Production Ergonomics: Identifying and managing risk in the design of high performance work systems

Neumann, Patrick

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Identifying and Managing Risk in the Design of
High Performance Work Systems

W. Patrick Neumann

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Department of Design Sciences
Lund University, Sweden

Arbetslivsinstitutet
National Institute for Working Life

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Department of Design Sciences
Division of Ergonomics and Aerosol Technology
Lund University
Sweden
www.lu.se

National Institute for Working Life – West
Production Ergonomics
Göteborg
Sweden
www.niwl.se

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Abstract

Poor ergonomics in production systems can compromise performance and cause musculoskeletal disorders (MSDs), which pose a huge cost to society, companies, and afflicted individuals. This thesis presents a research trajectory through the problem space by: 1) Identifying and quantifying workplace risk factors for MSDs, 2) Identifying how these risks relate to production strategies, and 3) Developing an approach to integrating ergonomics into a companies' regular development work.

A video analysis tool for quantifying postures while working was developed. The tools' reliability, accuracy, and ability to identify risks for MSD were evaluated. The tool had generally good accuracy and good to moderate reliability. Low back MSDs were strongly associated with working trunk postures. Operators with high exposure to peak flexion level had 4.2 times higher MSD risk than unexposed operators. Similarly high peak extension velocity increased risk by 2.9 times. (*Paper 1*)

Two pre-post case studies using multiple mixed methods were conducted to examine how production strategies can affect productivity and ergonomics outcomes. The case of electronics assembly, showed how automation can increase output while eliminating repetitive monotonous work. Automation to serial flow, however, resulted in increased repetitiveness at remaining assembly stations. Despite ergonomic workstation design efforts, shoulder loading increased 14%. (*Paper 2*)

The case of engine assembly compared cellular and line production strategies. The line demonstrated system, balance, and disturbance related losses resulting in forced operator waiting. Nevertheless, the line overcame productivity barriers in the operation of the cellular system. The line system showed increased repetitiveness with cycle times that were 6% of previous, uneven distributions of physical tasks such as nut running, and reductions in influence over work scales all implying increased risk. Teamwork in the line system contributed to significantly increased co-worker support – an ergonomic benefit. (*Paper 3*)

An action research project was initiated, with the same engine manufacturer, to integrate ergonomics into regular development work. The change process was slow and marked by setbacks, caused by both individual factors (e.g. disinterest, changing jobs, illness), and organisational factors such as inter-group communication barriers and short project timelines that limited uptake of new approaches. Despite these setbacks the resolute production manager, acting as a "political reflective navigator", was able to establish credibility, overcome resistance, and begin to integrate ergonomics into regular developmental processes. The process remains slow and is vulnerable so long as the manager is navigating alone. (*Paper 4*)

Workplace risk factors can be precisely and accurately quantified. These risks are embedded in strategic choices in the design process. Load amplitudes were determined by workstation layout and the material supply sub-system. Risk related to the pattern and duration of loading are determined more by flow and work organisation elements. Psychosocial risk factors appear to be affected by a combination of system design elements. Managing the emergence of these risks proactively requires attention to ergonomics throughout the design process, especially in strategic choices. Integrating ergonomics into early development stages implies changing roles for groups and individuals in the organisation. This approach appears feasible but is difficult and remains an under-utilised strategy for sustainable competitive advantage.

Keywords:
Production System Design, Strategy, Organisational Development, Human Factors, Musculoskeletal disorders, Manufacturing, Risk Measurement

Sammanfattning

Dålig ergonomi i produktionssystem kan äventyra prestationsförmågan och även orsaka muskuloskeletala besvär (eng. musculoskeletal disorders: MSD). Detta utgör en stor kostnad för samhälle, företag och drabbade individer. Denna avhandling presenterar en forskningsansats att 1) identifiera och kvantifiera arbetsplatsens riskfaktorer för MSDs, 2) identifiera hur dessa risker är relaterade till produktionsstrategier och 3) utveckla ett sätt att integrera ergonomi i ett företags vanliga utvecklingsarbete.

Ett instrument för videoanalys utvecklades för att kvantifiera arbetsställningar. Reliabilitet och indikatorers relation till risk för MSDs testades. Instrumentet hade generellt sett god till måttlig reliabilitet. Besvär (MSDs) i ryggens nedre del var starkt knutna till bålens arbetsställningar. Risken för MSDs hos operatörer med extrem bålflexion var 4.2 gånger högre än för oexponerade operatörer. För operatörer med hög flexionshastighet var risken 2.5 gång högre. (Artikel 1)

Produktivitet och ergonomiskt utfall studerades inom två svenska monteringsindustrier för elektronik respektiv dieselmotorer. Kvantitativa och kvalitativa metoder användes före och efter förändringar av produktionssystemen. Första studien (elektronikmontering) visade hur automation kan öka produktionsvolymen samtidigt som repetitivt och monotont arbete elimineras. Automatisering av transportfunktionen till seriellt flöde resulterade emellertid i ökat repetitivt arbete vid resterande monteringsstationer. Trots försök till ergonomiskt utformade arbetsstationer i designprocessen ökade belastningen på skuldrorna med 14 %. (Artikel 2)

I andra studien (motormontering), jämfördes produktionsstrategierna dock- och linjemontering. Linjen visade på system-, balans- och störningsrelaterade förluster, resulterande i påtvingad väntan hos operatörerna. Emellertid klarade linjesystemet delvis av de produktionsbarriärer som fanns i docksystemet. Vidare linjesystemet visade ökad repetitivitet med cykeltider som bara var 6% av docksystemet. Dessutom varierade rent fysiska arbetsuppgifter på linjesystemet mycket, exempelvis mutterdragning. På psykosocial nivå upplevde operatörna en minskning av inflytande över arbetet. Sammantaget pekar dessa faktorer på ökad MSD-risk jämfort med

docksystemet. Dock ökade arbetsgemenskapen i linjesystemet, som hade en team-baserad arbetsorganisation, vilket är en ergonomisk fördel. (Artikel 3)

I syfte att integrera ergonomi i det vardagliga utvecklingsarbetet initierades ett aktionsforskningsprojekt på fabriken för motormontering. Förändringsprocessen var i början långsam och kännetecknades av bakslag, orsakade både av individuella faktorer (ointresse, byte av arbete, sjukdomar, osv) och organisatoriska faktorer såsom kommunikationsbarriärer mellan grupper och korta tidsfrister i projektet. Detta begränsade införlivandet av nya arbetssätt. Trots dessa bakslag lyckades produktionsledaren, agerande som en "politiskt reflektiv navigatör", etablera trovärdighet, övervinna motstånd och påbörja en integrering av ergonomi i vardagliga utvecklingsprocesser. Processen var långsam och känslig även då projektet avslutades, därför att ledaren fortfarande var ensam om att navigera. (Artikel 4)

Avhandlingen konkluderar att arbetsplatsrelaterade riskfaktorer kan kvantifieras precist och tillförlitligt. Dessa risker är inbyggda i de strategiska valen i designprocessen. Belastningens storlek påverkades av utformningen av arbetsstationen och materialförsörjningssystemet. Tidsaspekter av belastning påverkades av systemflödesstrategien och arbetsorganisationen. Psykosociala riskfaktorer visade sig vara kopplade till en kombination av ovan nämnda element i systemutformningen. För att förebygga MSD-risker måste man ta hänsyn till ergonomi i hela designprocessen – tidigast besluten är ofta de viktigast. Integrering av ergonomi i tidiga utvecklingsfaser innebär förändrade roller för grupper och individer i organisationen som normalt inte uppfattar sig som ”ergonomer". Utveckling av dessa roller är viktig för skapandet av hållbara produktionssystem.

Sökord:
Utformning av Produktionssystem, Organisationsutveckling, Mänskliga faktorer, Muskuloskeletala besvär, Tillverkning, Riskmätningar

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Thesis Papers

Paper 1
Neumann, W. P., Wells, R. P., Norman, R. W., Kerr, M. S., Frank, J., Shannon, H. S., and the OUBPS working group (2001). **"Trunk posture: reliability, accuracy, and risk estimates for low back pain from a video based assessment method."** *International Journal of Industrial Ergonomics*, 28, 355-365.

Paper 2
Neumann, W. P., Kihlberg, S., Medbo, P., Mathiassen, S. E., and Winkel, J. (2002). **"A Case Study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry."** *International Journal of Production Research, 40(16), 4059-4075.*

Paper 3
Neumann, W. P., Winkel, J., Medbo, L., Mathiassen, S. E., and Magneberg, R. **"Productivity and ergonomics in parallel and serial flow production."** *Submitted for peer review.*

Paper 4
Neumann, W. P., Ekman Philips, M., and Winkel, J. **"Integrating ergonomics in manufacturing system development - Moving from reactive to proactive."** *Submitted for peer review*

1 INTRODUCTION

1.1 Topic Under Investigation

The problem under study in this thesis is the occupational source of work-related musculoskeletal disorders (MSDs). The opportunity under study is the ability of an organisation to apply knowledge about humans, 'Human Factors' or 'Ergonomics' (IEA Council, 2000), to create high performance work systems that are effective, profitable, and healthy workplaces. These two aspects – the human health, and the system performance – are central to the research approach of the 'Production Ergonomics' group at the National Institute for Working Life West in Gothenburg Sweden, from which this thesis emerges. It is through the joint optimisation of these two aspects that sustainable development can be achieved.

This thesis presents a 'systems' framework and new data for understanding how MSDs can emerge as an unintended result from the design of a work system. Four research papers are used to study the following problems:

1. How can one identify and quantify risk factors for MSD? (Paper 1)
2. How are risk and other productivity factors related to core 'strategic' elements in the design of the production systems? (Papers 2 & 3)
3. How can an organisation best integrate ergonomic considerations into their daily development processes? (Paper 4)

> **"<u>Ergonomics</u> (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance"**
>
> \- International Ergonomics Association, 2000

1.2 System Model

A 'system' model is proposed to help understand how ergonomics is handled in production system development and what consequences this has for MSDs and productivity.

A simplified system model describing the chain of events that can lead to work-related musculoskeletal disorder is illustrated in Figure 1. Skyttner defines a system as 'a set of interacting units or elements that form an integrated whole intended to perform some function' (Skyttner, 2001). This model builds on previous work, which identified relevant factors for ergonomic intervention at the level of the community, the company, and the individual worker (Hagberg et al., 1995; Mathiassen and Winkel, 2000; Westgaard and Winkel, 1997; Winkel, 1992). The model presented here focuses more explicitly on the chain of events that ultimately result in MSDs.

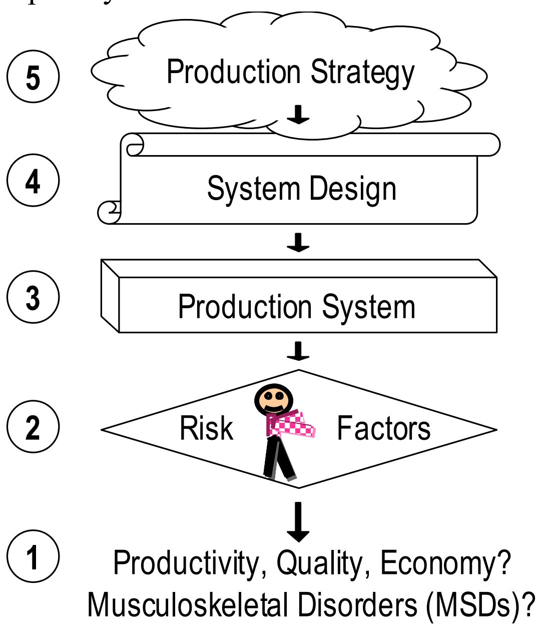

Figure 1: *A simplified systems model for analysing the development of musculoskeletal disorder (MSDs) in a work system. The company's development process can be seen to begin with conceptual choices of production strategy (5), followed by the design stage (4) to the eventual implementation of the production system (3). Production system operators are then exposed to the physical loads and psychosocial working conditions within the system that determine risk for MSD (2). The system outputs (1) include, for example, productivity and quality and also, as a side effect, MSDs.*

I will describe this model from the bottom (outputs, 1) to the top (strategy, 5) and then briefly also discuss the contextual issues related to the individual, company and society levels which can both affect MSD outputs (at 1) but can also affect how the system might react to intervention attempts.

1.2.1 System Outputs

Authors such as Oxenburgh (1991; 2004) have described in detail how health and safety in general can contribute to a firms financial performance. For the purposes of this thesis system outputs are assigned two categories: Musculokeletal disorders, and Productivity.

1.2.1.1 Musculoskeletal Disorders

Musculoskeletal disorders (MSDs) at work are a persistent problem in industrial nations costing a lot of money and causing much suffering. MSDs are an unintended output of many work systems.

