Industrial development of car disassembly - ergonomics and system performance

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Doctoral thesis

Department of Design Sciences
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Lund University

Arbetslivsinstitutet
WEST
National Institute for Working Life

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“Kiedy wymawiam słowo Przyszłość,
pierwsza sylaba odchodzi już do przeszłości…”

(W. Szymborska, Trzy słowa najdziwniejsze)

Abstract

A new EU directive on used vehicles has recently been introduced. It demands that for every scrapped car, at least 85% by weight must be recycled by the year 2006 and 95% by 2015. The current level is about 80%. The car disassembly industry was chosen as the study object of this thesis. Due to the increased demands on recycling, the disassembly industry may undergo comprehensive rationalizations and expand into a modern mass-type production. Rationalized car disassembly systems may be an alternative to shredding processes. The general aim of this thesis is to study the connections between expected rationalizations and ergonomics based on the case of the car disassembly industry. The studies in this thesis aim to collect empirical data on present production system performance and ergonomics (physical workloads) and possible future development.

Car dismantlers, manufacturers and authority stakeholders described current disassembly systems as ‘craft-type’, i.e. containing a rich variety of tasks and considerable periods of set-up time. The dismantling companies reported good profitability. Expectations about production systems in the future were that the amount of non-profit work per car would increase and more parts and materials than at present will have to be dismantled. These materials lack market value today. For production to stay profitable in spite of increased time in non-value-adding tasks, comprehensive rationalizations were anticipated. Design for Disassembly/Recycling was not fully applied at the manufacturing. However, the need for this strategy was expressed by both dismantlers and manufacturers, as was the need of cooperation between these two groups.

The ‘craft-type’ disassembly workers reported a high physical workload for the arm and for the low back. Pain levels were highest for the low back, with 29.5% of operators reporting pain to occur “often” during the last 12 months. Disassembly workers had higher pain scores than a general male population in Sweden. The psychosocial working conditions, i.e. demands, influence and social support were lower than the corresponding data for the Danish working population.

Technical measurements of physical workloads and time consumption in the current ‘craft-type’ Swedish car disassembly were made. Disassembly work implied high circulatory loads, much walking and high peak low back loads. Value-adding, ‘direct’, work comprised only 30% of the total working time, and implied more awkward postures and higher movement velocities for the head, arm, upper back and wrist than non-value adding tasks, as well as less time in rest.

The physical workloads and operators’ utilization of time were also assessed in a serial-flow ‘industrialized’ production system for car disassembly in the Netherlands. Time proportions of direct work as well as body postures were similar in the serial-flow car disassembly and in the Swedish craft-type. Peak low back load tended to be smaller in the serial-flow system, while the upper limb movement velocities appeared to be higher in this system.

The serial-flow disassembly system showed production deficits due to factors such as system losses, worker inexperience and teamwork deficits. A novel combination of flow and biomechanical simulation was presented in order to assess the physical loading consequences of alternative system configurations. A smaller variation in cycle times implied higher output in number of cars per week and larger operator cumulative loading on the low back. Reducing cycle times, on the other hand, resulted in higher output without significant change in utilization rates and thus unchanged cumulative load. Combined human and flow simulations may allow an integrated consideration of productivity and human factors in the early system development.

Reliability of the video-based tool for work task analysis was assessed. Task analysis was one of the core methods used in this research, and it may be more frequently used in 'rationalization' studies. In general, there was good agreement between observers both on overall task proportions and on the mean duration of sequences in most task categories. The variance between filmed subjects was larger than that between observers in most combinations of parameter and task category. The residual variance, interpreted as mainly being due to within-observer (test-retest) variability, was generally larger than the between-observer variability.

This thesis included transfer of research to practice through close cooperation with stakeholders in car disassembly and assembly, their branch organizations and authority stakeholders. The collaboration also included the serial-flow system developer and practitioners through a Reference Group. The transfer of knowledge from this research to the disassembly stakeholders is an underlying principle of the *proactive* 'intervention'.

Sammanfattning

Ett nytt EU-direktiv om uttjänta fordon har nyligen antagits. Direktivet kräver att från och med 2006 skall 85% av bilens vikt återvinnas och 95% från och med år 2015. Idag återvinns cirka 80%. Bildemonteringsindustrin har valts som studieobjekt i denna avhandling. De höjda återvinningskraven förväntas leda till att bildemonteringsindustrin genomgår omfattande rationaliseringar och övergår till en modern storskalig produktion. Rationaliserade bildemonteringssystem kan vara ett alternativ till fragmentering. Det övergripande syftet med avhandlingen är att studera kopplingar mellan förväntade rationaliseringar och ergonomi, med bildemonteringsindustrin som exempel. Föreliggande arbete redovisar empiri rörande nuvarande produktionssystem och dess prestanda samt ergonomi (belastningar) och framtida utvecklingsmöjligheter.

Representanter från bildemonterings- och tillverkningsindustri samt branschorganisationer beskrev de nuvarande bildemonteringssystemen som "hantverksmässiga", dvs. de innehåller många olika arbetsuppgifter och har långa omställningstider. De demonteringsföretag som deltog i studien rapporterade bra lönsamhet. I framtiden förväntas det icke-lönsamma arbetet per bil öka eftersom demontering av mer delar och material som idag saknar marknadsvärde krävs av den nya lagstiftningen. För att bibehålla lönsamheten i produktionen trots mer tid i icke-värde-skapande uppgifter förväntas stora rationaliseringar. För närvarande har *Design for Disassembly/Recycling* inte tillämpats under tillverkningsfasen, men både demonterare och tillverkare uttryckte behov för strategin, samt samarbete med varandra.

Demonterare i hantverksmässiga systemet rapporterade höga belastningar i armar och ländryggen. Besvären var mest uttalade för ländryggen och 29.5% av operatörerna rapporterade besvär "ofta" under de senaste 12 månaderna. Besvären var mer uttalade hos demonteringsoperatörer än hos en normalpopulation av män i Sverige. De psykosociala arbetsvillkoren, dvs. krav, inflytande och social stöd var lägre än motsvarande data för den danska yrkespopulationen.

Tekniska mätningar gjordes av belastningar och tidsanvändning i den nuvarande hantverksmässiga svenska bildemonteringen. Demonteringsarbetet innebar höga kardiovaskulära belastningar, mycket gående och höga toppbelastningar på ländryggen. Värdeskapande uppgifter (direkt arbete) utgjorde endast 30% av den totala arbetstiden men medförde mer belastande kroppsställningar och högre rörelsehastigheter för huvud, arm, bål och handled samt mindre tid i vila jämfört med de icke-värdeskapande uppgifterna.

Fysiska belastningar och tidsanvändning undersöktes också i ett 'industriellt' seriellt (linjebaserat) produktionssystem för bildemontering i Holland. Tidsanvändningen i de värdeskapande uppgifterna samt kroppsställningar var likartade i det linjebaserade systemet som i den hantverksmässiga svenska bildemonteringen. Toppbelastningarna

tenderade vara mindre i det seriella systemet. Däremot medförde linjesystemet högre rörelsehastigheter för armarna än den hantverksmässiga bildemonteringen.

Det seriella demonteringssystemet hade en del produktionsförluster p.g.a. faktorer som systemförluster, brister i operatörers erfarenhet och lagarbete. För att kunna bedöma konsekvenserna av den alternativa systemdesignen för den fysiska belastningen, presenterades ett nytt sätt att kombinera flödessimulering och biomekanisk simulering. Mindre variation i cykeltider resulterade i högre antal producerade bilar per vecka och högre kumulativ ländryggsbelastning för operatörerna. Å andra sidan resulterade kortare cykeltider i en högre produktivitet utan någon signifikant ändring i användningsgraden och således en oförändrad kumulativ belastning. Kombinerade flöde- och human-simuleringar kan möjliggöra att produktivitet och ergonomi integreras tidigt i systemutvecklingen.

Reliabiliteten hos ett videobaserat verktyg för aktivitetsanalys bedömdes. Aktivitetsanalys var en av huvudmetoderna som användes i detta arbete och det kan användas oftare i framtida studier kring rationalisering. Generellt, var det bra överensstämmelse mellan två observatörer. Variansen mellan filmade personer var större än den mellan observatörerna i de flesta kombinationerna av parameter och aktivitetskategori. En ”övrig” varians, tolkades som inom-observatör variabilitet (test-retest), var generellt större än mellan-observatör variabilitet.

Genom att inkludera representanter från bildemonterings- och tillverkningsindustri, respektive branschorganisationer och berörda myndigheter visar föreliggande avhandling hur forskningsresultat kan överföras till praktik. I samarbetet fanns också utvecklare av det seriella demonteringssystemet och praktiker representerade i en referensgrupp. Kunskapsöverföring från denna forskning till de berörda intressenterna är en grundläggande princip för *proaktiv* intervention.

Acknowledgments

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Karolina Kaźmierczak

Göteborg, November 2005

List of appended papers

The thesis includes the following five papers, referred to by Roman numerals in the text. It also includes results of a Questionnaire study, published only in this thesis.

Paper I:

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, pp. 1305-1324

Paper II:

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, pp. 263-273

Paper III:

Kazmierczak, K., Mathiassen, S. E., Neumann, P., Winkel, J. Observer reliability of industrial task analysis based on video recordings.

Conditionally accepted for publication in International Journal of Industrial Ergonomics

Paper IV:

Forsman, M., Kazmierczak, K., Palmerud, G., Carlzon, C., Neumann, P., Winkel, J. Ergonomics and time consumption – a serial-flow system versus traditional craft-type car disassembly.

Conference paper, Nordic Ergonomics Society, 10-12 October, 2005. Oslo, Norway, pp. 245-249

Paper V:

Kazmierczak, K., Neumann W.P., Winkel, J. A case study of serial-flow car disassembly: ergonomics, productivity and potential system performance.

To be submitted to peer-reviewed journal.

The author's contribution to the appended papers

	Paper I	Paper II	Paper III	Paper IV	Paper V
Planning	2	2	1	2	2
Data collection	3	3	-	2	2
Analysis	3	3	2	2	3
Writing	3	3	3	1	3

3 – responsible

2 – high participation

1 - participation

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1 Introduction

1.1 The scope of the thesis

The point of departure for the studies in this thesis is work-related sources of musculoskeletal disorders.

The car disassembly industry was chosen as a case for the studies. Due to the societal concern for the external environment, a recent European Union (EU) directive is increasing the demands on car recycling. The increased number of end-of-life vehicles poses a huge environmental threat to the societies. The car disassembly industry is crucial, particularly in the reuse of car components and disassembly for the recycling of materials. The stricter demands on recycling are thus expected to influence car dismantlers. Transformations of the industry and changes in production systems are anticipated. The research on rationalization procedures in the manufacturing industry shows that there may be ergonomic implications, leading possibly to an increased occurrence of musculoskeletal disorders.

On this background, the present studies aim to collect empirical data from the car disassembly industry with a focus on production system performance and ergonomics in order to predict the ergonomics consequences of the anticipated rationalizations. In addition, this thesis aims to contribute to development of production systems that are 'sustainable' with respect to efficiency, profits and ergonomics. In this thesis 'ergonomics' concerns the field of musculoskeletal disorders and their sources of physical and psychosocial workloads.

The thesis adds empirical information to the two key issues of the Production Ergonomics research program at the National Institute for Working Life West in Gothenburg, Sweden:

- Connections and interrelations between rationalizations and ergonomics
- Proactive ergonomic interventions; predicting physical workloads in the industrial systems that are under development before musculoskeletal problems emerge.

1.2 Musculoskeletal disorders

Occupational musculoskeletal disorders or work-related musculoskeletal disorders (WMSDs) are a significant problem in industrialized countries (Hagberg et al., 1995; The National Research Council, 2001). According to the European Agency for Safety and Health at Work the economic cost for work-related upper limb disorders corresponds to 0.5% - 2% of the gross national product in some European countries (Buckle and

Devereux, 1999). Musculoskeletal disorders are a substantial contributing factor to long-term sick leaves in Sweden (Lindwall and Skogman, 2001). The results of the 15th Survey on Work-Related Disorders (Swedish Work Environment Authority, 2005) reveal that almost a quarter of all employed persons in Sweden have suffered some form of muscular-related disorder (either physical or mental strain) associated with their work during the past 12 months.

