removal seems to be needed, an issue also in assembly systems (Engström & Medbo, 1997b).

Low back *peak loads* of the operators in the serial flow were lower than the corresponding loads from craft-type car dismantling (Kazmierczak et al., 2005). This may be due to the line design with an elevated work level that removed unnecessary bending and handling materials from the floor. Peak loading is an important risk factor for low back pain (Norman et al., 1998). The peak loads in the serial-flow disassembly were lower than those of assembly operators reporting low back pain in a large automotive assembly plant (Norman et al., 1998). They were, however, higher than those of a random population of operators in this assembly plant. The biomechanical loads could be reduced by the physical design/layout of the system as well as adoption of work techniques and use of tools (de Looze et al., 2001; Neumann, 2004). However, the product itself can cause a challenge for fast and easy removal.

4.2. Potential System Performance and Ergonomics Implications

Potential system performance as examined by flow simulations can be used to assess ergonomics implications related to system configurations. Several tools and procedures have been developed during recent years aiming at simultaneous consideration of ergonomics and performance (de Looze, van Rhijn, van Deursen, Tuinzaad, & Reijneveld, 2003; Jarebrant, Mathiassen, Öjmertz, & Winkel, 2004; Laring, Christmansson, Kadefors, & Örtengren, 2005). These studies also emphasize that the key ergonomic stakeholders are those designing, developing, and improving production systems.

Cumulative low back loading over the whole work shift (about 7.5 h) in all 16 simulated cases in the serial-flow disassembly was higher both for compression force and moment than the corresponding loadings for the assembly workers who reported low back pain in a large automotive facility (Norman et al., 1998). This may imply high risk for musculoskeletal disorders. This loading could be reduced by decreasing load amplitude and/or duration.

The system output provides an indication of the number of work cycles performed, which may also be used as an ergonomic indicator. The utilization pattern of the operator obtained from simulations is particularly interesting from an ergonomics perspective as it indicates the "active" periods and the pattern of inactivity, which may allow for rest (Medbo & Neumann, 2004) and for recovery (Kazmierczak et al., 2005). Such stoppages in the system, however, are not always perceived as a pause by operators (Neumann et al., 2006). Furthermore, the movement velocities for head, arm, back, and wrist were substantial and higher while working in the present serial-flow material disassembly than in parallel car parts removal (Forsman et al., 2005).

Based on the results in our study, the most important factors to improve system performance were cycle time and its variation, operator experience, and teamwork.

4.2.1. Cycle time and its variation. Large variation in cycle time reduced output and operator utilization (see Table 6), which in turn reduced cumulative loads. Variation in cycle time leads to losses in underbuffered line systems (Engström et al., 1996; Johnsson, 2005; Wild, 1975). Although, from an efficiency perspective, the goal may be to reduce cycle time to reach the levels similar to assembly work (e.g., cycle time of about 5 min; Neumann et al., 2006), it may be difficult to achieve in the disassembly line, as mentioned above. According to the system developer, a cycle time of 10 min would be optimal. Reducing cycle time without increasing utilization rate would result in the same load and better output (see Table 6). Cycle time may be reduced by increased training as well as improved tools and working techniques. Also, dismantling of the same model in batches may help reduce cycle time and its variation. Standardization of parts in cars designed for disassembly (DFD) might also facilitate efforts to decrease cycle time as seen in assembly (Helander & Furtado, 1992).

4.2.2. Operator experience. The inexperienced personnel tended to act more directly than experienced operators while disassembling a car. Work training has been shown previously to reduce load amplitudes (Parenmark, Engvall, & Malmkvist, 1988).

The simulations suggest that *operator experience* had a large effect on the system output, increasing the number of disassembled cars per week and also increasing the utilization rates, and thus cumulative loading as calculated by the model. Increased training, skills development, and specialization are associated with increases in productivity and better performance of the systems (e.g., Johnsson, 2005; Sengupta & Jacobs, 2004; Woodcock, 1996). However, this may be more difficult to obtain at the disassembly line due to large variation of cars (see previous section). Providing the input batches by car model, as in this case, may also increase learning and experience.

4.2.3. Teamwork. We found unexpected performance impairment from our simulated "teamwork" (Model I). Model II, used to examine this effect, indicated influence of walking time between stations. There was no significant effect of blocking in Model II, although we observed losses due to operators blocking each other at work or as experienced operators gave advice to inexperienced ones. Shorter moving times between stations could be achieved by a change in layout of the system and location of containers and tools.