In 2003 Sweden's total costs for work related sickness and absence were over 110 billion Swedish crowns (SEK) – an increase of almost 50% in just 4 years**.** The economic costs alone for work related ill health have been estimated by some European nations at between 2.6% and 3.8% of gross national product with about half of this cost being attributed to MSDs (EASHW, 2000b). In the US over 1 million people annually seek medical treatment for Back and upper limb MSDs and *"Conservative estimates of the economic burden imposed, as measured by compensation costs, lost wages, and lost productivity, are between $45 and 54 billion annually"* (NRC and Panel on musculoskeletal disorders and the workplace, 2001). Poor ergonomics in manufacturing not only results in direct costs associated with injury treatment and compensation, but also in indirect costs related to factors such as absenteeism, costs of administration, employee turnover and training, poor employee morale, as well as reduced productivity and quality (Alexander and Albin, 1999; Oxenburgh et al., 2004; WSIB, 2001). Indirect costs may be several times greater than direct costs and are often not measured by companies (Hagberg et al., 1995), which may lead them to underestimate the scope of the problem. For

> **"…in 1997, the overall economic losses resulting from work-related diseases and injuries were approximately 4% of the *world's gross national product.*"**
> **-** World Health Organisation 1999

the afflicted workers the consequences of injury are much more personal and include reduced physical, psychological and economic well being (Pransky et al., 2000; Tarasek and Eakin, 1995). While much research has been done on intervening to reduce MSDs in the workplace (Westgaard and Winkel, 1997) the problem appears to be continuing, arguably, unabated.

Work related musculoskeletal disorders (MSDs) are a heterogeneous group of disorders that, by definition, have a work-related cause and can include a broad range of body parts and tissues (Hagberg et al., 1995). MSDs are also difficult to diagnose with precision (Van Tulder et al., 1997). In the model presented (figure 1) MSDs form the final outcome of a chain of events over the course of the development of the production system. These disorders can be seen as unintended side effects of the production system that have negative consequences both for the operator and for system performance. This thesis focuses specifically on musculoskeletal disorders which form the single most expensive work related ill health category (WHO, 1999). The solution pathway for MSDs deals with many of the same issues that must be handled when trying to solve other work-related health problems. Thus we use MSDs as a kind of 'model' that might be applied more generally to other problems as well.

1.2.1.2 Productivity and Quality

Production systems are designed to maximise profits through productivity or quality outputs. This focus often excludes human factors.

There is increasing awareness of the strategic value of ergonomics for companies (Dul, 2003b). Konningsveld (2003) has described how ergonomics can be integrated with core business performance such as productivity, lead-time, reliability of delivery, quality, and flexibility. Recent research in the quality field suggests that around 30-50% of quality deficits are related to poor ergonomics (Axelsson, 2000; Drury, 2000; Eklund, 1995; Lin et al., 2001). The high rate of failure of manufacturing initiatives (Clegg et al., 2002) has also been associated with failures to accomodate human factors (Nadin et al., 2001). Under these circumstances it should be easy to justify ergonomics since multiple objectives

> **"…the time required for the task and the postural deficiencies were together able to account for 50% of the quality variance on each assembly line"** - Lin et al. (2001)

are achieved simultaneously. The case for productivity can be more difficult since the most obvious way to increase productivity is to simply make the production system operators work faster, thereby increasing MSD risk. Nevertheless economic analysis can demonstrate how profitability can be enhanced through better health and safety (Aaras, 1994; Hendrick, 1996; Oxenburgh et al., 2004).

In this thesis I argue for a joint optimisation approach whereby humans and other key system elements are simultaneously considered so that globally optimal solutions to the production problem can be developed. Achieving this in practice is, proverbially, easier said than done.

1.2.2 Risk Factor Exposures in the Production System

Many risk factors for MSDs, including physical and psychosocial factors, have been identified. Being able to measure risk factors is important as these act as *leading indicators* – allowing potential intervention before MSDs occur.

The exposure of production operators to risk factors (level 2 in the model in Figure 1) is an inescapable part of work. If ergonomic conditions are good risk will be low. That working postures and forces can cause musculoskeletal disorders has been known for over 300 years (Ramazzini, 1700). Nevertheless the last quarter of the 20th century saw a tremendous amount of research on the physical and psychosocial risk factors for MSDs and a number of excellent reviews exist (Ariens et al., 2000; Bernard, 1997; Bongers et al., 1993; Buckle and Deveraux, 1999; Buckle and Deveraux, 2002; de Beek and Hermans, 2000; Hoogendoorn et al., 2000b; Malchaire et al., 2001a; Netherlands, 2000). More recent epidemiological studies continue to corroborate these reports and enhance our understanding of the relationship between workplace demands and MSDs to the back (Hoogendoorn et al., 2000a; Hoogendoorn et al., 2001; Kerr et al., 2001), neck (Ariens et al., 2001a; Ariens et al., 2001b), neck & shoulder (Fredriksson et al., 2000; Östergren et al., 2001); and hand-wrist (Malchaire et al., 2001b). Conceptual models of MSD onset mechanisms have been developed (Armstrong et al., 1993; Kumar, 2001; McGill, 1997; NAC et al., 2001) that generally account for risk from high peak loads (Neumann et al., 1999c) as well as the accumulation of load or prolonged loading (Kumar, 1990; Kumar, 2001; McGill, 1997; Norman et al., 1998). Long exposure to very low amplitude load, or low variation repetitive movements, have also been associated with MSDs (Hagberg et al., 1995; Hägg, 1991; Westgaard, 1999; 2000; Winkel, 1985). These low level risks can be aggravated by poor psychosocial conditions, themselves an independent class of risk factor (Bongers et al., 1993; Karasek and Theorell, 1990; Kerr, 1997).

Utility of Quantifying Risk Factors: Identifying and quantifying risk factors may help understand how to prevent the emergence of these factors when production systems are created. Quantification of the factors associated with MSD is a useful approach to identifying potential problems before injury occurs – they present leading indicators of MSDs (Cole et al., 2003). Precise quantification can be used to provide specific design criteria to designers of the production system (Wulff et al., 1999a) as well as to help find solution pathways for problems identified in existing systems (Norman et al., 1998). Quantification of hazards can also act to build credibility in the negotiation of constraints for new designs (Perrow, 1983) and has potential to support the integration of ergonomics with other performance elements in the production system design process.

> **"It has been difficult to find the best compromise between the precision and cost of direct measurement exposure and the loss of precision and accuracy of less expensive …methods."** - Armstrong et al. 1993

Research Challenge: Measuring posturally related MSD risk factors poses an important measurement challenge (Burdorf, 1992; Burdorf and Laan, 1991). A number of approaches to risk factor quantification have been proposed including self report questionnaires, observational techniques and direct technical measurements (Mathiassen and Winkel, 2000; Neumann et al., 1999c; Van Der Beek and Frings-Dresen, 1998; Wells et al., 1997). Questionnaire approaches have not proven to be reliable (Burdorf and Laan, 1991). Observational techniques often try to account for the amount of time spent in particular posture categories (Neumann et al., 2001a; Punnet et al., 1991) but rarely capture the time-history of movement. Instrumented measurement approaches have identified movement velocities as a risk factor (e.g. Hansson et al., 2003; Marras et al., 1995), but are relatively expensive and require specialised training to operate. An approach is needed that can be used without special electronic equipment or educational requirements. Recently, video approaches have been developed to help workers identify and communicate specific physical workload related tasks (Kadefors and Forsman, 2000) and psychosocially problematic aspects of work (Johansson Hanse and

Forsman, 2001). While helpful, these approaches do not provide data on specific physical load demands, nor the dynamic or time aspects of working postures. Video analysis has potential for this kind of analysis although reliability, accuracy, and the indicators with best risk-predictive capability would need to be determined.

Paper 1 in this thesis presents a video-based approach to the quantification of posture-related risk factors for low back pain (LBP). In this study we tested the reliability, accuracy, and risk-relationship of indicators resulting from this measurement tool.

1.2.3 The Production System

Risk factors for MSD are related to the design of the production system and the nature of the work performed.

By production system I refer primarily to an operating system that manufactures a product (Wild, 1995) although many aspects of this discussion could also apply to other kinds of operating systems such as service provision. Risk factors emerge from the interactions between the individual operators and other elements (machines, materials) in the production system (Peterson, 1997). The production system has been described as a sociotechnical system with technical and social subsystems (Eijnatten et al., 1993).

> **"…production systems should be designed as tools for the shop-floor employee, that these employees are trained and motivated to use their judgment and abilities, and that such systems are organised for continuous innovation and market exploration. "**
> - Badham et al. 1995

It is the nature of the work itself that will primarily determine the operators' mechanical exposure profile (Allread et al., 2000; Kerr, 1997; Wells et al., 1999). The design of the system therefore will provide a number of performance constraints for the worker who must perform within the assigned parameters. From this perspective the design of the work becomes a critical element in determining the loading pattern, and hence injury risk. Many risk factor studies have focussed on operator aspects, such as posture or lifting activities (Bernard, 1997), fewer studies have identified risk associated directly with production system performance features such as cycle time (Silverstein et al., 1987). Mathiassen and Winkel (1996) found that reductions in work pace, controlled using the engineering methods-time-measurement (MTM) system, were associated with similar reductions in muscle activity, heart rate, perceived effort, and muscle tenderness. Bao et al. (1997) have shown that well balanced production lines with fewer production irregularities result in higher movement rates, increased time-density of muscle activation, and hence decreased tissue recovery time than less well balanced systems. These few studies suggest that risk factors in the realised production system are related to the design of the system itself. Where in the design process risk emerges does not appear to be well understood.

Papers 2 & 3 in this thesis both examine production systems that have undergone redesign after changes production strategy.

1.2.4 Ergonomic Impact of Production System Design

The production system itself is the product of a design process. The design process will shape the eventual production system which, in turn will determine MSD risk factor levels for system operators.

The design of the production system is divided into two main areas of concern: 1) the setting of production strategy, primarily the responsibility of corporate management, and 2) the system design process itself (Figure 1). Understanding the design process provides a first step to understanding how designers deal with ergonomic factors in their work.

Production system design decisions are made within the context of the direction established by the corporation's production strategy. Very few studies have examined this process with regards to ergonomics. Skepper et al. (2000) have described a deliberately simplified design process with a linear series of stages with iterative elements. In the case of product design, the process has been shown to be neither rational nor linear but instead represents a complex organisational process involving uncertainty, iteration, and negotiation (e.g. Broberg, 1997). Burns & Vincente (2000), examining control station design, have described the negotiation process involved in resolving the web of design constraints which often conflict. Designers of complex systems can face an overwhelming number of criteria and constraints and conflicts must be resolved based on personal interpretation as well as the influence of other stakeholders (Wulff et al., 2000; Wulff et al., 1999a; b). In this context, knowledge of ergonomic factors in design decisions does not necessarily guarantee their implementation, especially when these are seen as 'soft' or 'vague' criteria which are difficult to verify or demonstrate (Wulff et al., 2000; Wulff et al., 1999b). Even when ergonomic factors are applied to a local design aspect this does not guarantee success because locally optimal ergonomic design do not necessarily result in globally optimal solutions in the resulting system (Burns and Vicente, 2000). There has been little systematic documentation regarding the relationships between decision-making at this level and the emergence of MSD risk factors in the production system. Indeed it seems that there is generally a lack of feedback to designers about problems that emerge in the systems that they design:

> *"Short of a well publicised catastrophe, the design engineer will probably never know the consequences of his or her design, and top management will only hear of it faintly and perhaps not until the next project is already under construction."* (Perrow, 1983)

For this reason the model makes explicit the production strategies chosen in the development of the new system.

1.2.5 Production Strategy as an Ergonomic Determinant

Strategic choices in design may be a root source of MSDs. Production system designers react to strategic priorities set by senior management. Strategic thinking sets the stage for system design and eventual MSD risk factor patterns.

Some 75 years after Ramazzini began writing on the medical consequences of poor ergonomics (although the word "ergonomics" was not coined until 150 years later by Jastrzebowski in 1857 (Koradecka, 2001)), Adam Smith described the productivity benefits he observed in of the division of labour (Smith, 1776). By the twentieth century authors such as Taylor (Taylor, 1911) had extended the idea of division of labour into a strategy of 'Scientific management" whereby the work of assembly was atomised into minute tasks with each worker repeating their task many times. This strategy set the foundation for the modern assembly line as first realised by Henry Ford in his car factories (Ford, 1926). Since the time of Taylor we have seen a vast array of production strategies presented and discussed in both scientific and popular literature. Some of these, such as the famous 'lean manufacturing' (Womack et al., 1990), or 'reflexive production' (Ellegård et al., 1992), may really be thought of as a collection of strategic elements intended to work in concert. In this thesis I emphasise the importance of *'production strategy'* (at level 5 in the model in figure 1) because these reflect fundamental choices early in the development process that set the stage for risk factor patterns in the resulting system. Production strategies, I argue, present the seeds from which operators' MSDs can result. Compared to the volume of research around risk factors very little is known about production strategies from an ergonomics perspective.