There is, therefore, a great need for effective preventive actions. However, in order to intervene to prevent WMSDs, it is first necessary to understand their causes. Much research has been done on intervening to reduce MSDs in the workplace (Westgaard and Winkel, 1997; Silverstein and Clark, 2004). However this problem does not seem to be declining.

Work-related musculoskeletal disorders as a global or societal problem in terms of costs, represent the top level of a conceptual model (level 4 in Figure 1) which describes structural levels with risk factors leading to musculoskeletal problems at an individual level (level 1).

1.3 Conceptual 'system' models under study

Figure 1 presents a conceptual model describing structural levels in the generation of work-related musculoskeletal disorders. This intervention-oriented model is built on previous work by Westgaard and Winkel (1997), Mathiassen and Winkel (2000) and Winkel and Westgaard (2001) that identified relevant factors for ergonomic intervention at the society, company and individual levels. This model's structure is consistent with other system models' where influential factors evolve from these three levels (e.g. Rasmussen, 1997; Moray, 2000).

This thesis will discuss the case of the car disassembly industry in the context of the *'level'* model (Figure 1). The legislative demands from society for more extensive car recycling (level 4) will influence decisions and actions of company stakeholders in the development and operation of production systems (level 3). Both technology and work organization of production systems will influence work content of disassembly workers (level 2). The technology can be defined as the distribution of work tasks between machines and employees, and the work organization as the distribution of work tasks between the employees (Winkel and Westgaard, 1996). Thus, both technology and organization may reflect critical issues in terms of ergonomics/musculoskeletal risk factors. For instance, an increase in technological level through mechanization may reduce an operator's peak loads and thereby risk for musculoskeletal disorders. On the other hand, this may imply a higher repetitiveness for the individual operator to increase performance. This may, in turn, increase risk for musculoskeletal disorders ("ergonomic pitfall") (level 1).

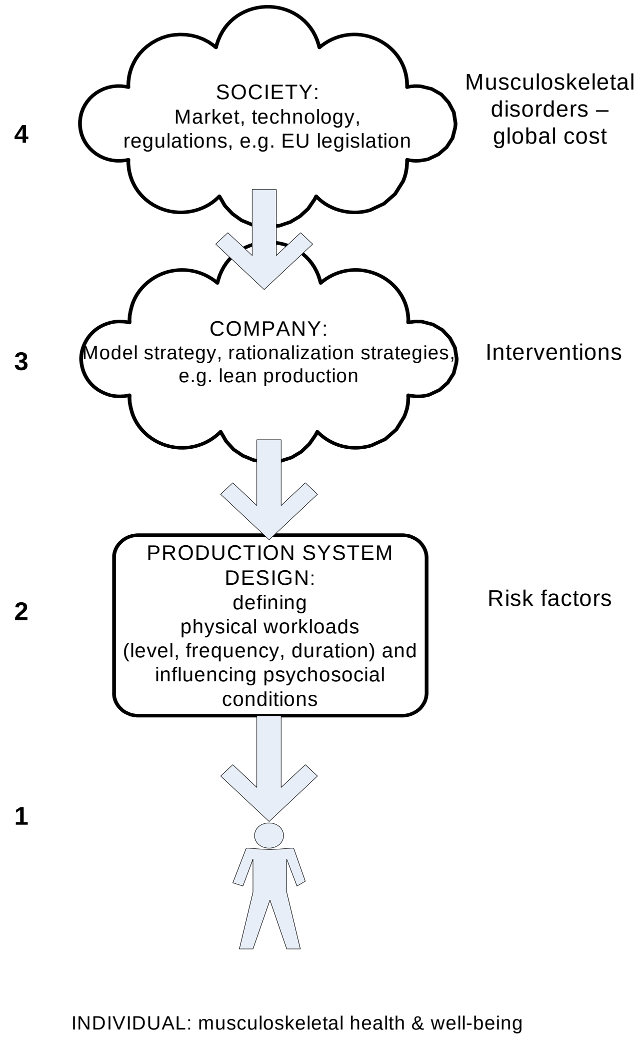

Figure 1. Structural levels influencing the development of work-related musculoskeletal disorders. Company's strategies on production system (level 3) are influenced by factors at the society level (4). The production system (2) defines the work content (the load profile including amplitude and time aspects) with psychosocial conditions of the workers. This in turn influences each individual's well-being (1). (Adapted from Westgaard and Winkel, 1997; Mathiassen and Winkel 2000; Winkel and Westgaard, 2001).

Figure 2 below presents the case of disassembly in a *'life cycle'* model. Raw materials are needed to produce cars. The development process starts with a concept; cars are then designed and developed either at the main manufacturer's site or by cooperating suppliers (1; "forward factories"). A chain of suppliers (1) exists that provides systems, components, materials and tools to the main manufacturer. After being manufactured and delivered to the market by car wholesalers and importers (2) the car reaches the final customer (3a). At this stage, service workshops (3b) assist in the car's correct functioning. At the end of their lives, the cars return as complex multi-component materials that cannot easily be converted into vehicles once more. Both newer crashed cars and old scrap cars are taken by car disassembly "backtrack" companies (4). At the car dismantlers, the end-of-life vehicles enter the process of depollution and removal of hazardous waste fractions (oil, brake fluid, coolants, etc.). Then, end-of-life vehicles are dismantled to obtain basic components with reuse potential (e.g. engine, wheels, rearview mirrors) and to obtain materials to recycle (e.g. plastics, glass, aluminium). After dismantling, the rest of the end-of-life vehicles is then shredded and processed in melting factories (5) (ferric components); toxic materials are processed and disposed of in landfills. Using 'post-shredder' technology some materials can still be separated, but the success rate largely depends on the car dismantling process, that is pre-shredding separation of materials.

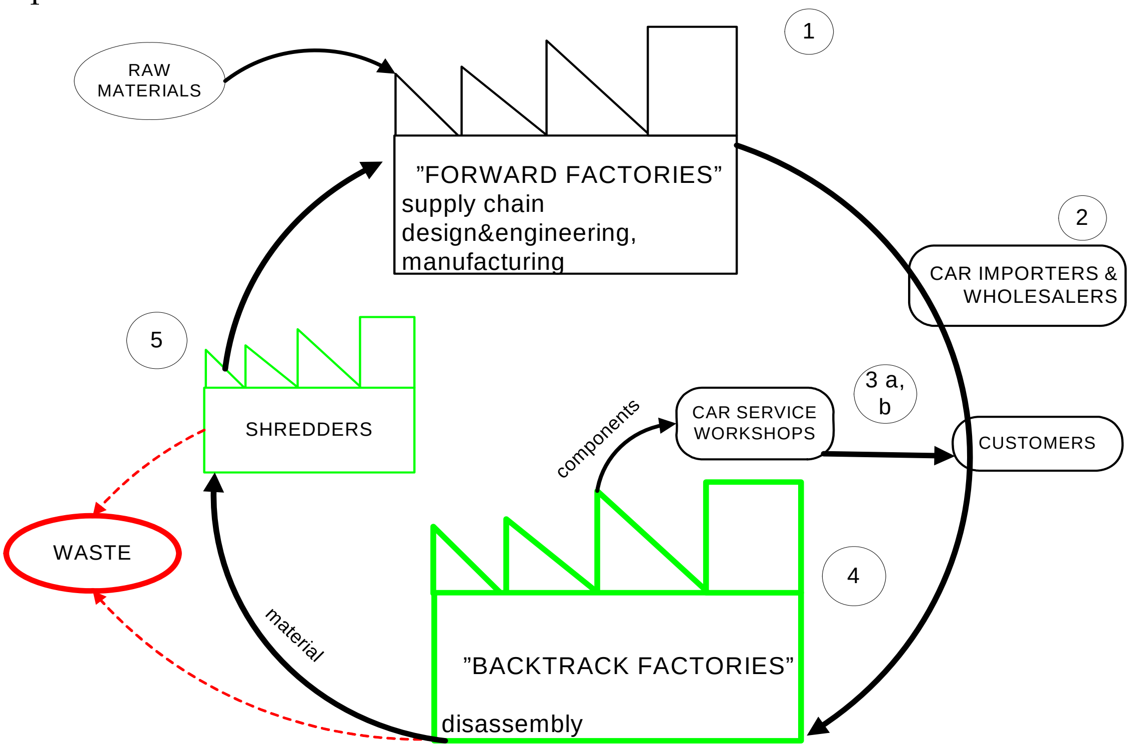

Figure 2. The case of car disassembly in the light of EU legislation increasing the demands on car recycling rates. The system context has a simplified life cycle perspective (raw materials – manufacturing – usage – dismantling – recycling).

Today in the European Union (EU) about 80%[1] of a car's weight is recycled. The recent EU legislation imposed by the society introduces comprehensive demands on car recycling. The legislation requires that, for every scrapped car, at least 85% by weight should be recycled by the year 2006 and 95% by 2015 (Directive 2000/53/EU). This may imply more work time per car, if the prerequisites and conditions remain as they are today, for instance maintaining the same technology level at disassembly companies. It also implies disassembly of larger volumes of parts and materials that today are not commercially attractive, which in turn creates the need to develop customers and markets for these materials. It is anticipated that there will be a comprehensive rationalization of the car disassembly systems so that this industry is able to stay profitable. A transformation of the dismantling industry and changes in production systems have already started. The research challenge in this thesis is to follow this rapid development and predict its implications on physical workloads.

[1] Sweden has adopted the demands of 85% recycling from the year 2002.

The next chapters will focus on the levels in Figure 1 from the bottom up, starting with risk factors for WMSDs that are present in production systems (level 2).

1.4 Risk factors

The World Health Organization has characterized "work-related" diseases as multifactorial to indicate that a number of risk factors (e.g., physical, work organizational, psychosocial, individual and socio-cultural) contribute to causing these diseases (WHO, 1985). The scientific reports, using defined criteria of causality, established positive relationship between work-related physical factors and the development of WMSDs (e.g. Bernard, 1997; Buckle and Devereux, 1999). There has been a tremendous amount of research on the physical and psychosocial risk factors for musculoskeletal disorders, and a number of recent reviews have identified risk factors for the neck (Ariëns et al., 2000), the neck and shoulders/upper limbs (Bongers et al., 1993; Malchaire et al., 2001), and the back (Magnusson and Pope, 1998; Hoogendoorn et al., 1999; Kerr et al., 2001).

Three main dimensions of physical workloads have been suggested to be key aspects of WMSD risk. These are load *amplitude* (level), for example arm elevation or neck flexion, and *repetitiveness* and *duration*, which are time aspects of the loading (Winkel and Mathiassen, 1994; Buckle and Devereux, 2002).

Time aspects of workloads in relation to rationalizations
An important aim of most rationalizations is to make more efficient use of time (Brödner and Forslin, 2002). Rationalizations may influence both levels of loading and their time patterns. An example of changes in the level domain can be higher mechanization, e.g. better tools that may reduce peak loads (de Looze, et al., 2001; Balogh and Ohlsson, 2002). Changes in the time domain may cause the working day to become less 'porous', thereby reducing the possibility to recover physically and mentally. Time aspects of loading, such as frequencies and variations across time, are suspected to be important for the risk of developing musculoskeletal disorders (Winkel and Westgaard, 1992; Kilbom, 1994b; Mathiassen and Christmansson, 2004). Measures describing loading levels are frequently found in the ergonomics literature. Loading measures describing time aspects have also been reported in the literature, although to a lesser extent than level measures (Wells et al., 1997; Norman et al., 1998; Mathiassen and Christmansson, 2004).

In the studies in this thesis we made an attempt for systematic loading measures to document time patterns of physical workloads that may be affected by rationalizations.

Despite the large amount of research on risk factors for work-related musculoskeletal disorders the problem still exists. Ergonomics intervention research has been identified by the scientific community as a matter of priority in reducing the occurrence of WMSDs and different approaches are presented in the next chapter.

1.5 Approaches to ergonomics intervention

Two different approaches to ergonomic intervention studies may be distinguished: retrospective and simultaneous. This thesis advocates a proactive approach to preventing the development of musculoskeletal problems.