Teamwork has been a central element of sociotechnical work system design (Eijnatten, Sitter, Gustavsen, Emery, & Beinum, 1993). There is a common belief of the beneficial effects of teamwork in assembly industries (Frieling, Freiboth, Henniges, & Saager, 1997; Murakami, 1997). However, the dilemma of teamwork and flexible operators has been addressed previously by Schultz, McClain, and Thomas, 2003. Van den Beukel and Molleman (2002) argued that the multifunctionality in team-based work could lead to underutilization of skills and overutilization of capacity (task overload).

4.3. Methodological Considerations: Flow Simulations and Human Modeling

In this article we have presented a novel approach to integrating production engineering and ergonomics. The intention for the simulation study was to understand the critical factors affecting system's performance, not to reproduce the existing system in the simulations.

Flow simulation software currently has limited possibilities to simulate human behavior, making simulation of "teamwork" difficult. "Smarter" teamwork in practice may show fewer losses than seen in the virtual analysis here.

Our illustration of a simple procedure for predicting and estimating consequences of system design on ergonomics and productivity allows the application of a biomechanical model that has been risk validated in epidemiological research for both peak and accumulated loading (Norman et al., 1998). The quality of this novel approach of integrating simulation and human modeling may be improved. Flow simulations may be improved by better quality video/time data, which are the main input to the models. There is potential to explore physical workload patterns by incorporating physical loading data from the activities, available from logger data recordings, inside each work cycle into the flow simulation (e.g., Forsman et al., 2005) and to expand the simulation to multiple activities beyond "utilized" and "nonutilized" time categories. Although the biomechanical parameters used here are risk validated, they do not have the kinematic predictive abilities of more advanced digital human models (e.g., Chaffin, 2005). We see utility in the extension of the approach described here—in which human and system models are integrated—to include risk-calibrated digital human models that can predict kinetic loading within the context of the flow simulation, allowing load prediction based on different system configurations.

Different perspectives on how time is used at work (see Table 1) pose a challenge to integrate ergonomics and productivity factors. Operators' utilized time obtained from the flow simulations includes all work activities and thus includes both "value added" and "non-value-added" time. The latter, in *business* terms, is thought of as loss to be minimized. In *engineering* terms, transport of the cars on the line is considered as utilized time, not as break period. However, in *ergonomics* terms, transport activity might offer muscular variety and recovery opportunities by using different muscle groups than during disassembly work.

4.4. Industrial Context

The business success of a car dismantling system depends not only on the production system. As indicated, continuous supply of high volumes of end-of-life vehicles and the market for dismantled material are crucial as well.

The ELV legislation puts pressure both on car manufacturing and dismantling, yet there is lack of support from the manufacturing side for the dismantling industry's developmental efforts. Today, car manufacturing supports the shredding solutions, which may bypass the car dismantling industry. However, according to personal communication with key car manufacturing stakeholders in Sweden, the need for efficient car dismantling will return within the next 5 years. Thus, investigations, like the present one, of issues related to future industrialized car dismantling may appear significant.

5. CONCLUSIONS AND COMMENTS TO PRACTITIONERS

Based on the present study, it may be concluded that due to legislative demands, new system requirements emerge, which in turn have implications for ergonomics.

The serial-flow disassembly system had reduced performance compared to the design specifications. Due to the line's layout, operators' peak lumbar loads are lower than those in the craft-type car disassembly. Cumulative lumbar loads, evaluated in the simulation, were higher than those of assembly operators reporting pain. Value-adding direct work comprises about 30% of the workday as in craft-type disassembly systems. An increased proportion of direct work may be possible to obtain, although achieving the 70% previously documented for assembly work may be difficult due to the complexity and nature of disassembly work.

The combination of flow and biomechanical simulation is a step forward in the assessment of physical load implications of alternative system configurations. This may allow an integrated consideration of productivity and human factors in further development of disassembly systems and could be applied by both engineers and ergonomists in early design phases. The future challenge is to support the development of car disassembly processes required to achieve the legislated environmental goals in a fashion that is sustainable in economic and ergonomic terms.

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REFERENCES

ACEA. (2004). European Automobile Industry Report. Retrieved from http://www.acea.be/.

ACEA. (n.d.) Statistics. Retreived from http://www.acea.be/ACEA/auto_data.html.

Bao, S., Mathiassen, S.E., & Winkel, J. (1996). Ergonomic effects of a management-based rationalization in assembly work—a case study. Applied Ergonomics 27, 89–99.

Car Recycling System. (n.d.). Retrieved from http://www.crs-europe.com/.

Chaffin, D.B. (2005). Improving digital human modeling for proactive ergonomics in design. Ergonomics, 48, 478–491.