> **"The greatest improvement in the productive powers of labour… seem to have been the effects of the division of labour"** *- Adam Smith (1776)*

Strategy is a broad and imprecise term. Mintzberg (1987) characterised strategy as a plan, a pattern, a position, a ploy, or as a perspective. Manufacturing can include a number of the characteristics outlined by Mintzberg (1987). 'Just In Time' (JIT), for example, has been termed a philosophy that incorporates a number of more specific strategies (Gunasekaran and Cecille, 1998) such as reduction in buffer sizes, and fast change-over. The extent to which a strategy is realised in practice may vary (Ghobadian and Gallear, 2001; Womack et al., 1990), with the gap between strategy and practice being apparently a more important indicator of (poor) performance than the strategy itself (Rho et al., 2001). It is difficult therefore to determine the ergonomic consequences of production strategies directly without considering the specific implementation for each case . Winkel & Aronsson (2000) have discussed the strategic objective of 'flexibility' with respect to potential ergonomic impacts in a number of performance areas. Reviewers suggest that some production strategies, such as business process reengineering, may provide better potential for good ergonomics than do other strategies, such as lean manufacturing (Björkman, 1996; Eklund and Berggren, 2001). Like other design decisions, strategies can be difficult to isolate and cannot always be directly measured but must be inferred from observation. Strategic decisions regarding manufacturing approaches occur relatively infrequently and are most obvious during the development of a new production system that may then operate for a number of years.

Health consequences of different production strategies are not well understood although the linkages between these strategies and ergonomics is readily apparent (Björkman, 1996). Vahtera et al. (1997) have found MSD risk to increase by 5.7 times during 'corporate downsizing'. The individuals' perception of the downsizing process itself also appears to affect health (Kivivmäki et al., 2001; Pepper et al., 2003). Landbergis et al. (1999), in their review of available literature, noted increased negative health outcomes are often associated with the adoption of Lean Manufacturing approaches. Karltun et al. (1998) found signs of increased physical loading with the implementation of ISO 9000 standards. Looking at more specific system design elements Coury et al. (2000) have demonstrated increased physical risk with partial automation strategies which couple workers more tightly to the production system. An increasing number of studies are finding risk increases with the adoption of line-based production approaches (Fredriksson et al., 2001; Neumann et al., 2002; Ólafsdóttir and Rafnsson, 1998). On the positive side, Kadefors et al. (1996) found that ergonomics improved in the application of long-cycle parallelised assembly flows without sacrificing productivity. This small but growing body of research demonstrates how higher level strategic decisions can result in increased, or decreased, MSD risk for employees. Nevertheless, not enough is known to develop tools by which industrial stakeholders can judge the ergonomic consequences of their decisions.

Research needs

In papers 2 & 3 in this thesis we attempt to isolate 'strategic' production *elements* that form a critical role in shaping the production system. By dealing with specific strategic design choices we attempt to move beyond the 'lean' 'not-lean' dialectic initiated by Womack et al. (1990). It is in the early stages of design that the greatest lattitude for good ergonomics exist while the system concept is still malleable (Burns and Vicente, 2000; Engström et al., 1998; Imbeau et al., 2001; Kilker, 1999). Early design choices allocate the majority of project resources and set critical initial design constraints (Buur and Andreasen, 1989; Wild, 1995). While design choices at subsequent stages in the design process may affect MSD risk these are generally less expensive to retrofit, and are thus possible targets for shop floor level improvement schemes such as participatory ergonomics (Haimes and Carayon, 1998; Haines et al., 2002; Nagamachi, 1995; Noro and Imada, 1991). Strategic design elements, however, tend to be 'locked in' and thus pose critical decisions with regards to ergonomics. The relationship

> **"One of the main difficulties faced by ergonomists is that their contribution is generally solicited too late in the design process"** *- Imbeau et al. 2001*

between ergonomics, productivity, and these strategic design choices is not well understood and poses a critical research need.

Papers 2 & 3 explore the relationship between 'strategic' production system elements and their consequences for productivity and ergonomics in the resulting system.

1.3 System Contexts

When considering the system model's structure or behaviour, recall that influential factors can come from societal, organisational, and individual levels.

Figure 2 presents a simple model of the context in which decisions are made by individuals in the system modelled in Figure 1. In this simplified model I present just three contextual levels: Society, Organisation, and Individual. This is consistent with other available models (Hatch, 1997; Mathiassen et al., 2000; Moray, 2000; Rasmussen, 1997).

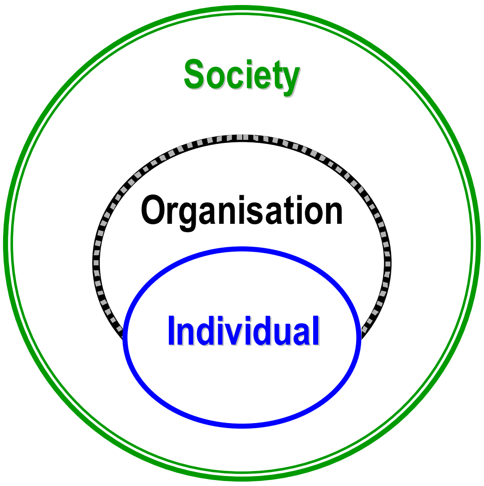

Figure 2: *A contextual model for the theoretical framework (in figure 1) identifying individual, organisational and society levels which will influence the development system's behaviour and response to intervention.*

1.3.1 Societal Context of Ergonomics

Companies are acting in a society with particular market conditions, legislation, and cultural attitudes. These forces create the context in which the organisation operates and can influence ergonomics.

Social contexts influence selection of production models (Boyer and Freyssenet, 2002), and influence change processes (Bamford and Forrester, 2003). Current social trends of relevance for ergonomics may include: rapid pace of change – with technology changing faster than management structures, increasing scale of industrial operations (globalisation), integration of operations (with tight supply chains), aggressive competition, work intensification, and deregulation (D'Aveni, 1994; Docherty et al., 2002; Mergler, 1999; Merllié and Paoli, 2000; Moray, 2000; O'Neill, 2000; Paoli and Merllié, 2001; Rasmussen, 2000; St.John et al., 2001).

This thesis does not specifically study social factors. Nevertheless, companies are social institutions (Hatch, 1997) and design is a social process that plays out in an array of conflicting interests (Gustavsen et al., 1996) and is thus inherently (micro) political (Broberg, 1997; Engström et al., 1998). Organisations and individuals both act on and are acted upon by their social environment.

1.3.2 Organisational Context of Ergonomics

How a company responds to an intervention effort will depend in part on the structure and culture of the organization. These factors can also influence how well human factors are incorporated in production system design.

The developmental model presented (Figure 1) is embedded in an organisation. Organisations have many features including a social structure, organisational culture, physical structure, technology, and strategic profile (Hatch, 1997), each of which can influence developmental and change processes.

From an interventionist perspective, involvement of a broad range of stakeholders in the organisation has shown good promise for effective ergonomics development (Gustavsen et al., 1996; Westgaard and Winkel, 1997). Securing support of these stakeholders may require an attempt to 'solve ergonomics problems in a profitable way' (Winkel and Westgaard, 1996). By emphasising the interconnectedness of ergonomics and productivity it may be possible to 'jointly optimise' these two output domains – an approach advocated by a growing number of researchers (e.g. Burns and Vicente, 2000; Clegg, 2000; de Looze et al., 2003; Gustavsen et al., 1996; Hendrick and Kleiner, 2001; Huzzard, 2003; Ingelgård and Norrgren, 2001). Achieving this is a problem of organisational change – an entire field of study itself (Hatch, 1997). Saka (2001), among others, has pointed out the organisational complexities here:

> *"The heavy emphasis in the literature on a rational-linear approach to understanding organisational change overlooks the significance of the cultural and political dimensions of organisational life."* - (Saka, 2001)

This irrational nature of organisational change might even be exacerbated by an organisation's own psychotic tendencies (De Vries, 2004). Broberg and Hermenud (2004) have also emphasised politicality suggesting that ergonomists need to act as 'political reflective navigators' as they attempt to negotiate priorities in a company's development projects amongst a network of different actors. Organisational actors such as production engineers tend, for example, to have no social mandate (Ekman Philips, 1990), to have little ergonomics training (Neumann et al., 1999a), and can be technology focussed (Kilker, 1999) which can provide a tremendous contrast to the ergonomist's own context.

1.3.3 Individual Contexts of Ergonomics

How individuals respond to the work demands will depend on their role in the company and their physical and mental capacities. We humans are only partially rational.

'Individuals' in this model are everywhere in the organisation – not just the production operator. The operator is important and individual tolerance to some physical load patterns vary with individual characteristics (Kilbom and Persson, 1987; NAC et al., 2001; NRC and Panel on musculoskeletal disorders and the workplace, 2001), and tolerance may be successfully improved (Westgaard, 2000; Westgaard and Winkel, 1997). This model attempts to highlight he role of all the stakeholders in the organisation who might influence the development process – and thus MSD risk factors – in the organisation. When dealing with a specific individual the arch types from general analysis (Ekman Philips, 1990; Neumann et al., 1999a) may not apply fully – the practitioner must be open to the uniqueness of the individual. Furthermore, humans tend to operate within a 'bounded' rationality (Schwartz, 2002); implying a certain amount of irrationality, or non-linearity, in the entire system (Guastello, 2003; Skyttner, 2001).

"When individuals are not involved in establishing their goals, they are much less likely to feel motivated to achieve them than when they are allowed to participate in the process" - *Hatch 1997*

1.4 The Challenge of Intervention in a Complex System

To be most effective ergonomic considerations should be a natural part of the development process focussed on improving total system performance. This is easier said than done.

While the system under study is complex (Backström et al., 2002; Guastello, 2003), research tends to be conducted along traditional academic lines. The problem, as Rasmussen (1997) points out, is that there is very little research that spans the problem domain. Since there are non-linear and dynamic connections between system elements, the models generated by different academic disciplines cannot be simply stuck together. Greenwood, from the social sciences, rails against this problem:

> *"The world does not deliver social problems in neat disciplinary packages, despite the pathetic insistence of most academic social scientists in defending their academic turfs against all other forms of knowledge"* (Greenwood, 2002).

What is needed, according to Rasmussen (1997), are 'vertical' studies of the system behaviour that engage a broad range of skills and perspectives. This is proving difficult as there is almost no attention to ergonomics, for example, in the management literature (Dul, 2003a) and the incorporation of management science perspectives in ergonomics may be similarly absent.

> **"…effective risk management strategies cannot be developed by the integration of the results of horizontally oriented research within the various disciplines… Instead vertical studies of the control structure are required."** *- Rasmussen (1997)*

Despite many successful ergonomics case studies (Aaras, 1994; Abrahamsson, 2000; EASHW, 2000a; GAO, 1997; Hendrick, 1996; Kemmelert, 1996; US Federal Register, 2000) researchers have generally had difficulty demonstrating consistent effects when trying to intervene in businesses for better ergonomics (Westgaard and Winkel, 1997). Karsh et al. (2001) have expressed the problem thus:

> *"A pressing problem that has plagued ergonomic intervention research is the lack of understanding as to why seemingly identical interventions work in some instances but not in others... We propose that research pay special attention to various implementation approaches to ergonomic interventions."* (Karsh et al., 2001)

From an organizational change perspective this is a classic problem, and from a systems perspective this is hardly surprising. Growing evidence (Burnes, 2004; Clegg et al., 2002) indicates that 50-75% of organisational change efforts and attempts to implement advanced manufacturing processes are not successful. Researchers are suggesting that these failures relate less to technical failures than to failures to accommodate people (Badham et al., 1995; Das, 1999; Nadin et al., 2001) – an example of how poor ergonomics can undermine system effectiveness.