The first and most common approach implies a *retrospective* intervention focusing on factors that have already caused musculoskeletal problems in a worker (individual level, see Figure 1) Westgaard and Winkel (1997) in their review of ergonomics intervention studies found that most single-factor physical workload interventions targeted load level, through workplace redesign. This approach may be efficient as a 'quick fix' of single details in the workplace in a running production system at the level of the individual worker (Christmansson, 1997). However, it does not seem to be sufficient to reduce the occurrence of WMSDs to any major extent. It is suggested in the review that this may be due to the fact that determinants of physical workloads and thereby associated risks for WMSDs exist in production system factors that are controlled by production planners rather than by ergonomists (Westgaard and Winkel, 1997).

The second approach may be defined as *simultaneous (integrative) to running production* as presented by the Cooperative for Optimization of industrial production systems regarding Productivity and Ergonomics (COPE) (Winkel et al., 1999; Mathiassen and Winkel, 2000). COPE promoted the view that sustainable ergonomic interventions against WMSDs are best achieved by providing company stakeholders with tools for integrating ergonomics in their on-going system development (levels 3 and 4 in Figure 1). Some examples of studies in which such an approach can be found are Christmansson et al., 2002; Forsman et al., 2002; de Looze et al., 2003; Kihlberg et al., 2005.

This thesis does not include 'classical' intervention studies but the data collected here contribute to a *proactive* (prospective) approach toward preventing the development of musculoskeletal disorders. The studies in this thesis intend to gain an understanding of the situation early in the development of production systems and to estimate possible physical workloads that may emerge from this development. This is an extension of the COPE strategy, namely to integrate ergonomics with engineering while planning production in order to yield solutions that are effective in both aspects.

1.6 Production systems, rationalizations and ergonomics implications

1.6.1 The production system

The term production system has been defined in many ways depending on the application. Wild (1995) defines a production system as an operating system that manufactures a product. This thesis focuses on "reversed" manufacturing systems, that is disassembly systems, which involve organized processes of taking apart a systematically assembled product.

Systems theory defines a system as "a set of interacting units or elements that form an integrated whole intended to perform some function" (Skyttner, 2001). This holistic approach is also discussed in a socio-technical context, which indicates that the system may consist of three elements that have to be considered as a whole: a technical subsystem, a social/personnel subsystem and work system design comprising an organizational structure and processes (Eijnatten et al., 1993). Winkel and Westgaard (1996) divide a system into a technical and organizational subsystem. They propose that, in a production system the allocation of tasks between operators and the sequence that an individual follows should be considered as the organizational level in the rationalization process, and the allocation of functions between operators and machines as the technology level. A production system determines the content of the job and, as Peterson (1997) states, risk factors emerge from the interactions between the individual operator and other elements in the production system (materials, machines) (see level 2 in Figure 1). Operators' physical workload profiles might be influenced primarily by the nature of the work itself (e.g. Allread et al., 2000; Marras et al., 1995). Thus, design of production systems will place several performance demands on the worker. In his thesis, Neumann (2004) discusses the sources of risk in production system design and concludes that the flow strategy and work organization influence the pattern of physical loading.

The next chapter will discuss rationalization strategies and production system designs with implications for ergonomics in the manufacturing industry, with applications to the car disassembly industry.

1.6.2 Rationalizations, production system design and ergonomics implications

Decisions on production system design are made on the basis of the corporate, business strategies. The corporate strategies are usually plans or perspectives to tune the production system to meet market demands in the most competitive way possible (Brassler and Schneider, 2001). An example of such decisions may be a rationalization. According to the Swedish National Encyclopedia rationalization is a term combining actions taken in order to make work more effective (Nationalencyklopedin; http://www.ne.se).

Principles for rationalizations change over time (Björkman, 1996). Adam Smith described the productivity benefits observed from the division of labor (Smith, 1776). Extending this idea, Taylor (1911) created 'scientific management' where the assembly work was divided into short tasks repeated many times by each worker. This approach has come to be referred to as Tayloristic job design. This strategy was first used in line assembly in Ford car factories and formed a foundation for the modern assembly line (Björkman, 1996).

In this thesis, the underlying aim of rationalization is to make work more efficient by increasing value-adding time at work and reducing non-value added time, i.e. losses. This may make a working day less 'porous', that is, there are fewer possibilities for physical and mental recovery.

One goal of rationalization may be to increase productivity by minimizing losses (De Geer, 1978; Westgaard and Winkel, 2002). Prevalent modern strategies for achieving this goal may include lean production, Time-Based Management and Business Process Reengineering. These manufacturing strategies will influence either the manufacturing task itself or choices in the design and operation of the manufacturing system (Rho et al., 2001).

Health consequences of different production strategies are not well understood although there are apparent linkages between these strategies and ergonomics (Björkman, 1996). Björkman suggested that the production strategies of business process reengineering and time-based management might provide better potential for good ergonomics than lean manufacturing. Aronsson (1997) has suggested that the above strategies have the common denominator of downsizing. Carayon and Smith (2000) discuss reengineering and downsizing as possibly resulting in increased workload demands, longer work shifts and job insecurity. Furthermore, Vahtera et al. (1997) found a relationship between downsizing and musculoskeletal injuries.

During the recent decade, most 'forward' factories (assembly plants) have adopted lean production strategies (Womack et al., 1990; Docherty and Huzzard, 2003; Metall report, 2003; Liker, 2004) with the aims to improve productivity, quality and profitability. The effects of lean practices on workers' health have been discussed, e.g. Berggren (1993) describes lean environment as *"… unlimited performance demands, the long working hours and requirements to work overtime on short notice, the recurrent health and safety complaints, the rigorous factory regime that constitutes a new and very strict regime of subordination"*. Lean practices have been associated with intensification of the work pace, leading to excessive job strain, and possibly to an increased occurrence of musculoskeletal disorders (e.g. Landsbergis et al., 1999). Looking more specifically at system design elements, one way of obtaining higher efficiency and reducing wastes might be through the adoption of a line-based system that comprises short-cycle tasks, controls the work pace and may eliminate rest pauses (e.g. Engström et al., 1996; Jürgens, 1997). A number of studies report physical risk increases with the adoption of serial-flow-based production approaches (e.g. Fredriksson et al., 2001; Neumann et al., 2002).

Alternative organizational trials have been made in 'forward' car factories, mainly in Sweden (Ellegård et al., 1991; Kadefors et al., 1996; Westgaard and Winkel, 1997). The so-called Reflective Production System was a radical alternative to the conventional moving assembly lines by returning to stationary production with its work enlargement (inclusion of indirect work activities), long cycle work tasks, worker autonomy and extended competence (Ellegård et al., 1994). Furthermore, improved ergonomics in the application of long-cycle parallelized assembly flow in this system did not sacrifice its productivity (the Uddevalla plant; Kadefors et al., 1996).

The trend that can be observed is the reintroduction of serial-flow assembly lines in the Scandinavian automotive industry (Jürgens, 1997) after decades of more sociotechnically-based approaches (Engström et al., 2004). The rationale behind this is improved man-hour productivity, product quality and ergonomics (Jonsson et al., 2004). However, the empirical validity of these arguments may be doubted (Medbo, 2003; Engström et al., 2004).

Corporate decisions on production concepts and rationalization actions in the manufacturing industry have ergonomic implications, and decisions have been made in current car assembly industry that may have aggravated the occurrence of musculoskeletal disorders.

Applications to disassembly

If the legislative demands on vehicle recycling are to be met, more components and materials need to be dismantled. Effective dismantling, prior to shredding, to obtain higher reuse and recycling rates seems to be needed (Seliger et al., 1997; Lambert and Gupta, 2005). The disassembly companies may be persuaded to consider changes in their business concept from "partial" disassembly of components for resale (e.g. engines, lights, whole seats) towards "complete" material disassembly (e.g. all interior plastics, PUR cushion foam, glass, etc.) for sale as "raw" materials for remanufacturing.

For material stream production to become profitable, rationalizations are anticipated. A serial-flow system may be one solution to create increased volumes of materials. The introduction of a serial-flow system may have ergonomic implications for the operators involved.

Thus, there is a need to understand the relations between production system performance and ergonomics in car disassembly in order to integrate ergonomics into rationalization processes. This in the long term would lead to the development of 'sustainable' production systems, i.e. effective systems with good ergonomics.

2 The aims of the thesis

The general aim of this thesis is to study the connections between rationalizations and ergonomics based on the case of the developing car disassembly industry. The empirical data on present production system performance and physical workloads as well as possible future development are provided by the appended five papers.

The aim of Paper I is to explore the current (year 2001) Swedish car disassembly industry in order to generate hypotheses based on information from key stakeholders on present and future production systems and ergonomics in the car disassembly industry.

The aim of the Questionnaire study is to assess perceived physical workloads, musculoskeletal pain and psychosocial conditions at work.

The aim of Paper II is to follow up and further investigate the hypotheses related to ergonomics and system performance issues from the exploratory study in Paper I. This is done by assessing physical workloads and time consumption in the current 'craft-type' Swedish car disassembly. Specifically, the aims are to: (1) assess physical workloads in present car disassembly systems for future comparison with rationalized systems, with particular emphasis on time aspects and (2) analyze disassembly work in terms of time consumption and loading in value-adding and non-value adding tasks by a loss analysis technique.

The aim of Paper III is to assess the reliability of the video-based tool for work task analysis used in Papers II, IV and V. The tool may be more frequently used in 'rationalization' studies that intend to grasp the changes in time consumption in different work tasks.

The aim of paper IV is to document physical workloads and operators' utilization of time in a Dutch serial-flow 'industrialized' production system for car disassembly in order to compare these data with the corresponding data in the Swedish car disassembly (Paper II).

Paper V investigates the same serial-flow system as in Paper IV with the aim to further evaluate the performance and ergonomics of the *present* implementation of the system. Further, the objective is to illustrate a developed simulation procedure for *predicting* system performance in terms of productivity and ergonomics.

The research in this thesis also aims to communicate relevant parts of the research to practitioners. In Paper I there is a close cooperation with stakeholders in car disassembly and assembly, their branch organizations and authority stakeholders. In Papers IV and V collaboration with the Dutch system developer and a Reference Group representing key dismantling companies in Sweden is established.

3 Methodology

This chapter describes the overall methodological approach of the thesis. Key methodological features of the five appended papers are presented in Table 1 (see page 17).

3.1 Methods Paper I

Explorative methodologies were utilized, including site visits, document searches and semi-structured interviews with representatives of key stakeholders (Miles and Huberman, 1994). The aim was to construct a sample that was information rich enough to understand the case studied (Needleman and Needleman, 1996). Three groups of stakeholders were interviewed: 1) owners of disassembly companies, 2) design engineers and 'environmental representatives' of the Interior & Climate group ('car seat group') of a major car producer in Sweden and 3) representatives of government and independent policy makers, and of branch organizations for the car manufacturing and shredding industries.

The selection of dismantlers was initiated via an Internet search of the Swedish Car Recyclers' Association (http://www.sbrservice.se). From 300 active companies, 47 were contacted and 17 expressed an interest in the study. The first 13 companies that responded were chosen for the interviews. Design engineers, a "recycling representative" and authority stakeholders were chosen on the basis of their job responsibilities and experience.

The site visits included seven car disassembly facilities, a car shredding plant and the design and engineering departments of a car manufacturer. Internet searches supplemented and validated parts of the information given by key informants. Literature and Internet searches identified aims, missions and policies of organizations, regulatory demands, national and international standards of relevance for this study, and companies that had attempted to find solutions to problems.

A one-day workshop on Design for Disassembly/Recycling (DFD/DFR) was organized to investigate key stakeholders' attitudes, viewpoints and ideas regarding DFD/DFR of car seating.

3.2 Questionnaire study

A Questionnaire study was carried out among Swedish car dismantling operators. The questionnaire was sent to 129 operators in 23 disassembly companies, which included all companies from the study in Paper I and Paper II, as well as those represented in the Reference Group (Paper V).