De Looze, M.P., Urlings, I.J.M., Vink, P., van Rhijn, J.W., Miedema, M.C., Bronkhorst, R.E., et al. (2001). Towards successful physical stress reducing products: An evaluation of seven cases. Applied Ergonomics, 32, 525–534.

De Looze, M.P., van Rhijn, J.W., van Deursen, J., Tuinzaad, G.H., & Reijneveld, C.N. (2003). A participatory and integrative approach to improve productivity and ergonomics in assembly. Production Planning & Control, 14, 174–181.

EGARA. (2003). Compliance with the ELV Directive (2000/53/EC). EGARA position paper, 2003.11.14. Retrieved from http://www.egaranet.org.

Eijnatten, F.M.V., Sitter, U.D., Gustavsen, B., Emery, F., & Beinum, H.V. (1993). The paradigm that changed the workplace. Stockholm: Arbetslivscentrum.

Engström, T., Blomquist, B., & Holmström, O. (2004). Reconstructing the history of the main Volvo Tuve plant. Some general trends, reasons and consequences for different assembly system designs. International Journal of Operations & Production Management, 24, 820–839.

Engström, T., Jonsson, D., & Medbo, L. (1996). Production model discourse and experiences from the Swedish automotive industry. International Journal of Operations & Production Management, 16, 141–158.

Engström, T., & Medbo, L. (1997a). Empirical analysis and assessment of automotive assembly work: An analysis procedure for work efficiency and ergonomic aspects. In P. Seppälä, T. Luopajärvi, C.-H. Nygård, & M. Mattila (Eds.), International Ergonomics Association, Proceedings of the 13th Triennial Congress—IEA 97, Organizational Design and Management, Tampere, Finland (pp. 171–173).

Engström, T., & Medbo, P. (1997b). Data collection and analysis of manual work using video recording and personal computer techniques. International Journal of Industrial Ergonomics, 19, 291–298.

Engström, T., & Medbo, L. (2003). Primary and secondary effects of using a parallel product flow assembly system designs: The reversing trajectory of assembly system design. In G. Spina et al. (Eds.), One World, One View of OM: The Challenges of Integrating Research and Practice. Proceedings of the First Joint International Conference of EUROMA and POMS, June 16–18, University of Padova, Cernobbio, Italy (vol. 2, pp. 581–590).

European Parliament and the Council on end-of-life vehicles. (2000). Directive on end-of-life vehicles 2000/53/EU.

Forsman, M., Kazmierczak, K., Palmerud, G., Carlzon, C., Neumann, P., & Winkel, J. (2005). Ergonomics and time consumption—A serial-flow system versus traditional craft-type car disassembly. Nordic Ergonomics Society Conference, October 10–12, Oslo, Norway (pp. 245–249).

Fredriksson, K., Bildt, C., Hägg, G., & Kilbom, Å. (2001). The impact on musculoskeletal disorders of changing physical and psychosocial work environment conditions in the automobile industry. International Journal of Industrial Ergonomics, 28, 31–45.

Frieling, E., Freiboth, M., Henniges, D., & Saager, C. (1997). Effects of team work on the working conditions of short cycled track work: A case study from the European automobile industry. International Journal of Industrial Ergonomics, 20, 371–388.

General Motors. (2004). Corporate Responsibility Report. Retrieved from http://www.gm.com/company/gmability/sustainability/reports/05/images/pdf/2004-05full.pdf.

Helander, M.G., & Furtado, D. (1992). Product design for manual assembly. In M. Helander & M. Nagamachi (Eds.), Design for manufacturability. A systems approach to concurrent engineering and ergonomics. London: Taylor & Francis.

International Automobile Recycling Congress. (2005). Conference proceedings, March 9–11, Amsterdam, Netherlands.

Jarebrant, C., Mathiassen, S.E., Öjmertz, B., & Winkel, J. (2004). Ergonomic value stream mapping—An ergonomic complement to a rationalization tool. In K. Bendix Olsen & O.J. Teller (Eds.), Proceedings of the Nordic Ergonomics Society 36th Annual Conference, Kolding, Denmark, August 16–18, 2004 (pp. 31–34).

Johnsson, D.J. (2005). Converting assembly lines to assembly cells at Sheet Metal Products: Insights on performance improvements. International Journal of Production Research, 43, 1483–1509.

Jonsson, D., Medbo, L., & Engström, T. (2004). Some considerations relating to the reintroduction of assembly lines in the Swedish automotive industry. International Journal of Operations & Production Management, 24, 754–772.