Researchers in both organisational development and ergonomics communities point out that "ergonomic" interventions engaging a broad range of organisational actors who own the process show most promise for success (Gustavsen et al., 1996; Westgaard and Winkel, 1997). Similarly Bamford and Foster (2003) point out that:

> *"In today's business environment, one dimensional change interventions are likely to generate only short term results and heighten instability rather than reduce it."* (Bamford and Forrester, 2003)

Considering the time dimensions of change Bateman and Rich (2003) claim that:

> *" 'Point Changes' without sufficient infrastructure to support improvements, at the business level, are unlikely to yield real and sustainable change."* (Bateman and Rich, 2003)

Considering this evidence we see a need to integrate ergonomics into the development process to avoid the expense and delay of retrofitting processes. In order to avoid 'one dimensional change' it may be helpful to emphasise the performance benefits along with the health benefits of good ergonomics (Dul, 2003b; 2004). Figure 1.4 provides an illustration of how design may lead to a doube-win, or synergy effect, if productivity and ergonomics goals are optimised jointly for increased total system performance (Gustavsen et al., 1996; Huzzard, 2003). If increasing the engagement of personnel in human factors is not to be a 'point change' then an evolutionary seems appropriate to accommodate the time needed to change organisational practice. In order to support better management of human factors throughout the development process, particularly in the early stages of development, we see a need to improve utilisation of leading indicators of MSDs, such as risk factors, in the design process. Achieving this will require 1) tools by which risk can be identified and quantified, 2) an understanding of how and where risk emerges in the design process, and 3) development of the design process itself so that ergonomic issues are actively managed and integrated with technology concerns throughout the process.

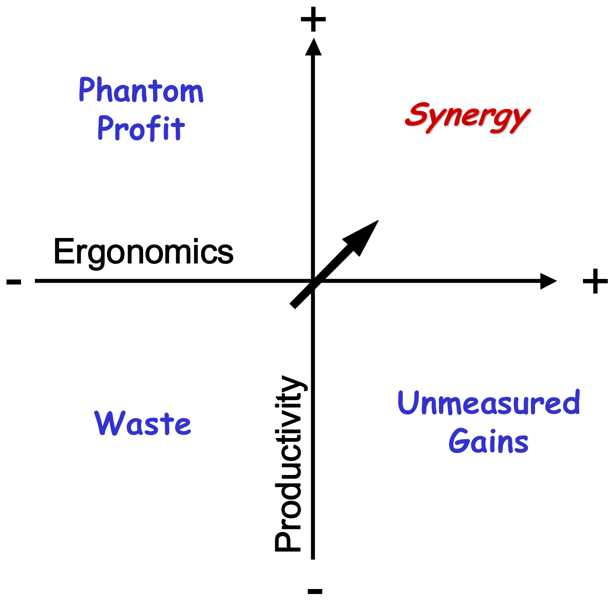

Figure 1.4: *A simple 2 dimensional model illustrates how a 'navigator' can attempt to steer development. A synergy effect may be achieved if ergonomics and other productivity aspects are optimised jointly (top right). Although good ergonomics may have 'hidden' gains not immediately visible in productivity data (bottom right), poor ergonomics may compromise anticipated productivity - phantom profit (top left).*

1.5 Thesis Papers & Research Aims

This thesis incorporates four (4) journal articles that study vertical linkages in the model (figure 1). First the ability to identify risk before MSDs occur is addressed. Then the sources of risk in production system development are explored. Finally an attempt to integrate human factors into regular development work is studied.

1. The aim of paper #1 was to develop and evaluate a video based tool for quantifying postural factors at work in terms of inter-observer reliability, accuracy, and association with risk of reporting low back pain at work. This paper illustrates the relationship between risk factors and MSDs illustrated at the bottom of the theoretical model (figure 1: level 2 to level 1 linkage).

2. The aim of paper #2 was to examine the productivity and ergonomics consequences of a strategic redesign of a production system. In this case automation of assembly and automatic serial-flow strategies were implemented in electronics assembly. In this study we attempt to link high-level system elements (strategy) to lower levels (risk & output levels) in the system model (Figure 1: level 5 to level 2 & 1 linkages).

3. The aim of paper #3, similar to paper 2, was to examine productivity and ergonomics consequences of a change in production strategy from a long-cycle parallel flow workshop to a serial flow line assembly. Here, as in paper 2, we make a 'vertical' analysis through the development system (Figure 1: level 5 to level 2 & 1 linkages).

4. The aim of paper #4 was to investigate how ergonomics might be integrated into a company's regular development process, with special focus on barriers and assists to achieving such integration. This study focuses on the organisational level (Figure 2) and includes the entire development process (Figure 1).

2 METHODS

2.1 Paper 1: A Tool for Quantifying MSD Risk Factors

Paper 1 describes the development and evaluation of a video-based tool to track working postures. The relationship of postural indicators to risk was then quantified by comparing workers with and without low back pain.

The Measurement tool (Figure 2.1) uses videotapes that can be recorded in the field without interfering with the operator. The section of video to be analysed is first digitised and stored on the computer. The analyst then controls playback speed while recording trunk flexion-extension and lateral bending position on continuous scales using a joystick. Twisting postures were recorded using a binary on-off scale and was considered present whenever the line between the shoulders was angled more than 20 degrees from the line between the hips. During analysis the computer would sample the joystick (or keyboard) input device once for every frame of video while providing feedback to the analyst with a mannequin image. The system provides a continuous time-history of posture, visually synchronised to video, from which exposure parameters relating to flexion amplitude, duration of flexed postures, and flexion velocity can be extracted.

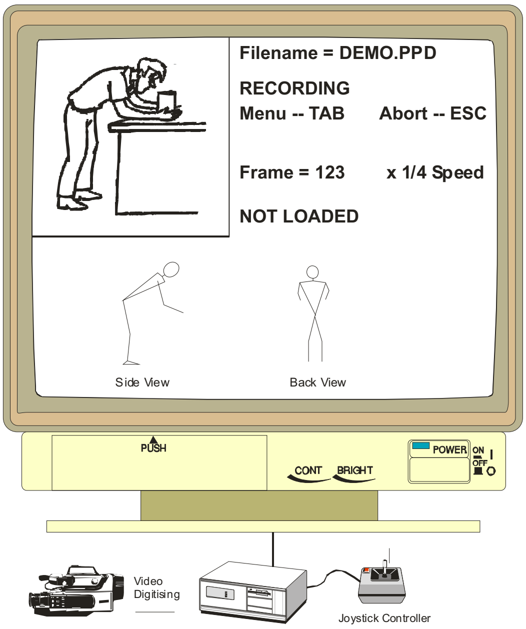

Figure 2.1: *Video analysis system in which field recorded video is digitised and then analysed using a joystick to track posture.*

The inter-observer reliability of the system was assessed by having seven (7) trained observers analyse video from the same ten (10) production jobs. The jobs were selected from the epidemiological study database to include the variety of work observed in the field. The inter-observer reliability data were analysed using intra-class correlation coefficients (ICC) to provide indexes of similarity between observers relative to the range of job exposures observed (Shrout & Fleiss, 1979).

System accuracy was determined by comparison to a laboratory based optoelectric reference system that was considered a 'gold-standard'. Eight (8) trained analysts each analysed the same 1 minute video which had been recorded synchronously with the referent system. Comparisons between the video and referent systems were made for both the time series data and for the amplitude probability distribution function (APDF) data. The accuracy assessment included the calculation of RMS differences between the APDF data from reference and new systems, and average differences for selected variables of interest, and Pearson correlations between observer results and those of the reference system for both time-series and APDF data.

Methodological Background – The Ontario Universities Back Pain Study (OUBPS)

The OUBPS examined physical and psychosocial risk factors related to low back pain in workers at General Motors in Canada. It remains one of the world's largest most comprehensive databases of workplace exposure measures.

In the 1980s and early 90's researchers were debating weather risk for low back pain (LBP) was entirely psychosocial or entirely biomechanical – a polemic Frank et al. dubbed 'unhelpful' (1995). In response to this controversy the Institute for Work & Health in Toronto, Canada initiated the Ontario Universities Back Pain Study (OUBPS), a large incident case-control study at General Motors in Ontario, Canada where 10,000 hourly employed workers formed the study base. The study, which engaged a multidisciplinary team from a number of universities in Ontario, included state of the art in epidemiological design as well as the best psychosocial and biomechanical data collection techniques available (Andrews et al., 1996; Andrews et al., 1997; 1998; Kerr, 1997; Kerr et al., 2001; Neumann, 1999; Neumann et al., 1995; Neumann et al., 1999c; Neumann et al., 2001a; Neumann et al., 2001b; Norman et al., 1998; Wells et al., 1997; Wells et al., 1993). Biomechanical exposure data was collected over 2 ½ years from a remote research centre established at the site where cars were produced 24 hours/day in two car plants and 16 hours / day in a truck plant. Biomechanical measure development, field operations, data collection, and data analysis were the author's primary responsibility from 1992 to 1996.

(see results section for further details on the OUBPS)

The risk association of exposure variables quantified by the system to the reporting of low back pain was determined within a case-control study of low back pain in the automotive industry. Incident low back pain cases (105), defined as workers who reported low back pain to the company nursing stations, were recruited. Controls (129) were selected randomly from the company rosters synchronously with incident cases. No subjects had reported pain in the previous 90 days. The relationships between kinematic indicators and case-status were explored in a series of bi-variable comparisons as well as through multivariable logistic regression modelling.

2.2 Paper 2: Automation Strategies in the Electronics Sector

In paper 2 we used multiple methods to examine ergonomics and productivity consequences in a case of automation technology implementation in electronics assembly.

The Case: An electronics company decided to increase automation of assembly and to adopt an automated line-conveyor system in its manufacturing of AC/DC power converters for the telecommunications industry. This automation was intended to improve the technical performance of the system. The company was concerned about ergonomic conditions in the new system and engaged the research team, through the COPE (Co-operative for Optimisation of Industrial Production Systems Regarding Productivity and Ergonomics) program (Winkel et al., 1999). The COPE team assisted the company in making its own ergonomics assessments for its work-organisation team from the design group.

Evaluation Approach: The research team evaluated the ergonomic and technical consequences of the production system re-design using detailed video analysis of working activities (Engström and Medbo, 1997; Medbo, 1998), production information available from company records and interviews with company personnel, and biomechanical modelling procedures (Neumann et al., 1999b; Norman et al., 1998). Comparisons were made at the level of the production system including data calculated to the ‘per product’ level and also expressed as a function of operator working hours. While information on psychosocial working conditions was gathered, this analysis focussed on the mechanical loading consequences of the re-design. A detailed analysis of ergonomic and technical performance at matching manual assembly was conducted. This allowed the assessment of some of the specific ergonomic consequences of the strategies applied in the new system.

In paper 2 the limited sample sizes available for comparisons of mechanical load variables precluded the use of statistical comparisons. Instead, multiple methods, supported with qualitative data (Cozby, 1989) from company personnel and researcher observations, were used in order to 'triangulate' and support key-findings (e.g. Mergler, 1999).

2.3 Paper 3: Cellular vs. Line Production Strategies

In Paper 3 we study productivity and ergonomics in a case of production strategy change from long-cycle cellular manufacturing to short-cycle serial line assembly.

The Case: This study was conducted in a Swedish company assembling large diesel engines. After decades of using a cellular manufacturing approach with parallel flow and long cycle times (1¼ hours), the company decided to implement a serial flow 'line' based assembly system with a cycle time under 5 minutes. This case appears consistent with a trend we have observed in Scandinavia to return to line-based production (Jürgens, 1997) after decades of using more sociotechnically based approaches (Engström et al., 2004; Forslin, 1990). This trend appears despite theoretical and empirical evidence that parallel flow assembly can be more effective (Ellegård et al., 1992; Engström et al., 1996; Medbo, 1999; Nagamachi, 1996; Rosengren, 1981) and have better physical and psychosocial ergonomics than conventional lines (Engström et al., 1995; Kadefors et al., 1996). This case allowed further exploration of the relationship between core system design elements, such as flow strategy or work organisation, and system outputs such as productivity and ergonomics. The product itself was largely unchanged between systems.

Evaluation Approach: We integrated qualitative and quantitative methods in the evaluation. Informal interviews and document analysis were conducted to understand both process and outcomes in the system redesign project. Production and economic data were obtained from company records and interviews. Questionnaires (n=54 pairs) were used to assess operators' perceptions of pain status (Kuorinka et al., 1987), workload (Borg, 1990), and psychosocial conditions (Karasek et al., 1998; Karasek and Theorell, 1990; Karasek, 1979; Rubenowitz, 1997). Video recordings were made and analysed (Engström and Medbo, 1997; Medbo, 1998) with respect to the time used for work activities including direct (e.g. value adding assembly) and indirect (e.g. getting components or checking instructions) work. Biomechanical models (Neumann et al., 1999b; Norman et al., 1998) were used to assess individual loading and flow simulation models were used to understand system behaviour and working patterns (AUTOMOD; AutoSimulations Inc, USA).

This was a pre-post case study and comparisons were made with 1year interval for 2 matching months to control for seasonal production variability. The data from these methods were used to support an analysis of the advantages and disadvantages, in terms of both productivity and ergonomics, for each of the major elements in the production system design: The adoption of serial flow with its associated reduction in cycle time, workstation layouts, material supply sub-system, change away from product kits, the adoption of automated guided vehicles (AGVs) for transport and IT systems, and the work organisation approach used. We focus our comparison on that portion of the production system which was changed from work cells ('OLD') to line assembly ('NEW').