Perceived physical workload was measured using Borg's RP-10 scale (Borg, 1998). *Pain and discomfort* symptoms were assessed using a modified version of the Standard Nordic

Questionnaire (Kuorinka et al., 1987). *Perceived fatigue* at work was assessed with a modified version of the Swedish Occupational Fatigue Inventory (SOFI) (Åhsberg et al., 1997). An instrument evaluating a typical workday with regard to physical and psychosocial aspects included 12 questions with response alternatives from 1 to 5 (see Appendix). The psychosocial work conditions were assessed using a short version of the Copenhagen Psychosocial Questionnaire (COPSOQ), containing the dimensions of *work demands*, *influence* at work with *possibilities for development* and *social support* (leadership, feedback, social relations) (Kristenssen et al., 2002).

3.3 Methods Paper II

The study was conducted at five car disassembly plants in Sweden that participated in the first study (Paper I). A total of ten (two at each company) disassembly workers, with a minimum work experience of one year, participated in the study. The subjects did not, according to our observations, differ in any systematic way from the general population working at the investigated plants with respect to work tasks and personal characteristics. The measurement days were reported by all subjects to be "typical" working days.

Data were collected by means of video recordings of work and direct technical measurements of physical workloads. Video recordings were analyzed (activity analysis system; Engström and Medbo, 1997) with respect to the time used for work activities including direct (e.g. value-adding disassembly) and indirect (e.g. material and tool handling) work. The task groups in disassembly are showed in Figure 3 and Figure 4.

Figure 3. A disassembly worker performing value-adding disassembly work (to the left) and material/tool handling (to the right).

Figure 4. A disassembly worker during casual (indirect) work (to the left) and unplanned breaks (to the right).

The measurements of physical workloads comprised recordings of postures of the head, the upper back and the upper arm by inclinometers (Åkesson et al., 1997) and wrist postures by goniometers (Penny and Giles Biometrics Ltd., Gwent, UK; Hansson et al., 1996). Figure 5 and Figure 6 show a disassembly worker with the applied inclinometers and the goniometer.

Figure 5. To the left - inclinometers to measure head, upper back and arm postures applied on a disassembly worker's forehead, neck and upper arm. Figure 6. To the right - goniometer placed on a disassembly worker's right hand.

Job-related physical workloads were assessed by heart rate measurements (Polar Vantage NV ™, Polar Electro OY, Finland; Bao et al., 1996), number of steps (pedometer; Selin et al., 1994) and low back peak loads by a biomechanical model (Ergowatch, University of Waterloo; Neumann et al., 1999). Physical workloads according to task categories were obtained by synchronizing video and posture recordings (Christmansson et al., 2002; Forsman et al., 2002).

3.4 Methods Paper III

Video recordings of assembly work were used as material in Paper III. The subjects were all included in a larger study on engine assembly. These operators were chosen with the assistance of the production supervisor. This was done in order to represent a range of operators' performance capability in a normal assembly population.

The job was final assembly of truck engines. The video recordings of nine subjects were analyzed using an activity analysis system (see Paper II) in order to differentiate between value-adding and non-value adding work. Each of the nine videos of the different workers (subjects) was analyzed by two independent observers who had an engineering background. The observers assigned all activities to one of four task categories. On the basis of these files, data were obtained for each task category concerning the mean duration of uninterrupted sequences in that category and the relative time proportion of the task category in the job. We estimated variance caused by disagreement between observers, variance due to differences between filmed subjects, and residual "unexplained" variance (an estimate of within-observer variability and possible interactions between subject and observer).

3.5 Methods Paper IV

Paper IV and Paper V describe the same case study of the serial-flow disassembly system in the Netherlands.

Data were collected by the video recordings of disassembly work for five operators, with the minimum work experience of one year. The task categories were similar to those in Paper V and are presented in Figure 7 and Figure 8.

The measurements of physical workloads with data loggers: inclinometers and goniometers, as well as heart rate and number of steps estimations were made in the same way as in Paper II.

3.6 Methods Paper V

Qualitative and quantitative methods were included. Document (business plan) analysis and interviews with the system line developer as well as disassembly operators were conducted in order to better understand the current system performance. The video recordings and analysis of disassembly work were made using the activity analysis system introduced in Paper II. Task categories are shown in Figure 7 and Figure 8.

Figure 7. Disassembly workers in the serial-flow disassembly during direct work (to the left) and material handling (to the right).

Figure 8. Disassembly workers in the serial-flow disassembly during casual task of work-related communication (upper left), transport (upper right) and unplanned breaks.

A biomechanical model (Ergowatch, University of Waterloo; Neumann et al., 1999) was used to estimate operators' peak loads on the lumbar back (see Figure 9), as well as cumulative loading in one operator during one cycle of disassembly work. Flow simulations (Simul8 student version 9, 1993-2002) were used to investigate the potential performance of the disassembly system in a number of operative scenarios in terms of cars disassembled/week, and in terms of utilized time at work. Based on the observations and interviews, five factors were chosen as having a potential to improve system performance, and these were used as the input factors to the simulations: operators' experience, teamwork, cycle times, coefficients of cycle times and distribution shape.

The cumulative loading was used for the integrated analysis with the flow simulations in order to understand how different system configurations may affect cumulative load of operators.

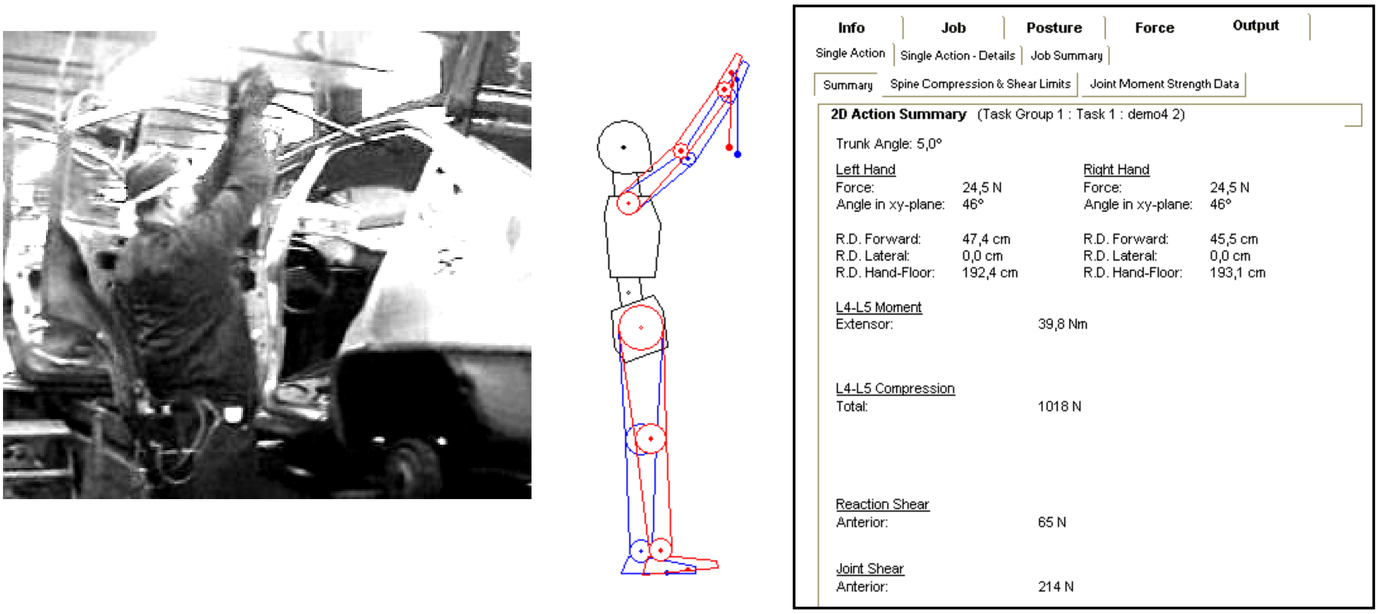

Figure 9. An example of one disassembly posture obtained from the video and transferred to a human manikin with the loading output.

The study in Paper IV and Paper V was done with the cooperation with a Reference Group of ten key dismantling representatives and their branch organization in Sweden. The Reference Group acted as a "reality check" for validating the data collected, and also facilitated dissemination of the knowledge gained in the research to industrial decision makers.

Table 1. Methodological overview of the appended papers.

	Paper I	Questionnaire	Paper II	Paper III	Paper IV	Paper V
Focus level *(level in Figure 1)*	Society: industry & company *(l. 4 & 3)*	Individuals *(l. 1)*	Production system & individuals *(l. 2 & 1)*	Production system (motor assembly) *(l. 2)*	Production system & individuals *(l. 2 & 1)*	Production system *(l. 2)*
Country	Sweden	Sweden	Sweden	Sweden	The Netherlands	The Netherlands
Time point	'Today'	'Today'	'Today'	Not applicable	'Possible future'	'Possible future'
Research approach	Qualitative/ exploratory	Cross-sectional survey	Sector level study	Method evaluation	Case-comparison	Exploratory; case study approach
Methods	Semi-structured interviews; document and literature search; site visits - disassembly and shredding plants, engineering departments of the car manufacturer; a workshop	Questionnaire	Video recordings; task analysis; direct measurements of physical workloads: posture and movement velocities; heart rate measure, number of steps; biomechanical modeling of peak lumbar loads	Video recordings; task analysis	Video recordings; task analysis; direct measurements of physical workloads: posture and movement velocities; heart rate measure, number of steps	Video recordings; flow simulation modeling; biomechanical modeling of peak lumbar loads and cumulative lumbar back loads; interaction with Reference Group; semi-structured interviews; document analyses
Partici-pants/ subjects	13 owners of disassembly plants, 4 car design engineers 5 "authority" stakeholders, branch organizations, government institutions	Response rate approximately 70% (n=91 disassembly workers)	5 disassembly plants with 10 disassembly operators	2 observers analyzing video recordings of 9 motor assembly operators	5 disassembly operators	5 disassembly operators; the Reference Group: 10 owners of most active disassembly plants in Sweden

4 Summary of results

4.1 Results Paper I

The study showed that car disassembly of 'today' in Sweden (in the year 2001) included two main tasks. One was removing hazardous components (including fluids) to meet environmental demands, and the other dismantling of valuable parts for resale. The latter activity allowed for good business economics in all investigated companies. The performance demands were in general low and resembled a 'craft-type' production, that is the work comprised a rich variety of tasks performed under low time pressure. As expressed by one dismantler:

> *'…now there is a job with a lot of variety and moving around a lot and doing different things which is good for the body…'*

Musculoskeletal disorders seemed not to be a significant issue. Interviews with stakeholders from the auto company showed that Design for Disassembly/Recycling was not a significant issue in the manufacturing industry of today. Accordingly, communication between dismantlers and design engineers was sporadic. However, in a long-term perspective, the key stakeholders considered such interaction important to obtain more efficient disassembly systems. Expectations about future production systems were that the amount of non-profit work per car would increase. To comply with the legislative demands on recycling, the respondents emphasized that parts/materials without present market value will also need to be disassembled from cars in the future. These include glass/windows, plastics/interior and cables. The need to create a value for these items was expressed. Rationalizations of the disassembly production systems were expected to bring about consequences such as inferior ergonomics. Transformations of the dismantling industry were expected. For instance, a reduction of the number of the authorized disassembly companies was expected due to the legislative requirements as well as environmental, economical and competitive demands. The remaining plants would continue to disassemble cars for spare parts and remove all liquids. In addition, it was anticipated that new 'regional plants' for old end-of-life vehicles would emerge, that would perform rational materials dismantling of 8000-9000 cars/year on a line-type system. One scenario was described with regard to future jobs in disassembly systems concerning specialization within end-of-life vehicle factories; one job type would be glass dismantling. It was emphasized that future jobs would require greater knowledge and competence among dismantlers, especially in systems for dismantling valuable parts for resale.

4.2 Results of Questionnaire study

The overall response rate was 70%. Perceived workload rates ranged from 2-4 ("light" to "somewhat hard") on the Borg scale. The largest physical workload was reported for the lower arm/wrist/hand region and for the low back. Pain levels were highest for the low back with 29.5% of operators reporting perceived pain "often" during the last 12 months. For the neck and elbow/wrist/hand region this was reported as 33%. Figure 10 illustrates the average overall scores of pain levels for the Swedish dismantlers compared to the corresponding values for a general male population in Sweden.