Kazmierczak, K., Mathiassen, S.E., Forsman, M., & Winkel, J. (2005). An integrated analysis of ergonomics and time consumption in Swedish "craft-type" car disassembly. Applied Ergonomics, 36, 263–273.

Kazmierczak, K., Winkel, J., & Westgaard, R.H. (2004). Car disassembly and ergonomics in Sweden: Current situation and future perspectives in light of new environmental legislation. International Journal of Production Research, 42, 1305–1324.

Lambert, A.J.D., & Gupta, S.M. (2005). Disassembly modeling for assembly, maintenance, reuse, and recycling. Boca Raton, FL: CRC Press.

Laring, J., Christmansson, M., Kadefors, R., & Örtengren, R. (2005). ErgoSAM: A preproduction risk identification tool. Human Factors and Ergonomics in Manufacturing, 15, 309–325.

Law, A.M., & Kelton, W.D. (2000). Simulation modeling and analysis. Boston: McGraw-Hill.

Medbo, P., & Neumann, W.P. (2004). Samband mellan ergonomi och teknisk prestanda—Exempel på en diskret händelsestyrd simuleringsstudie. Arbetslivsinstitutet & Chalmers (Technical report in Swedish), Gothenburg.

Murakami, T. (1997). Works councils and teamwork in a German car plant. Employee Relations, 21, 26–44.

Neumann, W.P. (2004). Production ergonomics—Identifying and managing risks in the design of high performance work systems. Doctoral dissertation. Lund University, Sweden. Retrieved from http://www.niwl.se.

Neumann, W.P., & Kazmierczak, K. (2005). Integrating flow and human simulation to predict workload in production systems. In Nordic Ergonomics Society, October 10–12, Oslo, Norway (pp. 308–312).

Neumann, W.P., Kihlberg, S., Medbo, P., Mathiassen, S.E., & Winkel, J. (2002). A case study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry. International Journal of Production Research, 40, 4059–4075.

Neumann, W.P., Wells, R.P., & Norman, R.W. (1999). 4D Watbak: Adapting research tools and epidemiological findings to software for easy application by industrial personnel. In Proceedings of International Conference on Computer-Aided Ergonomics and Safety, Barcelona, Spain.

Neumann, W.P., Winkel, J., Medbo, L., Magneberg, R., & Mathiassen, S.E. (2006). Production system design elements influencing productivity and ergonomics in a case study of parallel and serial flow strategies. International Journal of Operations and Production Management, 26, 904–923.

Norman, R., Wells, R., Neumann, P., Frank, J., Shannon, H., Kerr, M., et al. (1998). A comparison of peak vs cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. Clinical Biomechanics, 13, 561–573.

Òlafsdóttir, H., & Rafnsson, V. (1998). Increase in musculoskeletal symptoms of upper limbs among women after introduction of the flow-line in fish-fillet plants. International Journal of Industrial Ergonomics, 21, 69–77.

Olausson, M. (1992). Statistisk försöksplanering—faktorförsök. (in Swedish), Sveriges Verkstadsindustrier. IVF-resultat 92602.

Parenmark, G., Engvall, B., & Malmkvist, A.-K. (1988). Ergonomic on-the-job training of assembly workers: Arm-neck-shoulder complaints drastically reduced amongst beginners. Applied Ergonomics, 19, 143–146.

Schultz, K. L., McClain, J. O., & Thomas, L. J. (2003). Overcoming the dark side of worker flexibility. Journal of Operations Management, 21, 81–92.

Seliger, G., Hentschel, C., & Kriwet, A. (1997). Recycling and disassembly—Legal burden or strategic opportunity. In K. Shimokawa, U. Jurgens, & T. Fujimoto (Eds.), Transforming automobile assembly; Experience in automation and work organization (pp. 380–394). Berlin: Springer.

Sengupta, K., & Jacobs, F.R. (2004). Impact of work teams: A comparison study of assembly cells and assembly line for a variety of operating environments. International Journal of Production Research, 42, 4173–4193.

Van den Beukel, A.L., & Molleman, E. (2002). Too little, too much. Downsides of multifunctionality in team-based work. Personnel Review, 31, 482–494.

Van Schaik, A., & Reuter, M.A. (2004). The time-varying factors influencing the recycling rate of products. Resources, Conservation and Recycling, 40, 301–328.

Wild, R. (1975). On the selection of mass production systems. International Journal of Production Research, 13, 443–461.

Woodcock, D. (1996). How skills development affects manufacturing's competitive capability. Integrated Manufacturing Systems, 7, 38–44.