2.4 Paper 4: Integrating Ergonomics into Development Work

Paper 4 reports on an 'action' research project in which we collaborate in a company's efforts to improve the way ergonomics issues are handled in the development and operation of their production systems.

In this longitudinal case study, a carry-on from the study in Paper 3, we adopted an 'action research' stance (Badham et al., 1995; Reason and Bradbury, 2001) as we participated cooperatively with the company in their efforts to integrate ergonomics into their business processes. This provides a close insider perspective on the organisational change process as it evolves over time (Toulmin and Gustavsen, 1996) allowing greater insight into the complexity of company processes (Ottosson, 2003). Throughout the process we participated in meetings and discussions providing advice and information to the best of our abilities. We also strove to avoid an overbearing "relationship of dependance" (Westlander, 1995) where the process became too dependent on the researchers which might lead it to collapse once we left the company (Siemieniuch and Sinclair, 2002). Our role therefore was more like a coach or advisor than a consultant or contractor. Field notes were made during and after site visits and meetings were tape recorded for review or sharing amongst the research team.

> **"Standardised questionnaires, structured interviews, and statistical analyses cannot begin to grasp the complex fabric of organizational change."** *– Badham et al. 1995*

Organisational change is incredibly complex (Ottosson, 2003). It is not possible to represent the 'whole' reality of this change in a linear narrative of limited length (such as this thesis)(Sørensen et al., 1996). It is important therefore, to acknowledge the 'filtering' process which necessarily occurs in presenting such a project (Pålshaugen, 1996). In this case we attempt to reflect on the case in terms of the theoretical base described in our introduction opening a kind of dialectic between theory and observation (Greenwood, 2002; Pettigrew et al., 2001; Vicente, 2000; Yin, 1994). Some researchers have argued that, since theory is created to reflect an evolved practice, action research is 'beyond' theory as it focuses on advancing current practice (Toulmin and Gustavsen, 1996). Here we also take the opportunity to advance current theory. In reporting this study we attempt to identify those aspects of the case which might, in a coherent fashion, be useful to other practitioners and researchers who are faced with their own organisational change 'mess' (Saka, 2001).

A paradigm shift in methodology?

The methodology adopted in paper 4 marks a departure from classical positivistic research. I will refrain from an extended discourse on research paradigms but agree generally that the use of numbers and statistics, must always come back to the world of language to become meaningful and, through this transition, enter the social domain of language mediated reality (Collins, 1984). With this in mind, I don't really understand the positivist hostility to social constructivism or what Ottosson refers to as the quantum (as opposed to the classical 'Newtonian') paradigm (Ottosson, 2003). With tongue in cheek I would say that positivists are simply social constructivists who tend to operate in a state of denial. More fruitfully I can say that we are moving into what Gibbons and colleagues have dubbed "Mode 2" knowledge generation in which knowledge regarding solutions to complex problems are studied *in situ*, transdisciplinarily, with a

> **"The underlying assumptions of positivism are indefensible: objectivity, controls, rational choice, etc. – all of these pillars have been taken down"** *- Greenwood, 2002*

focus on solution efficacy, and embedded knowledge exchange mechanisms that go beyond the usual peer review oversight (Gibbons, 1994). ‘Mode 2’ is seen as a response to societal needs for solutions to complex problems and diffusion of research occurring as a natural part of the process rather than the narrow communications channels institutionalised in the traditional disciplinary research (Mode 1) model. The ‘action research’ approach applied in paper 4 is one method for achieving this.

2.5 Methodological Overview

Table 1: *Key methodological features of the two papers presented in this thesis.*

Study Feature	*Paper 1*	*Paper 2*	*Paper 3*	*Paper 4*
Study Type	Epidemiological & method evaluation	Exploratory & Demonstration of causal theory	Exploratory & demonstration of causal theory	Action research & feedback intervention
Point of Focus	Individuals	Production systems	Production systems	Organisation
Study Design	Case-Control	Pre-Post Case	Pre-Post Case	Longitudinal intervention case
Industry	Automotive assembly	Electronics assembly	Motor assembly	Motor assembly
Study Location	Canada	Sweden	Sweden	Sweden
Subjects/ participants	Industrial workers, analysts	Industrial workers	Industrial workers	Managers, engineers, operators
Study Sample Size	Method evaluation (n=7-10) Epi. study (n=234)	Varies with level of analysis: video (n=1-5), Questionnaire (n=100+)	Varies with level of analysis: Video (n=1-12), Questionnaire (n=100+)	1 Society, 1 Organisation, 1-200 individuals
Focal Body Part	Low back	Shoulder & neck	Back, shoulder, neck, wrist & psychosocial	Whole body & psychosocial
Production focus	Not included	Production volume & changes in labour usage	Production volume, quality, changes in labour usage, costs	Companies own indicator set
Assessment Approach	Quantitative (video analysis)	Mixed qualitative and quantitative methods	Mixed qualitative and quantitative methods	Qualitative
Key Analysis	Inter-obs. reliability, criterion accuracy, case-control differences	Pre-Post productivity and ergonomic conditions of production system	Pre-Post productivity and ergonomic conditions of production system	Change process, change initiation

3. RESULTS

3.1 Paper 1: Tool Performance and Postural Risks for LBP

The tool appeared to have generally good performance characteristics for flexion/extension postures. Operators reporting low back pain bent their trunks more, further, and faster than operators not reporting low back pain.

Tool Evaluation. The results of the reliability study showed that the ICC for peak flexion and time-in-posture categories exceeded 0.8. Dynamic indicators such as peak velocity, average velocity, and flexion movement variables tended to have somewhat lower reliability coefficients. Inter-observer reliability was not good for variables relating to twisting and lateral bending. The accuracy assessment showed that flexion-extension time series data was highly correlated (r = 0.92) to data from the criterion optoelectric imaging system. The amplitude probability distribution function (APDF) data had, on average, an RMS difference of 5.8^{o} from the criterion system's APDF.

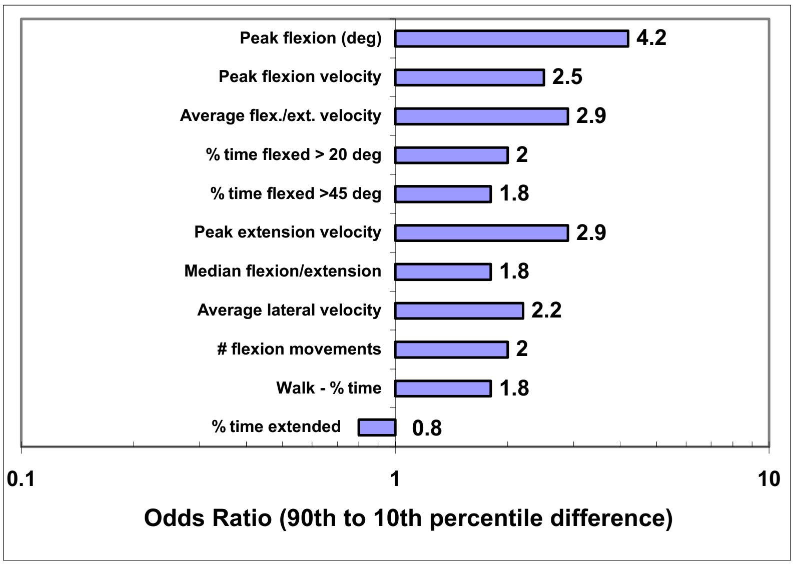

Figure 3.1: *Odds Ratios, plotted on a log scale, for trunk posture and movement variables with statistically significant case-control differences.*

Background Results – Main Findings of the OUBPS

The Ontario Universities back Pain Study (OUBPS) study showed clearly that biomechanical factors, psychosocial factors, as well as psychophysical factors were all independently associated with risk of low back pain reporting (Kerr, 1997; Kerr et al., 2001). Analysis of the biomechanical databases revealed that peak load and shift-cumulative load were both simultaneously and independently associated with LBP reporting risk, a result for which we received the International Biomechanics Society's *'Elsevier Clinical Biomechanics Award'* in 1997 (Norman et al., 1998). In my masters thesis (Neumann, 1999), I demonstrated how a pencil and paper based load and posture sampling technique can quantify peak and cumulative spinal load, both LBP risk factors (Neumann et al., 2001a) and how checklist, questionnaire, load and posture sampling, and video digitisation compared in quantifying peak spinal load: all methods identified risk at the group level but they could not always be used interchangeably at the individual level (Neumann et al., 1999c). Taken together these results demonstrate a number of different approaches to identifying and quantifying risk to both physical and psychosocial workplace factors associated with MSDs and that these factors all provide independent contribution to an individual's 'total' MSD risk. Noteworthy is that these independent risks **multiply** when present in combination.

The risk relationship study confirmed the importance of trunk kinematics as risk factors for low back pain reporting. Odds ratios for variables with significant case-control differences are plotted in Figure 3.1. In bi-variable logistic regression comparisons peak flexion accounted for the most variability in case status and had the highest odds ratio. Other significant predictors included peak and average velocities as well as the 'percent of time spent in flexion' category indicators. Multivariable modelling resulted in a final model with peak flexion level and average lateral velocity as risk factors. This model also included percent time in laterally bent postures, which was not significant in bi-variable comparisons, as a protective factor in the multivariable model.

3.2 Paper 2: Partial Automation in Electronics Assembly

The introduction of automation appeared to increase output efficiency. The assembly work remaining however showed increases in load amplitude and monotonous movement frequency.

The implemented re-design included strategies of automation of assembly, adoption of an automatic line transport strategy, construction of adjustable sit-stand workstations, and adoption of a new work organisation strategy. The technical and ergonomic consequences of the automation strategies implemented are qualitatively summarised in Table 3.2.1. The resulting system increased output volume 51% and reduced per-product labour inputs 21%. Management personnel reported the amount of quality work (required to reach 100% quality for delivered products) to be unchanged between the old and the new system. The automation strategies used resulted in a 34% reduction in manual assembly work and some increases in other work such as loading cases onto the new conveyor system and monitoring automatic machines. The line system had less buffering between stations and thus a reduced amount of work-in-process (WIP). Utilisation of manual assembly operators decreased due to forced waiting caused by occasional stoppages in the line-system related to the linear flow strategy.

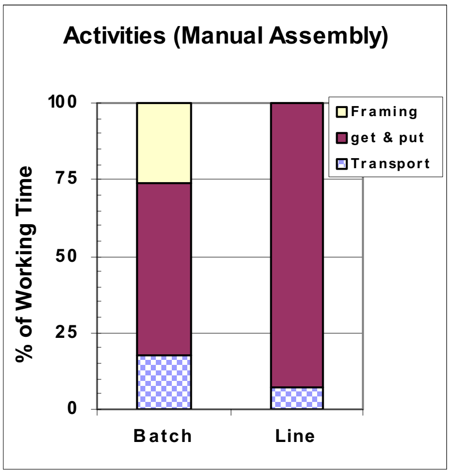

Figure 3.2.1: *Activity analysis for comparable manual assembly stations in the two production systems (from video analysis data used in biomechanical model)*

The examination of manual assembly work showed that, although both the old and new stations were responsible for approximately the same amount of assembly work, the new line-based workstation had less task variety and consisted almost exclusively of repeated reaching for and inserting ("get & put") components (Figure 3.2.1). The old system also included the activities of transporting product and mounting the product into a frame for the soldering operation. Task time analysis used with the biomechanical modelling procedure indicated a reduced task variety with over 90 percent of the new manual assembly operators time during uninterrupted production spent in "get & put" activities compared to 56% in the old parallel system. Increases in the percent of time with arms elevated, and increased average shoulder load were also observed (Figure 3.2.2). Head postures, however, tended to be less inclined as operators looked up when reaching to components elevated above table height. The workstation design provided sit-stand capability but postural changes by the operators were not frequently observed during field visits.

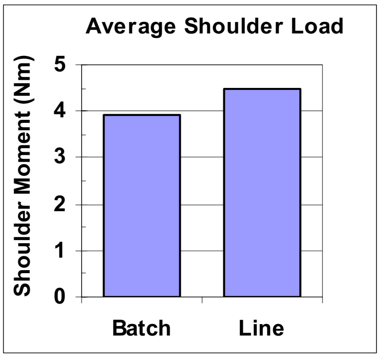

Figure 3.2.2: *Average shoulder load for operators at comparable manual assembly stations (from biomechanical model).*

The workforce on the new system consisted of fewer company employees and a larger number of individuals hired from a temporary agency compared to the old system. The work organisation strategy, developed by the work organisation team, was not implemented. Management personnel, who had not been involved in designing the work organisation strategy, felt the plan was unworkable. Instead particular operators staffed the jobs with complex loading patterns, such as robot supervision, without job rotation. Operators who rotated every shift in an informal pattern filled the remaining positions. The jobs in which rotation occurred tended to be low in task variability, such as manual assembly and visual inspection work, with frequent montonous upper arm movements.