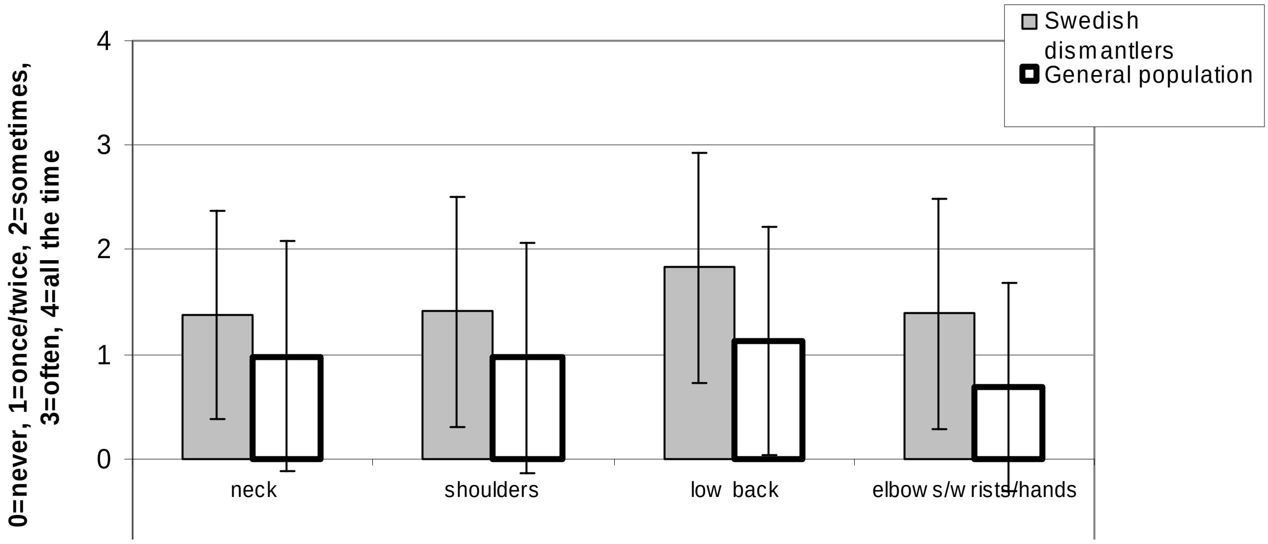

Figure 10. The average overall scores of pain levels (+- 1SD) for the investigated Swedish dismantlers (n=86) and a general male population (n=2600; modified from Ektor-Andersen, 2002). The differences between these two groups were significant (t-test; p<0.05) for all the body parts.

Results on a typical working day are presented in Appendix.

Figure 11 shows the mean values for the psychosocial conditions for the disassembly workers compared with the Danish working population.

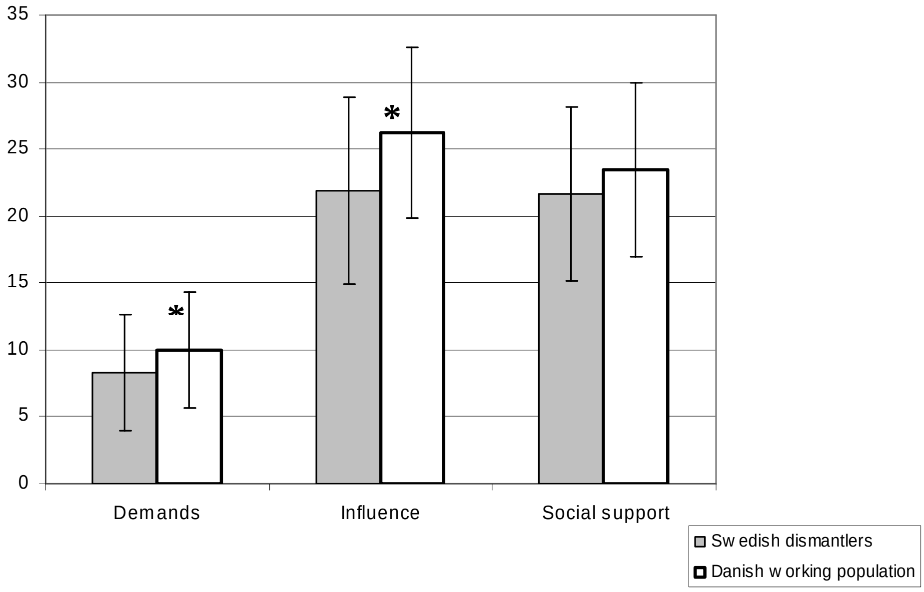

Figure 11. Mean values (+- 1 SD) for the psychosocial dimensions of demands, influence and social support at work obtained for the Swedish dismantlers (n=90) and Danish working population (n=1211). Demands and influence differed significantly from the reference group (t-test; p<0.05).

4.3 Results Paper II

In general, a Swedish disassembly operator was responsible for all dismantling tasks on a particular car. About 25% of the working time was devoted to old end-of-life vehicles, and the remaining time to newer 'insurance' cars, typically crashed in accidents. Judged from the video recordings, the mean cycle time for disassembling an end-of-life car was about half an hour while insurance cars took three to 16 hours to dismantle. This cycle time is a simple measure of 'repetitivity', i.e. whether the same work operations are repeated over and over again in the job (Moore and Wells, 1992; Kilbom, 1994b; Mathiassen, 2003).

4.3.1 Job-related workloads

The median heart rate ratio was 31% for the full workday for all disassembly workers (range 20-45). Disassembly workers walked an average of 1667 steps/hour (range 874-2302). Disassembly work implied high peak compression forces on the low back, median 3645 N (range 2890-6735 N). Peak reaction shear force was median 526 N (range 318-827 N) and peak moment 205 N (range 142-386 N).

4.3.2 Task distribution

Direct work (value-adding) comprised about 30% of the total working time. The largest proportion of the time, almost 40%, was devoted to material and tool handling. The distribution of the investigated tasks is presented in Figure 12 in section 4.5.1, in comparison to task distribution in serial-flow disassembly (Papers IV and V).

4.3.3 Task-related workloads

The workloads in the disassembly value-adding and non-value adding tasks are presented according to the following variables: posture levels (percentiles of the cumulative posture distribution), percent of time spent in neutral and extreme postures, velocity levels (percentiles), percent of time spent at low and high velocities, and frequency of 'micro-recovery' that is number per minute of periods longer than 3 s in a neutral posture.

Posture percentiles

Value-adding work (direct work) implied higher arm elevation at the 50-, 90- and 99-percentiles than the other tasks ($p<0.01$). The disassembly workers had their heads bent backward more than 20^{o} during 10% of the value-adding working time. For the upper back, value-adding work implied the largest extension for 10-, and largest flexion for 90- and 99-percentiles. The postures of the wrist were similar in all the tasks. The posture range, that is the difference between the 10- and 90-percentiles, was larger in value-adding work than in the other tasks.

Time in neutral and extreme postures

Value-adding tasks implied the shortest time spent in a neutral posture with very slow movement for all investigated body regions. Unplanned breaks offered the longest time in a neutral posture for the wrist, arm and head. The longest time spent in extreme postures for all investigated body regions was during value-adding tasks.

Velocity percentiles and time at low and high velocities

Value-adding tasks implied the highest 99-percentile velocities for the arm and wrist both in deviation and flexion-extension. Low velocities (i.e. "static" postures) occurred less in value-adding tasks than in the other tasks, while unplanned breaks showed the largest occurrence of low velocities. Value-adding tasks implied the longest time spent in high velocities for the arm and wrist.

Frequency of 'micro-recovery'

Value-adding tasks showed fewer recovery periods than the other tasks for the head, back and wrist while material/tool handling was the most strenuous task for the arms in this respect.

In summary, value-adding tasks implied, to a greater extent than non-value-adding tasks, physical workloads that are suspected to be associated with increased risks for musculoskeletal disorders.

4.4 Results Paper III

Variance components were determined using ANOVA. For each parameter and task category, the results from the two observers were entered in a 2-way crossed ANOVA (observer x subject) to estimate the variance caused by systematic disagreement between observers, the variance due to differences between filmed subjects, and the residual variance.

The transition points in time between task categories were analyzed and summarized for each observer and video recording (subject). Thus a file was generated that contained information about start and stop times of the four task categories in the processed video recordings, and for each single video frame it was determined whether the two observers agreed on the task classification. For each of the nine (9) video recordings, the time history agreement between observers was summarized in a 4 x 4 contingency table (see Table 2) showing the opinion of observer A by task category (columns) versus that of observer B (rows).

Table 2. Time history agreement (seconds) between the two observers for *one* example subject.

Observer A Observer B	Direct work	Indirect work	Disturbances	Non-work
Direct work	3875.8	130.6	3.4	73.9
Indirect work	275.9	981.6	14.2	18.3
Disturbances	13.6	81.9	90.2	155.7
Non-work	0.9	56.9	37.3	408.2

Table 3 illustrates the time history agreement between the two observers. In total, the observers agreed on the task category for 7055.4 seconds of a total of 8087 seconds of the video recordings (i.e. *87%* agreement), thus disagreeing for 13% of the total time. As an example, *67.5%* of the total analysis time was agreed to be direct work by both observers. They both also agreed that 23.6% time should be classified in other task categories than direct work. For 8.6% of the time, observer A classified what he saw as 'direct work' while observer B did not.

Table 3. Time history agreement (s) between the two observers (in parentheses: percent of total analysis time). Each cell contains the average of the results from the individual tables (n=9). In italics: percent time that the two observers agree on a specific task category.

Observer A Observer B	Direct work	Indirect work	Disturbances	Non-work	Sum observer A
Direct work	**5461.5** *(67.5%)*	250.9 (3.1%)	39.0 (0.5%)	2.6 (0.03%)	5754.0 (71.1%)
Indirect work	301.0 (3.7%)	**1027.2** *(12.7%)*	59.4 (0.7%)	11.0 (0.1%)	1398.6 (17.3%)
Disturbances	9.8 (0.1%)	4.1 (0.05%)	**140.1** *(1.7%)*	19.2 (0.2%)	173.2 (2.1%)
Non-work	97.9 (1.2%)	100.1 (1.2%)	136.6 (1.7%)	**426.7** *(5.3%)*	761.3 (9.4%)
Sum observer B	5870.2 (72.6%)	1382.3 (17.1%)	375.1 (4.6%)	459.5 (5.7%)	

This study showed, generally, good agreement between observers, both on overall task proportions (Table 3) and on the mean duration of sequences in most task categories. The variance between filmed subjects was greater than that between observers in most combinations of parameter and task category. The residual variance, which we interpret as mainly being due within-observer (test-retest) variability was generally larger than the between-observer variability.

4.5 Results Paper IV

4.5.1 Task distribution

Time consumption in the tasks in the serial-flow car disassembly was compared to the corresponding data from the craft-type disassembly reported in Paper II. As seen in Figure 12 time proportions of direct work were approximately the same in both systems. The largest differences in proportions were in casual tasks; in the craft-type work, administration and computer work were included in these tasks.

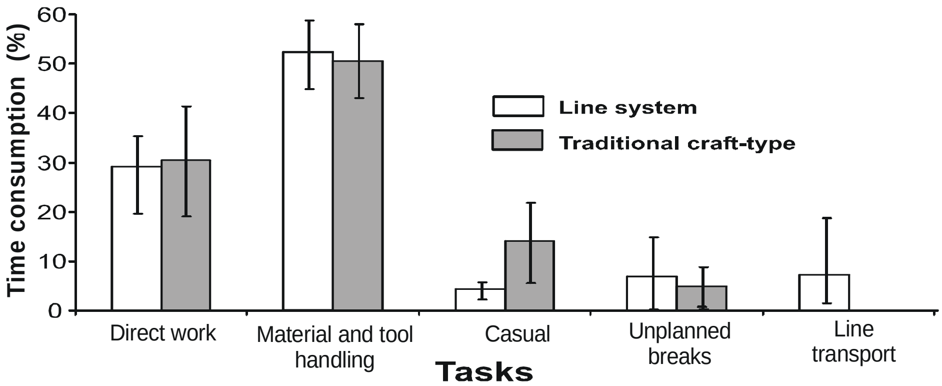

Figure 12. Mean relative duration of tasks in the serial-flow (n=5) and in craft-type disassembly system (n=10; Paper II). Line transport of cars occurred only in the serial-flow system. The bars show range (line system) and standard deviation (craft-type).