Table 3.2.1: *A qualitative summary of the production and ergonomic consequences of the two partial automation strategies implemented in the re-designed production system. The table also identifies 'side-effects' that were observed in this case but appeared to be either sub-ordinate to or unintended effects from the implementation of the chosen strategy.*

	Production		Ergonomic	
Strategy	**Benefit**	**Deficit**	**Benefit**	**Deficit**
Assembly Automation	Reduced manual assembly work		Overall decrease in monotonous work (system)	
		Increased machine support work	Increased variable work	Some awkward bending and reaching
Side Effect (Some parts could not be automated)		Shift of components back to manual assembly workers		Increased shoulder loading (parts on elevated rack)
Automatic Line Transport System	Reduced manual transportation work	High capital costs		Reduced variability of work
	Reduced handling of product in preparation for assembly		Some reduction in handling activities	Increased arm elevation & average shoulder moment
Side Effect: (Disturbances in un-buffered system)	Reduced work in process (WIP)	Decreased operator utilisation (due to forced waiting)	Forced waiting may provide recovery time for some, but not all, operators.	

3.3 Paper 3: Results

The new line system had slightly higher output with higher costs, poorer physical ergonomics and worker autonomy, but better co-worker support compared to the old cell assembly.

OLD system (left side Fig 3.3.1): The OLD production system, designed with 18 'dock' stations, was studied having 12 Docks and a small 'learning line' in parallel for newer Operators. Operators worked alone at each dock to assemble each motor. Operators were required to finish 5 engines per day, which increased to 5.5 shortly before measurement. Operators could stop working once this quota was reached. The system was designed, based on standard times, to allow 6.2 motors to be completed per shift per dock but this target was not enforced and not all operators were believed to be capable of this pace. Hand steered motorized carts allowed transport and lift-tilt position adjustment of motors. Parts were supplied to the dock using a 5-shelf 'kit' stocked with variant specific components by 'order pickers'.

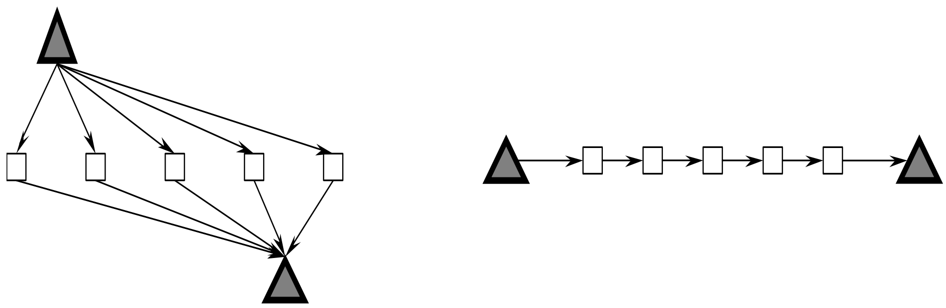

Figure 3.3.1: *Schematic diagrams, abridged to illustrate flow principle with 5 stations (squares) between 2 buffers (triangles), for the OLD parallel flow system (left) and the NEW serial line system(right)..*

NEW system (right side Fig. 3.3.1): The NEW line system used a serial flow of 18 stations. Automated Guided Vehicles (AGVs) provided motor transport and eliminated short walks between assembly cycles. Parts were supplied directly to the line in large crates. Operators retrieved parts directly from the crates occasionally adopting awkward postures. The AGV contained a computer monitor providing part numbers for the particular variant to the operator. The product itself was largely unchanged between OLD and NEW systems requiring about the same component assembly work. There were however many product variants requiring different components that, for lower volume variants, were positioned further away from the operators' workstation resulting in load carrying.

Production volumes, a primary change driver, were 12% higher in the NEW system where cycle times had been reduced to 6% of those in the OLD system. Time to learn a single station in the new system was about 1 day although time to learn the entire system, an organisational objective, was about the same in both systems at 1 month. Total staffing levels were about the same with 46 people in the OLD and 47 in the NEW system – 6 persons were no longer needed to pick OLD kits, but 7 more people were needed along the NEW line. Unit labour costs were 3% higher in the NEW system when adjusted for scheduled wage rate increase. Costs per motor were 32% higher in the NEW system in the period of comparison driven mostly by capital and support costs for the new high-tech AGV system.

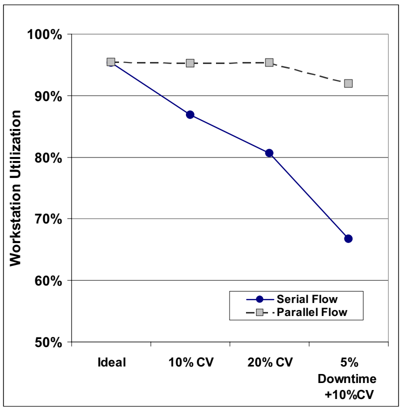

Figure 3.3.2: *Flow simulation illustrating effects of operator variability (modeled here using a coefficient of variation (CV) of 10%, 20% of mean cycle time, and 10% CV with 5% machine downtime) on workstation utilisation – an indicator of operator/station efficiency.*

As predicted by the companies own corporate standard *"serial flows with short cycle times generate waiting times that are not experienced as pauses but as disturbances in the work rhythm. This also generates accelerated work with poor ergonomics as a consequence."* (Backman, 2003). We observed this in the video analysis where waiting was 0.1% of assembly time in the OLD system and 18% of assembly time in the NEW system. This waiting was largely caused by starving and blocking disturbances that are inherent in serial flows with normal human variability in performance. Flow simulation illustrated (Figure 3.3.2) the effects of human variability and the additional vulnerability lines have to other disturbances such as machine downtime.

Psychosocial indicators revealed significant ($p<0.05$) reductions in Decision latitude and control over work scales and significant improvements in co-worker support and team climate scales. Figure 3.3.3 depicts the spread of operators' opinions when asked to make direct comparisons of the two systems themselves.

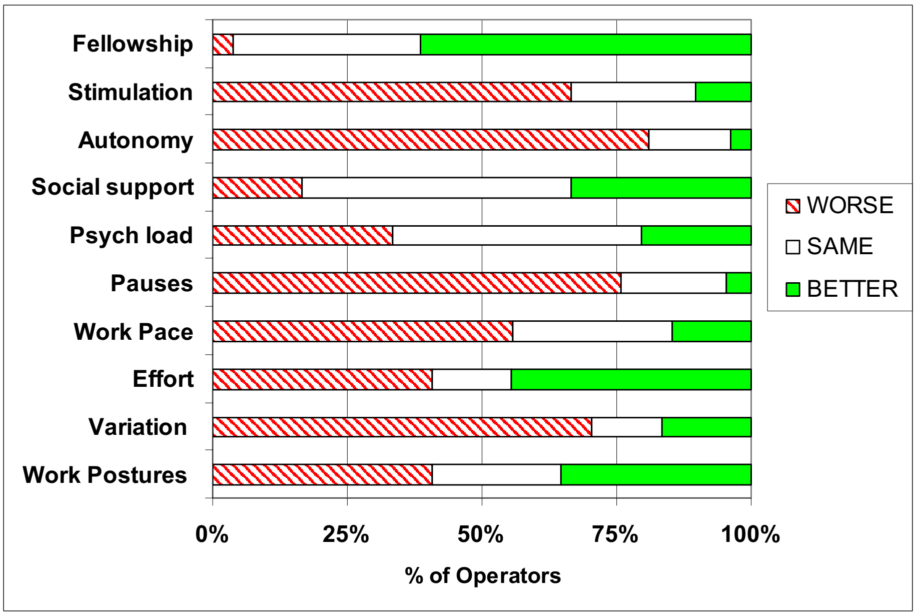

Figure 3.3.3: *Spread of opinion of operators with regards to how the OLD and NEW systems compared. 'Better' for each index is the response associated with better ergonomics e.g. reduced load, increased fellowship or increased variation at work.*

Pain levels were highest for the low back with 72% in the NEW system reporting pain in the previous 3 months, down 9% over OLD. Hand-wrist pain was also high and similar in both systems with 62% reporting pain in both systems. Shoulder pain increased 28% in the NEW system with 60% of operators reporting pain in the past 3 months. Perceived physical exertion rates showed a pattern similar to the pain reporting, ranged from 5.3-6.5 ("hard" to "very hard") on the Borg scale, and tended to be lower in the NEW system but were only significantly ($p<0.05$) reduced for the Back. We examined nut running activity on video recordings as an indicator of upper limb loading and found a range from under 500 nuts/day to just under 3000 nuts/day depending on the workstation. In comparison the old system, with its production quota, had a consistent load of about 1200 nuts/shift based on designed work pace. This unevenness of load was also observed for peak spinal loading which, when considered system wide, was similar in both systems with 470 N L4/L5 Shear load and 2600 N compression. In the NEW system however not all operators were exposed to the 'worst case' lifting situation every day.

Table 3.3.1 summarises the strategies' consequences observed in this case.

Table 3.3.1: *Summary of advantages and disadvantages, in terms of both ergonomics and productivity, observed with key design elements in this case. The dotted line between some elements indicates the tighter coupling of these particular elements.*

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

3.4 Paper 4: Integrating Ergonomics into Development Work

The change process was slow with inhibitors coming from both individual and organisational factors. The production manager, using internal knowledge to act as a 'political reflective navigator', was able to steer the process forward.

3.4.1 The Case Story

Initiation: When the results from paper 3 were presented to the project steering group the production manager (PM) emphasised his vision statement that "*operators should be able to continue to work in these systems up to retirement"*. Having seen the systems comparison (in paper 3) he wished to see action to capitalise on the new knowledge. Realising that the steering group was too large to analyse the problem effectively he created an 'Analysis group' charged with identifying opportunities for improvement as part of a 'Production Ergonomics' (ProErg) initiative. The analysis group included union, health & safety service, line supervision, engineering and research representatives. After a series of discussions the group returned suggesting the creation of three working groups: 1) 'Return to Work' for rehabilitation issues, 2) 'Future' group for line development, and 3) 'Measurement' group to improve information gathering and utilisation. These groups began to form and, as needed, created sub-groups to deal with specific tasks or activities such as making improvements based on an ergonomics audit. Initiation of activity was fastest when it involved persons already engaged in the process and took some time when persons new to the process needed to be recruited. This period was marked by considerable activity surrounding 'ergonomics' in the company and many small improvements were implemented. The group could not deal with improvements related to more central system features such as the material supply system as they were too expensive.

Reflection – The group structure chosen initially made sense to the company. The researchers had entered the company through the production department via the PM who provided strong support and a clear vision. The structure created appeared to reinforce the position of ergonomics as a 'production' issue with little engagement of system developers from engineering. For those not previously involved in the ProErg initiative the new tasks appeared to pose *additional work – not integrated with regular duties. Ergonomic problems relating to core system features appear to be "locked in" once built.*

Problems Emerge: A dramatic slowdown in activities was observed immediately after summer holidays with many meetings cancelled or postponed. It emerged that each of the three group leaders was being transferred to new positions in the company. Problems also emerged as some of the sub-group's activities began to intersect with other activities. Individuals with heavy workload were not sure how the 'new' ergonomics tasks should be prioritised, particularly when their supervisor from another department was not fully supportive of the initiative. Toward the end of this stage the company's safety engineer, who had been coordinating and driving the process, left work on sick leave and, sadly, died in January 2004 marking a low point in the project.

Reflection – Individual factors, including normal life events such as promotion, retirement, marriage, and cancer, all appeared to influence individuals ability and/or willingness, to engage in the change effort. Organisationally engineering groups responsible for system development remained distanced from the process, which thus remained a 'production' issue. The process was insufficiently anchored in daily work routines to survive the turbulences of ordinary life.

New opportunities: The production manager (PM) and researchers reflected upon the situation in the fall of 2003. The PM decided to lift the issue up to the site management group to inform and engage senior managers from other departments. At this meeting it became clear that developing the new system, not retrofitting the old system, was the primary focus of the engineering groups. The site manager called for a workshop so that knowledge gained from the system evaluation (paper 3) could be spread to the new system's design team. Having reviewed the system comparison data in the workshop, engineering management decided that developing ergonomics capabilities needed to be done outside the current development project which had tight budget and time constraints. Following the workshop a number of discussions were initiated engaging both engineering and the health and safety service. For example, the consideration of ergonomics through computer simulation technologies (Medbo and Neumann, 2004; Neumann et al., 1999b) was demonstrated and discussed in connection with development being made by the engineering groups.

Upon further reflection of how to better anchor ergonomics into the development process, the PM arranged for the company Ergonomist and Safety engineer to join the 'Assembly steering group', which was responsible for managing all assembly development via the company's product development gate system, the 'Global Development Process' (GDP). The PM saw the integration of ergonomics into the GDP as a strategy for locking in ergonomics considerations throughout the development process. Another tactic pursued by the PM was to establish an ergonomics training program for leadership, design teams, and assembly personnel to help improve knowledge and communications surrounding the management of MSD risk.

Reflection – Here we see the PM acting politically to gain support for his vision. Having researchers present 'hard' data on both technical and human factors appeared to establish credibility for ergonomics concepts and created a forum for further development of ergonomics capability in design. By integrating health and safety personnel into the steering group the PM signalled the importance of this issue in development. Targeting the GDP as an area for ergonomic improvement sets the stage for the PM to 'lock-in' ergonomics and provides a practical opening to engage the H&S personnel in early stages of process development.

3.4.2 Stakeholder Analysis

The company had divided responsibility for development between a number of organisational units. 'Product development', for example, was based in different city from the manufacturing facility. 'Pre-Production Engineering' was responsible for the basic form and flow strategy of the system, while 'Production Engineering', closest to the production system, was responsible for more detailed workstation layouts and assembly task distribution. 'Purchasing' and 'Logistics' were responsible for supply of components to the system including the choice of parts containers – frequently large crates from which parts were manually extracted on the line.

Reflection – By mapping these stakeholders onto the development model (Figure 3.4.2) we were able to see how influence on the design task was distributed through the organisation. 'Engaging engineering' as an objective for ergonomics therefore is not a simple task but affects a number of groups, some of whom had not yet been engaged by the ProErg initiative. Similarly, *the responsibility for system ergonomics is distributed across a number of groups each trying to make their zone of responsibility as efficient as possible – leaving the possibility for poor ergonomics to emerge as these disparate elements are combined with crucial risk determining consequences.*

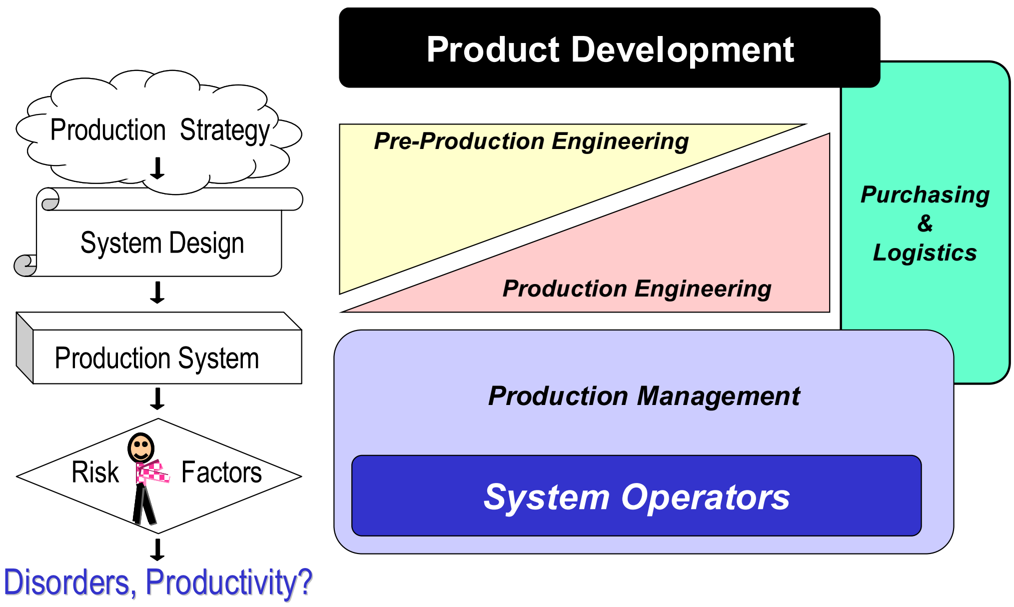

Figure 3.4.2 *Stakeholder map illustrating key organisational groups positioned according to their role at different stages in the development and operation of production system as modelled in Figure 1.*

4 DISCUSSION

This discussion reflects upon the model presented in the introduction in terms of what has been observed in these studies and attempts to further develop the theoretical model.

The re-examination of theory in light of empirical evidence allows both ‘testing’ of the model – is it useful? – and also further development of the model in areas where it is found lacking (Gustavsen et al., 1996; Yin, 1994). The intent here is to see how the papers, as a whole, interact and contribute to the understanding of the system and to the development of theory.

4.1 System Outputs: MSDs & Productivity

Clear relationships have been demonstrated between MSDs and workplace risk factors, in this case postural factors. Companies seem to have much more detailed data on productivity & quality than they do on MSDs.

Results - Paper 1 demonstrated the close coupling between risk factors at work, in this case working postures, and musculoskeletal disorder (MSD), in this case risk of reporting low back pain. This result is consistent with other methods applied in the same study (Neumann, 1999; Neumann et al., 2001a), and is also consistent with the broader literature (Bernard, 1997; de Beek and Hermans, 2000).

Papers 2 & 3 demonstrated the interconnections between strategic elements in the production system design and the ergonomic and productivity outputs of the system. The difficulty in using MSDs as an outcome in such a system design evaluation led to our using risk factors and pain reporting, proven to be leading indicators of risk in studies such as Paper 1, for MSD related disability as suggested by Cole et al. (2003). The complex interactions between productivity and risk associated with different strategies and the interactions observed amongst the strategies themselves (described in section 4.5) emphasises the need for designers to consider human factors and productivity outputs simultaneously throughout the design process.

The case of engine assembly (Papers 3 & 4) , highlighted the challenge for a company that had general sickness absence as a pooled outcome. Swedish regulations on privacy inhibit the gathering of more detailed information allowing a better understanding of the pattern of MSD related absenteeism inside the organisation. This in turn inhibited the company's efforts to manage this problem. In this case we saw that the company's gathering of quality and productivity data was much more detailed, and frequent, than for sickness and absence data. This provided a much richer source of feedback into the organisation and may be inhibiting uptake of ergonomics. Interestingly in both Papers 2 & 3 we observed changes in the way the company gathered their production data at the same time as the production system changed. Implementing an indicator improvement at such a time makes it difficult to compare the performance of the new and old system and reduces the risk that the new system might be seen as inferior to the old system – it eliminates the chance of failure.

Model Issues – Despite the possible variability of the risk-performance relationship, the model (Figure 1) points out that production systems with humans will always have some measure of risk. Systems theory points out that, in dynamic systems, the relationship between elements (in this case say risk factors and productivity) can be unstable over time and unexpected linkages can emerge (Skyttner, 2001). While the model (and this thesis) focuses on MSDs, other work related health outputs could be considered as appropriate to the situation being examined.

Methodological issues – Measurement of health outputs is currently much more difficult and imprecise than productivity outputs. More precise and reliable diagnostic tools might help. The health outputs and performance outputs occur in different time frames – making it difficult to correlate these two different types of outputs. While high spinal loads may cause low back pain very quickly, exposure to prolonged and repetitive loading combined perhaps with psychosocial strain, may take months or even years to develop an MSD (Cole et al., 2003). This delayed response is a particular problem for providing feedback comparable to that available for other outputs to production system designers. Under these circumstances we have relied more heavily on 'symptom' or pain surveys (e.g. Kuorinka et al., 1987) and especially physical and psychosocial risk factors that provide a more leading indicator of potential problems (Cole et al., 2003).

4.2 Risk Factors

This thesis demonstrated a 'risk calibration' of a tool to measure trunk posture at work from video. These tools may be useful as 'leading' indicators of MSD outputs that are more closely connected to current system design.

Paper 1 demonstrated how an exposure measurement tool that can be evaluated and risk-calibrated. This tool showed the importance of trunk movement factors, particularly peak flexion level, in the reporting of LBP at work consistent with the literature (Marras et al., 1995; Neumann et al., 1999c). It also showed that analysts without special technical skills could measure these dynamic parameters precisely and easily. In principle these parameters could be predicted from simulation during design (e.g. Sundin, 2001). Peak flexion exposure can be related to a number of mechanisms, including increased lumbar loading from the mass of the torso, worsened mechanical advantage due to changes in musculoskeletal configuration, as well as possible localised tissue loading due to deformation effects in extreme postures (Hagberg et al., 1995). The results from this study also confirm velocity as a risk factor, previously identified by Marras et al. (1995). High velocities, in a fixed range of motion, imply high acceleration and, according to Newton's second law (Force = Mass * Acceleration) (Newton, 1687), high force with related potential for tissue overload (McGill, 1997).

Musculoskeletal disorders are multifactorial in nature (Frank et al., 1995). While paper 1 focuses on a single method for posture quantification, the larger OUBPS study identified a number of physical and psychosocial risk factors (Kerr et al., 2001; Norman et al., 1998). This broader range of risk factors is studied subsequently in papers 2 & 3. Meaningful interventions will need to consider as broad a range of risk factors as possible any one variable rarely carries more than 10% of the injury variance. If an interventionist manages to cause a 10% decrease in such a single risk factor, then the challenge will be to isolate the anticipated 1% drop in MSD in a workplace with 20% variability in sickness absence data.

Model Issues – The model seems consistent with observations that there is always some measure of risk in any work system. The correlation between risk factors and MSD is well demonstrated (eg Paper 1). While examples exist demonstrating correlations between MSD risk factors and quality (Axelsson, 2000; Drury, 2000; Eklund, 1995; Lin et al., 2001) and also profitability (Hendrick, 1996; Oxenburgh et al., 2004), the data here is not as extensive as for MSD. It is possible that other human 'risk' factors for poorer productivity, beyond those for MSDs, exist and could be identified. These 'poor productivity' risk factors may vary depending on the nature of the production system.

Measurement of MSD risk factors is a tricky business. Variables of interest have a wide range in frequency characteristics, which affects sampling strategy effectiveness. Infrequent events, of concern for peak loading, might only occur once or less each day and pose a sampling challenge (Kihlberg et al., 2000). Wrist movement, in contrast, contain relevant signal frequency components content up to approximately 5Hz (Balogh, 2001). Muscle activity levels, recorded using electromyographic techniques, contain relevant signal up to 400Hz (Merletti et al., 1999) and are often sampled at over 1000Hz. Measures sensitive to the nuances of human performance, like electromyography, may be swept away by larger variability in the production system – for example during an unusual downtime cause by supplier-side delays or machine breakdowns. In papers 2 & 3 it was particularly important that methodological and sampling strategies account for the behaviour of the production system and system boundaries if the measures are to represent operators' exposure in a meaningful comparison.

4.3 Production System

The difficulty we observed in making ergonomic improvements to existing systems highlighted the need to integrate ergonomics into system design. Once built key performance and risk aspects of the system are 'locked in'.

While paper 1 focussed on the individual at work in a production system, papers 2 & 3 focus more on the production systems directly. Here we attempt to understand the *strategic design elements* (production strategies) that contribute to a particular risk profile for the system. These will be discussed subsequently.

In trying to integrate ergonomics into the engine-manufacturing organisation (Paper 4) we observed problems trying to make changes in the existing system. By the time the system comes into operations most (if not more than all!) of the project budget is spent – few resources remain for further development. While relatively simple changes can be implemented given sufficient time, risks associated with more central design features are 'locked in'. This highlights the importance of trying to integrate human factors into the early stages of production system design (Burns and Vicente, 2000; Engström et al., 1998; Imbeau et al., 2001; Jensen, 2002).

> **"Paying insufficient attention to human resource issues until after the technology has been selected and implemented creates a risk of problems that are so severe that the capital investment in new technology may be completely negated"** - Johansson et al., 1993

Model Issues: The distinction between the existing system, the system design, and the production strategy as formulated in the system model can become confusing. The production system is an 'artefact' of the design process which in turn is guided, or bounded, by demands and constraints established by decision makers. The separation of these aspects in the systems model supports consideration of time sequence and separate stakeholder groups: the senior managers who chose strategies, the engineers who figure out how to implement them (and perhaps lobby for specific strategies), and the production staff who operate the resulting system. These distinctions proved helpful in understanding the complex situation in the engine assembly organisation.