4.5.2 Job-related workloads

Posture 10th, 50th and 90th percentiles for head, back and arms were similar in the serial-flow and the craft-type work. However, all three percentiles of angular velocities were higher in the serial-flow system (see Figure 13). In addition, the median duration with the right arm in neutral position (angle< 20° and velocity< 5°/s) was shorter in the line (2.1%) compared to the craft-type work (4.0%).

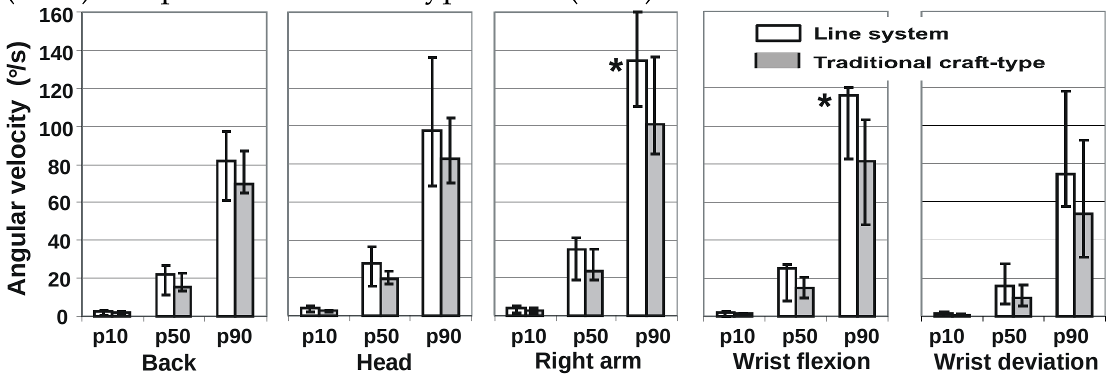

Figure 13. Median percentiles of angular velocities for the line system (n=5) and traditional craft-type work (n=9; Paper II). The bars show ranges for the individuals. The asterisks mark statistically significant differences (Wilcoxon rank sum test; p < 0.05).

The median duration with the right wrist in neutral position was shorter in the serial-flow (4.7%) compared to the craft-type work (6.5%).

The median heart rate ratio for the serial-flow workers was 32% (31% for the craft-type workers), and the median total number of steps was 1853 and 1668, respectively.

4.6 Results Paper V

4.6.1 Observations and interviews

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, which is about 40% of the designed capacity.

Based on the researchers' observations and the interviews with the system developer and the operators, the system showed production deficits due to factors such as system losses, that is 'normal' losses from the serial-flow production due to cycle time variability, as well as operators' inexperience and teamwork deficits.

4.6.2 Simulated system

Simulations of the production system indicated that the *cycle times* factor had the largest effect on the system output, increasing the number of cars per week by almost 58. O*perators' experience* had the second largest effect on the system output. Unexpectedly, *teamwork* had a negative effect on the output. The highest simulated output 183 cars/week was obtained with ten experienced operators working two at each station, without teamwork, working with reduced cycle time variability.

Simulations indicated that *coefficients of variation of cycle times* had the largest effect on utilization rates, increasing of 9.4%. *Operators' experience* had the second largest effect. *Teamwork* had a negative effect and decreased operator utilization.

A simulation of "alternative teamwork" showed that boundless teamwork across stations 1-3 had a minor negative effect on system output; however shortened moving time between stations had a significant positive effect on output.

4.6.3 Peak lumbar loads

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

4.6.4 Integration of human modelling and flow simulation

The average loading during 'utilized' and 'non-utilized' time is presented in Table 4.

Table 4. Time-weighted average loads on the lumbar back during work and non-work activities.

Average load	Moment (Nm)	Compression (N)	Shear (N)
Utilized time: work activities (incl. transport)	38.2	1011	78
Non-utilized time: non-work activities (breaks)	14.5	633.8	41.2
Difference non-utilized time/utilized time	38%	63%	53%

The cumulative compression loading over the work shift across the simulated cases is presented in Figure 14.

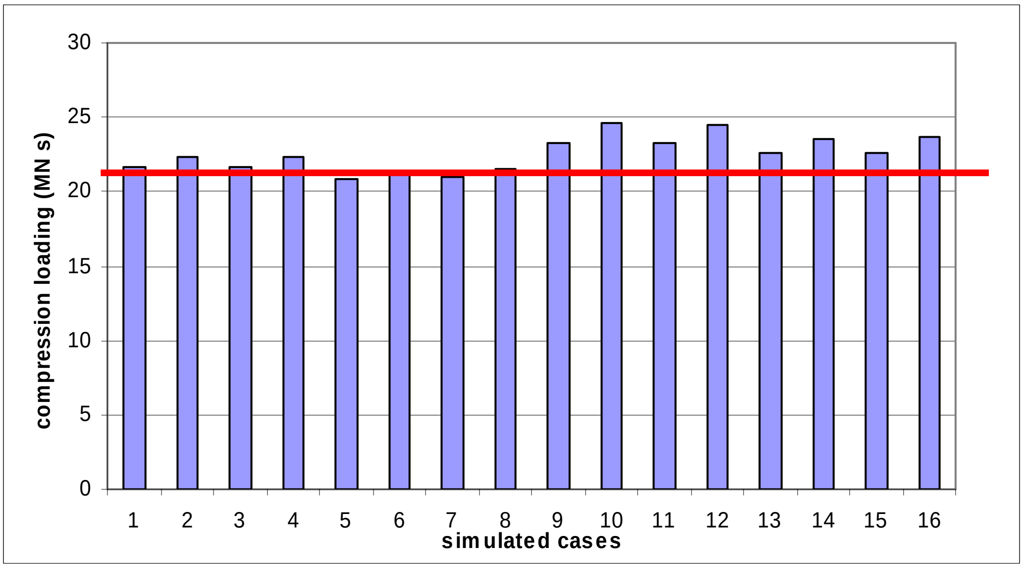

Figure 14. Cumulative compression loading (MN s) for the whole shift organized for the 16 simulation cases. The horizontal line represents the level of cumulative compression loading for the assembly operators reporting low back pain in a large automotive facility (Norman et al., 1998).

5 Discussion

5.1 Methodological issues

The discussion in this chapter focuses on methods and approaches in the studies included in this thesis.

5.1.1 Combination of qualitative and quantitative data in this thesis

The interviews with the three investigated groups: disassemblers, representatives from car manufacturing and authority stakeholders, and the researchers' site visits gave a consistent description of present and expected future car disassembly production systems, as well as design for disassembly/recycling. The independent data sources provided consistent descriptions of the current and anticipated future situation. This allowed finding patterns of convergence and independent corroboration of these descriptions, which is termed as triangulation (Mays and Pope, 2000). The authority stakeholders were asked to describe the present organization of car disassembly systems, to check convergence to the dismantlers' descriptions. Crosschecking material from interviews with documents and Internet information provided a further opportunity for triangulation. There were no obvious divergences in the opinions and viewpoints. However, the opinions given by one dismantling representative were more sophisticated than those of other respondents', specifically about future disassembly production systems. This may be due to the respondent's specific experience in the disassembly industry and his concrete investment plans for end-of-life vehicle line systems. According to Mays and Pope (2000) attention to negative/alternative cases is one tactic that can be used to improve the quality of explanations in qualitative research.

The second study (Paper II) supported the hypotheses made in Paper I on physical workloads and time consumption, and thus can be considered as methodological triangulation (Ammenwerth et al., 2003). The high workloads caused by the awkward postures and heavy lifting occurred occasionally, although for only a short duration. The average postures in the different tasks confirmed the subjective opinions about "lack of significant ergonomics problems". The video-recordings of disassembly work confirmed the stated variety of tasks in the interviews in Paper I.

A combination of qualitative and quantitative approaches was also used in Papers IV and V. Document searches, interviews and discussions with the system developer were conducted throughout the data collection phase in order to better understand the current system performance. An interview with the operators working in the serial-flow system supplemented the technical measurements and supported our observations and findings about system's performance.

Interaction with the Reference Group was used as a reality and validity check of the data collected and results in the studies reported in Paper IV and Paper V. The research questions and the results were discussed during the meetings with the Reference Group.

5.1.2 Risk parameters and time aspects

This thesis discusses the risk factors for musculoskeletal disorders with a special focus on time aspects, which are crucial in relation to rationalizations. Physical workload parameters with time aspects were derived on both the task and job levels in Paper II and on the job level in Paper IV and Paper V.

Time patterns of loading can be expected to change in a future rationalization of car disassembly, in addition to changes in loading levels, owing for example to increased mechanization. Time aspects of loading, such as frequencies and variation over time, are strongly suspected to be important to the risk of developing musculoskeletal disorders (Winkel and Westgaard, 1992; Kilbom, 1994b). Traditionally, ergonomics epidemiology and intervention studies have concentrated on the level dimension, that is postures and manual material handling (e.g. Winkel and Mathiassen, 1994, Westgaard and Winkel, 1997). Frequency and duration, both related to time aspects of loading, seem to be reported to a smaller extent in the literature than are metrics for amplitude (Mathiassen and Christmansson, 2004). In Paper II, the frequency dimension (*'micro-recovery'*) was assessed through the occurrence per minute of "long" periods (>3s) in a neutral posture. This parameter was intended to reflect the extent and timing of opportunities to recover. Thus it resembles the "long gap" frequency parameter suggested for expressing rest patterns in muscle activity (Jensen et al., 1993). Frequency of posture changes may be considered as one expression of posture "variation". Lack of variation may be a risk factor, comprising physical as well as psychological elements (Hagberg et al., 1995). As a simple measure of posture variation, we assessed the posture range through the difference between the 10- and 90-percentiles. In addition, the extent of variation was assessed through the proportion of time spent at low movement velocities for more than 3 s in succession, i.e. in "static" postures. Movement velocities of the arms and wrist were assessed in Paper II and Paper IV, since velocities are suspected to be indicative of risk (Marras and Schoenmarklin, 1993; Schoenmarklin et al., 1994).

In Paper II the loading parameters were derived for each task category. The categories were defined according to an engineering approach focusing on value-adding tasks vs. losses (Engström and Medbo, 1997). This may enhance the usability of the results in a proactive 'intervention' approach by facilitating predictions of what may happen in the course of rationalizations of production systems that change the time proportions of value-adding and non-value-adding tasks.

Cumulative loading on the lumbar back was assessed in Paper V. Cumulative biomechanical variables are important risk factors in low back pain (Norman et al., 1998; Kerr et al., 2001). Postures were analyzed using the loading measurement tool that has been earlier evaluated and risk-calibrated (Norman et al., 1998; Neumann et al., 1999).

5.1.3 Video-based task analysis and its reliability

Analysis of video recordings is a useful approach for estimating time proportions of tasks in a job. This approach may well become common in research on changes in time distribution of different tasks, as an indicator of, e.g. the result of different rationalization practices.

The reliability of video-based task analysis was assessed in Paper III. The between-observer variance was small, which implies that, across a large number of analyses, different observers will reach mean values that do not differ a lot. However, as shown by the large residual variance, observers may disagree substantially in results for individual subjects. This residual, "unexplained" variance was interpreted as a measure of within-observer variability, based on the assumption of a marginal systematic interaction between observers and subjects. An example of such interaction could be that a particular observer believes that Swedish workers, as a rule, are lazy, and thus spend more time in indirect work.

The general tendency that within-observer variability was larger than between-observer variability stands in contrast to results of a study of video-based task analysis in car parts assembly by Medbo (1998b). Medbo's study suggested that the variance within an observer when making repeated analyses is generally lower than the variance between observers for task proportions, frequencies and mean duration of sequences. A study by Chaikumarn (2001) also indicated good consistency when one observer performs repeated task analyses on the same video recording. These two studies explicitly addressed within-observer variance, while in Paper III we estimated within-observer variability indirectly by the residual variance in our ANOVA, which may contain some variance from other sources as well.

Differences between observers can be caused by different understandings of the activity definitions. In our study one observer had been involved in data collection while the other had not. This source of disagreement is probably influenced by the number and complexity of tasks; as complexity increases, disagreement between observers can be expected to increase (Kilbom, 1994a). The motivation to make the analyses may also vary between observers, which can influence for instance the speed of analyses, and the willingness to backtrack the tapes to reassess difficult parts. In our study, one observer intended to use the data in her own future research while the other was a temporary employee at the department.

Although complete agreement is strived for, it is obviously impossible to reach. In our study the time history agreement between observers was 87%. This seems reasonable when comparing with e.g. 80% agreement between observers in a study of posture classification in construction work (Buchholz et al., 1996).

Variability between observers could probably be reduced with an even more careful and exact definition of activities. Thus, Burt and Punnett (1999) made the following suggestions to reduce the between-observer variability in postural observations:

operational definitions are simple and unambiguous; long and multiple training sessions precede data collection; and the number of observed (in their case) postures and the level of detail is limited. Other studies have shared these viewpoints, with the suggestion of extensive common training for observers in order to reduce variability between them, and a pilot investigation of reliability (van der Beek et al., 1992; Medbo, 1998b). In our study, the between-observer variability was low; thus it seems that the training procedure was effective. The study also suggested that within-observer variance can be substantial. The size of performance variance may be caused by uncontrolled factors in training protocols such as individual differences in experiences or intelligence, and unexplainable random errors (Tang, 2000). Ways to reduce within-observer variability could thus be better training of observers, including instructions for making the analysis more carefully, for instance taking more breaks or taking time to make double-checks in case of uncertainty. A digital video interface may also speed up error correction and foster improved precision.

The analyses of agreement between the two observers on the time history of task categories showed notable differences for direct and indirect work. Apparently, observers may agree reasonably well on total proportions while they disagree on the occurrence in time history of a particular task category. Time history agreement is important when the activity analysis is synchronized to other data sources, for instance extracting task loading in recordings of physical workload (Medbo, 1998a; Winkel et al., 1999; Forsman et al., 2002). In this case, disagreement on the exact times of transitions between activities leads to misclassification of the tasks, and thus to erroneous task loading.

5.1.4 Integration of human and flow simulations

Several tools and procedures have been developed during recent years that aim at simultaneous consideration of ergonomics and performance (de Looze et al., 2003; Jarebrant et al., 2004; Neumann, 2004; Laring et al., 2005). Altogether, these studies emphasize that key ergonomic stakeholders are those who design, develop, and improve production systems.

The potential of flow simulation has earlier been discussed to provide information on the time aspects of operators' physical work pattern, such as time utilized in work, to provide indications of the pattern of physical loading (Mathiassen et al., 2002). Neumann and Medbo (2005) suggest that higher utilization rates can imply higher loading and reduced recovery time (poorer ergonomics) along with higher output.

Paper V presents a novel approach to integrate production engineering and ergonomics. There may be potential errors in in-data that should be accounted for: biomechanical cumulative loading data were assessed for only one operator during one work cycle at one station; the assessment was made on the basis of "average postures" for working actions; the average loading did not change for utilized working time (it was the same weight average). Potential errors may also lie in the time ratios of different tasks. Nevertheless, while errors in loading duration or amplitude would affect the cumulative load levels, this approach allows comparison of the cumulative loading between different system configurations. It allows the application of a loading measurement tool and indicator that has already been validated in epidemiological research (Norman et al., 1998). Other human simulation tools could be used to predict loading even before a system is built, which may facilitate proactive work against musculoskeletal problems.

Flow simulations currently have limited possibilities to simulate human work and behavior making for example simulation of "teamwork" difficult. "Smarter" teamwork in reality may show fewer losses than can be seen in the virtual analysis here.

The quality of the novel integrated approach might be improved. Flow simulations might be improved by better quality video/time data, which are the main input to the models. There is a potential to explore physical workload patterns by incorporating physical loading data from the activities, available from logger data recordings, in each work cycle, into the flow simulation.

5.2 General discussion

The transformation process in the car disassembly industry may be considered a possible microcosm of larger/slower processes of industrialization in industry in general.

5.2.1 System performance and ergonomics in craft-type systems

The "business" approach in craft-type systems was mainly towards disassembly of valuable components and materials for resale as spare parts. The minimum removal of hazardous materials required by regulations was also performed. Business economics were good and worker performance demands were low, with a rich variety of tasks.

The craft type work implies high circulatory loads, extensive walking and high peak low back loads. The heart rate ratio of 31% in the disassembly is over the suggested upper limit for an eight-hour workday with varied physical work with material handling (Jørgensen, 1985). Extensive walking (1668 steps/h) seemed to influence heart rate, and it was larger than for furniture removers (Karlqvist et al., 1994) and truck engine assemblers (Neumann, unpublished data). The peak low back loads were higher than in assembly work (Norman et al., 1998). The average lumbar peak compression for disassembly workers exceeded the limit for lifting tasks (3400 N) recommended by NIOSH. The high peak lumbar loads were confirmed by the operators' self-reports on experienced low back pain. Perceived workload rates were smaller (range 2-4 on the Borg scale) than for the assembly operators (5.3-6.5 on the same scale) in a study by Neumann (2004). Demands at work as well as influence and development possibilities were significantly lower for the disassembly workers than the Danish working population (unpublished data, Borg and Kristenssen).

The value-adding (direct) tasks in disassembly in Paper II implied higher arm elevation than found in cases of assembly of sewing machines (Bao et al., 1996) and material kitting work (Christmansson et al., 2002). The corresponding arm angular velocities were, however, considerably lower in value-adding disassembly as compared with material kitting. An explanation might be that disassembly work is often performed e.g. under, inside or on a car that is placed high up on a lift; this type of work cannot be performed with very fast arm movements. The work performed under cars may have influenced operators' head bending backward over 20^{o} during 10% of the value-adding working time. The trunk postures in the disassembly were less flexed than in assembly and material kitting. The time distribution of wrist flexion–extension in disassembly was similar to results of automobile assembly workers in a study by Hägg et al. (1997). Wrist velocities were smaller than in material kitting. Value-adding disassembly tasks implied a shorter time spent resting in a neutral posture than non-value adding tasks for the arm, head, trunk and wrists, and a larger proportion of time spent in extreme postures. Value-adding tasks also exhibited fewer opportunities to recover in a neutral posture without moving. Low velocities occurred less often in value-adding tasks than in the other activities. Thus, value-adding tasks generally implied to a greater extent than non-value-adding tasks, physical workloads that are suspected to be associated with a risk for developing musculoskeletal disorders.

Value-adding tasks comprised 30% of the total working time. It was expected that there was a large potential for rationalization, which would increase the proportion of direct work. Such an increase towards values observed in manufacturing (Bao et al., 1996; Engström and Medbo, 2003; Neumann, 2004) might lead to fewer opportunities for recovery, as suggested by the less ''porous'' loading profile of direct work as compared to other task categories in the job.

5.2.2 System performance and ergonomics in rationalized systems

Line-based systems were anticipated to emerge in the future (Paper I). The "hardware" of such systems exists (http://www.crs-europe.com). Papers IV and V examined this system in terms of ergonomics and performance.

This rationalized serial-flow system conceptually presents a different way of organizing disassembly work. However, this way may become common in the future. Serial-flow may be a solution to performing "complete" material dismantling in order to create material streams both to meet legislative demands and to become economically viable.

Papers IV and V showed one interesting and, contrary to our expectations, finding of time proportion of direct work (value-adding tasks) in the serial-flow system being nearly the same as in the craft-type (about 30%). These proportions are much lower than in assembly work (70%; Bao et al., 1996; Medbo, 2003; Neumann, 2004). What we expected was that the serial-flow system would offer a larger proportion of time in direct work due to shorter work cycles and thus fewer tools and materials to handle. There are, however, large differences between car assembly and disassembly due to the complexity and nature of this work (Lambert and Gupta, 2005). Although all cars on the line during one day are of the same brand – they are all individual wrecks, with unpredictable conditions and qualities, requiring different tools to disassemble "the same part". Many large material units are disassembled, and it is difficult to effectively buffer materials. Furthermore, there is still a lack of theoretical background and methods in systematically evaluating disassembly processes (Tang et al., 2004).

The mean postures were approximately the same for the disassembly workers in the serial-flow system (Paper IV) and craft-type work (Paper II). However, the movement velocities were higher in the serial-flow. High wrist and back velocities are known risk factors for musculoskeletal disorders (Marras and Schoenmarklin, 1993; Marras et al., 1995); the back velocities in the car disassembly are higher than those associated with a high risk level given by Marras et al. (1995). The differences in velocities could possibly depend on the specifics of line work; when the same task is repeated, the movements become more "automatic". Furthermore, in the serial-flow system, there was a lack of computer data-entry work, which is rather static.

Another explanation for the differences in the velocities could be that only end-of-life cars are disassembled in the serial-flow system (Paper IV) and the product is raw material, which may be torn down from the cars. The way these car wrecks are disassembled depends much on the operators' experience, as confirmed by the interviews and researchers' observations in Paper V. Experienced operators first examined a car and then disassembled it, while the inexperienced operators tried to act more directly by applying force. The experience may affect both amplitude and the time aspects of loading.

The design of the line with an elevated work level appeared to remove unnecessary bending and handling materials from the floor, which may have reduced peak low back loads in the serial-flow as compared to those in craft-type work. The peak loads in the line system were also lower than those of assembly operators reporting low back pain in a large automotive plant (Norman et al., 1998); however they were 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 improved work techniques and use of better tools (de Looze et al., 2003; Neumann, 2004). Depending on their duration and frequency, lower peak loads can also reduce cumulative loads.

Cumulative loading in the low back (compression force and moment) over the whole work shift in the simulated cases in the serial-flow disassembly was higher than for the assembly operators reporting pain (Norman et al., 1998). This may imply increasing risk for musculoskeletal disorders.

Simulations in Paper V suggested that operators' work experience can have a great effect on the system output, increasing the number of disassembled cars per week and also increasing the utilization rates (% time working). Increased training, specialization and skill development are associated with increases in productivity and better performance of the systems (Woodcock, 1996; Sengupta and Jacobs, 2004; Johnson, 2005). Providing the input of cars in batches grouped by model, as in the case in Paper V, may increase learning and experience. This may also increase the speed of work and decrease variation in cycle times.

The larger variation in cycle times implied smaller output and reduced operator utilization. Variation in cycle times leads to losses in underbuffered line systems (Wild, 1975; Engström et al., 1996; Johnson, 2005). Thus, from the efficiency perspective, the goal may be to reduce cycle times and their variation. This, again, may be difficult to achieve in disassembly due to the large variation in product brand, age and their conditions (Lambert and Gupta, 2005). Better tools and improved working techniques may reduce cycle times.

One of the underlying features of the serial-flow system is work in teams. Teamwork has been a central element of sociotechnical innovation (Eijnatten et al., 1993), implying a reduction in the risk for musculoskeletal disorders (Karasek and Theorell, 1990). There is a common belief of the beneficial effects of teamwork on efficiency in assembly industries (Frieling et al., 1997; Murakami, 1997). However, the study in Paper V showed counter-intuitive results. The dilemma of teamwork and flexible operators was addressed by e.g. Schultz et al., 2003. Van den Beukel and Molleman (2002) argued that multifunctionality in team-based work could lead to an underutilization of skills and task overload. However, as shown by the simulations in Paper V, teamwork would increase output if moving time between stations were shorter. This could be achieved by a change in the layout of the system and location of containers and tools.

In terms of ergonomics, the system output provides an indication of the number of work cycles performed at the system level. 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 and Neumann, 2004). In terms of ergonomics this may offer opportunities for recovery (Paper II). Such stoppages in the system, however, are not always perceived as a pause by operators (Neumann, 2004).

A widespread application of the serial-flow production system in the car dismantling industry may demand a careful joint optimization between rationalization and ergonomics to avoid an increased occurrence of musculoskeletal disorders.

5.2.3 Product design for disassembly

Paper I focused both on production systems and product design, where special attention was given to Design for Disassembly/Recycling. According to Broberg (1997) "design and production engineers have a great influence on ergonomics in manufacturing" and there are interconnections between product design and production system design. Thus, product design may also influence the work content and ergonomics in disassembly.

The Design for Assembly (DFA) concept was developed in the late 1970s to facilitate assembly activities and to reduce costs in 'forward' factories (Boothroyd et al., 2002). An additional benefit was also simplification of products (Kuo et al., 2001). The DFA concept has been transferred to disassembly, that is products need to be designed for easy disassembly and component recycling in order to reduce their total life-cycle cost (Kuo et al., 2001). Design for Disassembly (DFD) is related to time demands for dismantling a product; improved DFD may shorten the time. Design for Recycling, on the other hand, is associated with the market value of components and materials, an important prerequisite for disassembling a product. Thus, the interdependence of these concepts should be considered.

Higher market value of the dismantled parts may in turn allow for longer disassembly time and thereby reduced time pressure with possible effects on ergonomics. Attempts have been made to create a market value for car glass/windows in e.g. Norway (http://www.hasopor.com/meraker.html) and for recycling of plastics in Sweden (the car manufacturer, personal communication; Kantz, 2000). The Netherlands seems to be a leader with their efforts to recycle and commercialize increasing amounts of material from scrap end-of-life vehicles (http://www.arn.nl/engels/index.php).

Car components seem to be increasing in complexity; a good example was the investigated car seat, today often including, e.g. airbags and electronics. In the interviews conducted in Paper I it was emphasized that new and more complex car components create a need for increased knowledge and training of disassemblers. Accordingly, educational systems need to be developed to secure good ergonomics practice and efficient work performance.

The study in Paper I showed that car manufacturers were aware of the importance of design for disassembly/recycling, despite the fact that in practice these issues were inadequately considered by the manufacturer as regards internal organization and design engineering. There seemed, however, to be mutual interest in cooperation between dismantlers and manufacturers.

Although the first study (Paper I) showed potential and a good foundation for cooperation between manufacturers and dismantlers, new solutions for obtaining optimal component and material recovery and recycling seemed to change this situation. These two groups of stakeholders appeared to support different solutions to end-of-life vehicle handling. The car manufacturers focus now on "post-shredding" separation technologies due to the low or absence of cost in environmental take-back processing (personal communication; IARC, 2005). These "post-shredding" technologies are continuously being improved (shredding industry stakeholder, personal communication; GM Corporate Responsibility Report), although they are not yet effective enough to meet legislative demands (EGARA position paper, 2003). Effective dismantling, pre-shredding to obtain higher reuse and recycling rates through material-sorting could help to resolve this problem (Seliger et al., 1997; Lambert and Gupta, 2005), but would require a Design for Disassembly/Recycling strategy to be on the manufacturers' agenda. Furthermore, inclusion of more electronics components and air bags in the future cars may still require manual disassembly.

5.2.4 Industrial development context

Industrialization of the car disassembly industry represents a possible microcosm of a larger process of industrialization in general. The underlying driver of this process is societal concern about the external environment. This has resulted in EU legislation on the higher car recycling rates (2000/53/EU). Parallel to external environment concern there is global concern about musculoskeletal disorders as a serious social and economic problem (WHO, 1999).

Parallels can be drawn between the industrialization of the car disassembly and car manufacturing. Ford broke the tradition of craft production by devising a new mass production paradigm to fill the needs of the early 20th century (Liker, 2004). The needs of the early 21st century seem to be reducing the use of resources and increasing recycling in order to contribute to environmentally sustainable development (Ennals, 2001).

The system approach in this thesis (see Figure 1 and Figure 2 in Introduction) is consistent with Moray's (Moray, 2000) treatment of ergonomics as a system approach to upcoming changes in society. Thus, it seems reasonable to encourage a *proactive* approach in ergonomics intervention studies: while observing trends at the society level, e.g. legislation, forecasting consequences on ergonomics. As in this thesis, the studies on connections between rationalizations, system performance and ergonomics provide empirics and knowledge that is transferred to the target branch. Furthermore, this thesis proposes the tools of video-based task analysis and the combination of human and flow simulation that allow using the current knowledge on ergonomics and production system performance to predict what may happen with these two in the course of rationalization.

A larger mass proportion of end-of-life vehicles needs to be dismantled for recovery. For companies to remain profitable, a comprehensive rationalization of the process is anticipated. As showed by the studies in this thesis transformation of the dismantling industry and changes in production systems have already started. This transformation has both economic implications for the companies and ergonomics implications for the operators involved. Attention in this thesis is paid to how changes in the car disassembly approach might affect operators' risk for musculoskeletal disorders and system performance. Focus is placed on time aspects of the loading, since they are especially important in relation to rationalizations of production systems.

The studied rationalized system for car disassembly is an alternative to the shredding industry. The underlying objective is to perform "complete" dismantling and to create material streams for use as raw material in new manufacturing processes, along with the recovery of reusable components performed previously. Thus, a 'line' based production strategy was applied in order to achieve economies of scale required to be profitable in the new 'material creation' business model. In order to realize business profit, besides having the production system, two additional prerequisites should be met. These are supply side, that is continuous supply of high volumes of end-of-life vehicles, as well as a market for dismantled materials where customers will offer the higher material value for the larger and cleaner volumes.

There is still a large gap between car disassembly and manufacturing. The disassembly branch has been able to stay profitable without market pressure and having 'craft-type' production. The EU legislation puts pressure both on car producers and dismantlers, yet there is a lack of support from the manufacturing side in developmental efforts in dismantling. Today, car manufacturing supports the cheaper shredding solutions that may bypass the car disassembly industry. However, according to unofficial information given by key car manufacturing stakeholders in Sweden, comprehensive needs for efficient car dismantling will return within the next five years (personal communications). Thus, studies, as those described in this thesis, of issues related to future industrialized car dismantling may appear significant.

The research in this thesis aims to contribute in the long term to the development of sustainable production systems that is systems in which efficiency and profitability are integrated with good ergonomics.

6 Conclusions

The following conclusions can be drawn on the basis of the results of the studies and the literature review in this thesis:

With regard to ergonomics and system performance:

- Craft-type car disassembly systems have good business economics, while focusing on minimal required removal of hazardous materials and selected components for reuse; there are low worker performance demands and a rich variety of tasks;
- The psychosocial working conditions (demands and influence at work) are significantly lower for the craft-type disassembly workers compared to the general Danish working population;
- Craft-type work involves high circulatory loads, much walking and high peak low back loads; and the car disassembly operators report substantial perceived pain in the low back;
- Value-adding direct work in Swedish craft-type disassembly and Dutch serial-flow disassembly comprises only 30% of the total working time, compared to 70% in assembly;
- Direct work implies physical workloads believed to be associated with larger risks for musculoskeletal disorders than the other tasks at work. Thus, if the proportion of direct work increases, risks can be expected to increase;
- The number of tasks is smaller in the serial-flow system than in the craft-type, e.g. lack of computer-based registration of car parts;
- Upper limb movement velocities appear to be higher in the serial-flow disassembly system than in the craft-type. Peak loads on the lumbar back, on the other hand, tend to be lower than in craft-type work;
- The serial-flow system exhibited production deficits due to factors such as system losses, insufficient worker experience and teamwork deficits. Nevertheless, the flow simulation shows the potential of the system to reach a high output of cars, and suggestions were made to improve teamwork and operators' experience.

With regard to product design and ergonomics:

- Design for easy Disassembly and Recycling (DFD/DFR) is not fully considered in manufacturing; however the need for the DFD/DFR strategy as well as cooperation between car dismantlers and manufacturers is expressed by both groups;

With regard to the tools and methodologies:

At the 'micro-level':

- Methodological consideration of 'new' parameters of risk for musculoskeletal disorders shows differences in time aspects of loading between value-adding and non-value-adding tasks, e.g. faster movement velocities, less time for recovery (*face validity*);

- The novel combination of flow and biomechanical simulation shows potential in assessing the physical loading consequences of alternative system configurations; hence it might be an appropriate tool to be used by engineers and ergonomists;
- Video-based task analysis can be used both by engineers and ergonomists for assessing time proportions of tasks and activities at work with a satisfying reliability.

At the 'macro-level':

- The EU legislation has provided an example of how macro-level decisions affect ergonomics. This has provided a case for studying industrial developmental processes so as to potentially facilitate a proactive approach to ergonomics intervention.

7 Recommendations for further work

Further work should focus on practical implications of the findings in the development of a strong industrial sector of car dismantling. The 'sustainability' of the production systems should be secured, that is efficiency gains should go along with good working environment. This also concerns broadly defined health and safety issues.

Rationalization in the car dismantling sector is a European issue. It is recommended make combined scientific efforts on a European level in order to facilitate for the disassembly sector to fulfill the environmental goals of the directive on end-of-life vehicles, to remain economically viable and to offer European workers healthy working conditions.

A prerequisite for sustainable rationalized car disassembly systems is a market for the recycled materials and components. Thus, there is a need to examine the current situation and to create potential markets. A recommendation is to bring together researchers and practitioners who could work on the common issue through e.g. workshops.

Another research issue concerns the proactive ergonomics studies that might be needed in order to prevent musculoskeletal disorders. For this, predictive tools would need further development and evaluation. Better connection of flow simulations to load estimating tools (both load amplitude and time dimensions) would be needed, e.g. data loggers. Flow simulation tools should be developed beyond the 2-level of 'utilized' and 'non-utilized' time at work, to give the possibility of including more levels of work to accommodate task time variability.

Finally, a strong emphasis on Design for Disassembly is needed. Cooperation between dismantling and design engineering would be desirable, including engagement of researchers. Considering human-friendly design for disassembly may facilitate other Design for X strategies, such as design for assembly and service/maintenance.

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Paper I

Car disassembly and ergonomics in Sweden: current situation and future perspectives in light of new environmental legislation.

Kazmierczak, K., Winkel, J., Westgaard, R. H.

International Journal of Production Research 42, 2004, pp. 1305-1324

Paper II

An integrated analysis of ergonomics and time consumption in Swedish 'craft-type' car disassembly.

Kazmierczak, K., Mathiassen, S.E., Forsman, M., Winkel, J.

Applied Ergonomics 36, 2005, pp. 263-273

Paper III

Observer reliability of industrial task analysis based on video recordings.

Kazmierczak, K., Mathiassen, S.E., Neumann, P., Winkel, J.

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Paper IV

Ergonomics and time consumption – a serial-flow system versus traditional craft-type car disassembly.

Forsman, M., Kazmierczak, K., Palmerud, G., Carlzon, C., Neumann, P., Winkel, J.

Conference paper, Nordic Ergonomics Society, 10-12 October, 2005, Oslo, Norway, pp. 245-249

Paper V

A case study of serial-flow car disassembly: ergonomics, productivity and potential system performance

Kazmierczak, K., Neumann, W.P., Winkel, J.

To be submitted to a peer-reviewed journal

Appendix

E. TYPICAL WORKDAY

The following questions are about your typical working day:

		1	2	3	4	5		
E1. Are there usually many interruptions or stops when operating machine?	Many	☐	☐	☐	☐	☐	Few	3.1
E2. How are working conditions on the whole?	Difficult	☐	☐	☐	☐	☐	Easy	3.3
E3. Does your work allow physical variation? (e.g. changes between standing / sitting / moving, working with different major parts of the body)?	Little	☐	☐	☐	☐	☐	Much	3.4
E4. How is the working pace on average during a working day?	High	☐	☐	☐	☐	☐	Low	2.4
E5. How interesting and stimulating is your working day?	Little	☐	☐	☐	☐	☐	Much	3.3
E6. Are you able to take breaks during the day when you feel the need to?	Seldom	☐	☐	☐	☐	☐	Anytime	3.3
E7. Are there possibilities for you to plan and organise your own work?	Few	☐	☐	☐	☐	☐	Many	3.2
E8. How varied are your work tasks during a typical day?	Little	☐	☐	☐	☐	☐	Much	3.0
E9. How does your body feel after a typical working day?	Fatigued	☐	☐	☐	☐	☐	Fresh	2.4
E10. How does your mind feel after a typical working day?	Tired	☐	☐	☐	☐	☐	Alert	2.6
E11. How is your typical working day from a social point of view?	Lonely	☐	☐	☐	☐	☐	Sociable	3.8
E12. How stressed do you generally feel when the working day is over?	Tense	☐	☐	☐	☐	☐	Relaxed	3.3
		1	2	3	4	5		