Methodological Issues: Production systems are dynamic in their daily operations, and continuously changing with ongoing interventions constituting 'design' changes. This can make measuring 'normal' system outputs like trying to hit a moving target. Our analyses reflect a particular window in time at a particular stage in system development. To help control for system variability calculations have used production averages over a month or more. Biomechanical models, which allow the application of 'standard' data to particular work situations, can be particularly useful as it bypasses or systematizes some the system's variability to allow unambiguous comparison of different situations. In other instances, for example when using flow simulation (paper 3), this variability is of critical importance as it can influence the extent to which system parts influence or interfere with one another. The choice of when to include or bypass system variability must be made carefully depending on what aspect of system function one wishes to explore. It can be helpful to get operators', engineers', and supervisors' opinions and experiences with the system so as to understand system behaviour before making critical measurement decisions ("oh yeah, on Fridays we run just half a shift – that won't affect your measurements will it?").

Some performance indicators might, under a strict interpretation, be considered 'internal' to the system. 'Work in Process' (WIP), for example, provides an indicator of how much material is in the system and represents an operating cost (Wild, 1995). These indicators are not always well tracked and can be difficult to quantify. Gaining access to raw data to obtain indicators not usually used by the company can, on occasion, test a researcher's skills of persuasion.

4.4 Production System Design

Even if ergonomics is considered during design, such as through workstation layout, this is not always enough to deal with problems related to production strategies.

In our close collaboration with the engine production facility in Papers 3 & 4 we became aware of the complex dynamic between the stakeholders at the production system's operational level and those responsible for design of the system. In this case we saw that the selection of the work organisation was heavily influenced by production personnel, while the technical system was largely chosen and designed by the engineering group. This can be seen as a separation of the social and technical subsystems as problematised in classical sociotechnical systems theory (Eijnatten et al., 1993). In this case we, similar to Wulff et al. (Wulff et al., 2000; Wulff et al., 1999a; b), saw that corporate standards for human factors were not fully embedded and used in the design process. We also observed that a number of different organisational groups are responsible for different aspects of the design a common practice and problem in engineering design (Johansson and Medbo, 2004; O'Brien and Smith, 1995). This implies that 'engaging engineers' may be a more complex task than originally conceived. The specific structure or distribution of the design process is likely to be specific to the case of study – the problem of managing emergent human factors in distributed design environments however is quite general and warrants further investigation (Burns and Vicente, 2000).

> **"…engineers and designers had poor knowledge of both the formal design processes in use in their company and how to apply ergonomics principles."**
> - Skepper et al 2000

Discussion

Workstation Design – The design of workstation layouts appeared to occur after other choices of production system design and is here discussed as a ‘design’ issue rather than a ‘strategic’ one. In the case of electronics assembly (paper 2) considerable investment was made in the design of ‘ergonomic’ adjustable sit-stand assembly stations. This sit-stand capability, however, did not really address the dominant arm-shoulder loading risk factors related to repetitive, monotonous ‘get & put’ activities. While the intention to produce ergonomically adjustable sit-stand workstations was good, the effort failed to account for the pattern of work created by the choices surrounding the serial flow system set at the very earliest stages of the design project. The ergonomic importance of early design decisions has been previously discussed (Burns and Vicente, 2000; Helander, 1999; Imbeau et al., 2001; Jensen, 2002).

Model Issues: A critical aspect of the design process not accounted for in this model lies in the design of the product itself. Design of a product that can be quickly and easily assembled could, in principle, contribute greatly to reducing physically awkward postures or forceful actions. In the case of engine assembly product designers were based in a different city from production system designers creating a barrier in communications. Neither product strategies nor product design issues are explicitly included in the current model. As mentioned previously, there is a certain ‘fuzziness’ between ‘design’ and ‘strategy’ elements and these two activities are closely linked in the model (Figure 1). It is perhaps best left up to the analyst/investigator to make this distinction according to the particular development process under study.

Methodological Issues: Our approach to understanding the design process was essentially qualitative. The action research approach allowed us to develop an intimate understanding of how this process was running and the subtle individual and organizational forces that were shaping this particular design project. Unfortunately the bulk of strategic decisions were already made as we began to come into regular contact with the design team – gaining early access is an important issue. Isolating a decision in a design process can be quite difficult (Langley et al., 1995).

4.5 Production Strategy

Production strategies pose core choices that affect both ergonomics and productivity of the resulting system. These strategies interact. Understanding the relations between specific strategies and their ergonomic and productivity consequences appears critical to improving total system performance.

In both electronics and engine cases (Papers 2 & 3) the companies were concerned with increasing production volume. Changes in production strategy were observed to flow patterns, to the use of automation, to material supply sub-systems, and to the work organisation. In general we found benefits and drawbacks in both ergonomics and performance consequences of these strategic elements. Understanding how these individual strategies can contribute to both good performance and good ergonomics seems essential to facilitate the joint optimisation (of human and technical factors) necessary to find system solutions that are globally optimal and thus maximally productive (Axtell et al., 2001; Burns and Vicente, 2000; Clegg, 2000; Hendrick and Kleiner, 2001; Ingelgård and Norrgren, 2001; Neumann et al., 2002). Like others (Kuipers et al., 2004) we attempt to move beyond debates about archetypes like 'lean' tayloristic or 'reflexive' sociotechnical systems (labels Engström and colleagues suggest are "pretentious" (Engström et al., 1998)) that has populated the literature (Adler and Cole, 1993; Adler and Goldoftas, 1997; Babson, 1993; Berggren, 1994; Björkman, 1996; Cooney, 2002; Ingelgård and Norrgren, 2001; Landsbergis et al., 1999; Sakai, 1990; Womack et al., 1990). Thus, instead of engaging in a 'line' vs. 'cell' debate, we seek instead a more nuanced understanding of the interplay of strategic elements in determining system outputs – including both productivity and ergonomics factors.

> **"…top management personnel are indifferent to good human factors design… the social structure favours the choice of technologies that centralise authority and de-skill operators and … encourages unwarranted attributions of operator error."**
> - Perrow 1983

In paper 4 we observed that the early choice of production strategy, made by highest managers, inhibited the consideration of alternatives by the design team who were already overloaded with the task of realising the design assigned to them. This illustrates how ergonomics can be 'locked in' by early design choices. These strategic choices were made by senior managers who are perhaps most distanced from the daily risk exposure of the system operators. Since the vast majority of resources are allocated (Mortensen, 1997), early choices become a critical domain for maintaining approaches that include potential for good ergonomics:

> *"The true leverage points of design occur in the negotiation of contextual constraints, the making of wise decisions early in a project, and in negotiating ergonomic priorities with designers from other domains"* (Burns and Vicente, 2000)

Applying 'ergonomics' principles after key decisions have already been made, or after the system is fully functional, may not be sufficient to substantially reduce MSD risk.

Model Issues: The interconnectedness of production system elements can make it difficult to isolate a '*strategic*' design element. In general the 'production strategy' choices tend to be decisions implying core features, with a large portion of the system cost, chosen in the early stages of the project. The analyst's final determination will depend on the site context and research intent. Larger issues of corporate strategy are not included in the model – although these must surely influence the selection of production strategies.

Methodological Issues: When faced with a given case, isolating a chosen 'strategic' element is essentially a qualitative exercise. This is complicated by the distance between strategic decision (level 5) and the observed resulting system (level 3). As Langley et al. (1995) point out:

> *"It is a perplexing fact that most executive decisions produce no direct evidence of themselves and that knowledge of them can only be derived from the cumulation of indirect evidence."* (Langley et al., 1995)

Compared to muscle EMG for example which one might sample at 1000 Hz, strategic production elements are chosen once for the life of the production system – and may in fact span a number of system life-cycles until new strategies are chosen. There is a fundamental difference in time frame. Following along the design process longitudinally as done in Paper 4, can allow the decision chain to be better understood (Langley et al., 1995).

4.5.1 Flow Strategies: Serial and Parallel Flows

In both Paper 2 and Paper 3 we saw cases in which parallel flow strategies were replaced with automated serial flow. This change was most pronounced in the engine assembly case (Paper 3). The move to serial flow reduced cycle times and thereby also decreases the physical variability of work at the workstation level. The observed physical and psychosocial drawbacks of this strategy are consistent with previous literature (Bildt et al., 1999; Fredriksson et al., 2001; Melin et al., 1999; Ólafsdóttir and Rafnsson, 1998). We observed that the flow strategy controls the pattern of physical loading throughout the shift, although this is modified by the work organization features such as job rotation.

Serial flows have inherent inefficiency due to system losses (Engström et al., 1996; Medbo, 1999; Wild, 1975; 1995), which we observed in both cases. Interestingly, in paper 3, operators did not perceive these disturbances as a 'pause', although it *does* seem to reduce physical workload levels (Palmerud et al., 2004). While this knowledge existed inside the company's corporate standards it did not appear to be used by the design team. Buffering can mitigate these negative effects of serial flow although this increases WIP levels and is particularly expensive with AGV conveyance systems. This represents a kind of 'interaction effect' between the different system design elements. Having the workforce shift flexibly up or down the line to overcome flow irregularities as part of a 'team working' approach, as observed in paper 3, is another strategy for reducing system losses. Unexplored here is the extent to which reducing these system losses will affect ergonomics with possible increases in mechanical loading, decreases of recovery time, and psychosocial effects in response to reductions in forced 'waiting'.

4.5.2 Automation Strategies

We observed automation of assembly as a production strategy in the case of electronics assembly (Paper 2), and automation of transportation functions as an expensive part of both cases' production strategies (papers 2 & 3). Automation has been associated with improved firm performance (Fawcett and Myers, 2001) and appeared to have improved labour efficiency in Paper 2. At the system level the strategy to automate assembly reduced the total exposure of operators to repetitive monotonous assembly work – an ergonomic benefit. For the individuals at manual assembly stations, however, the loading pattern tended to increase in time-density and monotony with operators performing repeated and rapid ‘get & put’ movements almost continuously with increased MSD risk (Veiersted, 1994; Veiersted et al., 1993; Westgaard, 1999). In the engine assembly case the AGV transport system (combined with serial flow) eliminated the short walks operators took delivering the motor to quality control after assembly – also a reduction in physical variation. Partial automation strategies have been linked with increased exposure to MSD risk factors (Coury et al., 2000). Thus the remaining work can be as important as the automated work when considering the ergonomic effects of automation. In the case of automation of transport ,Arndt (1987) has described how operators struggling to match a machines pace can result in elevate muscle activity levels and hence increased MSD risk.

In both cases the implementation of new technology did not go as smoothly as planned and required extra resources to bring to full functioning. Interactions with other system strategies were observed. In the electronics case for example, problems buying components suitable to robotic assembly (a problem in the material supply sub-system) resulted a shift of these components to manual assembly stations where space constraints resulted in elevated parts and thus elevated shoulder loading. Implementation of the AGV’s in the engine assembly case also interacted with the physical workstation design, as power tools were elevated 10-20 centimetres to avoid collision with the AGV’s monitor. This problem, now corrected with some effort, also lead to increased shoulder loading for operators. These examples illustrate how a division of design tasks can lead to ergonomics problems when the different elements finally come together.

4.5.3 Material Supply Strategies

The material supply sub-system (MS) is an important aspect of operating systems with potential to contribute to both performance and health and safety (Wild, 1995). The relation between ergonomics and the MS can be obvious, as in the peak spinal loading observed in engine assembly when operators reach to retrieve heavy parts from the bottom of a large crate. This illustrates how the MS can influence risk due to load amplitudes. The type of container can affect loading experienced during picking activities (Christmansson et al., 2002), as can the positioning of the container at the workstation.

In paper 4, we observed that attempts to change the parts container interacted with business agreements with parts suppliers. Change here would require both engagement of the purchasing department and the supplier company - a daunting task for a busy production engineer. One solution to space constraints is to create a product kit as observed on the cell system in paper 3, a strategy particularly useful in cases with many product variants (Bozer and McGinnis, 1992). The design of the component kit is critical to performance in long cycle dock assembly as it provides all necessary components and implicit guidance in assembly sequence to complete the assembly task without leaving the workstation (Bozer and McGinnis, 1992; Medbo, 1999; 2003; Nagamachi, 1996). A well designed kit can facilitate both fast learning times and fast assembly times (Medbo, 1999; 2003; Nagamachi, 1996) although, in the case in paper 3, assembly speed and learning were both seen by the company as weaknesses in the existing cellular assembly system in paper 3. The picking of the kit itself remains a weak spot in this MS strategy and was seen in the engine assembly case as one reason for abandoning the cellular manufacturing strategy. Parallel flow cellular assembly strategies will likely remain unpopular unless more efficient kitting approaches can be developed.

4.5.4 Work Organisation Strategies

The absence of a rotation scheme in the automotive site used in Paper 1 made it feasible to quantify physical workload on many operators since each operator needed only to be assessed working on their particular workstation. In the electronics case (Paper 2) the issue of work rotation was more complex. Managers rejected a team-based rotation plan. Part of the reason for this rejection appears to be the use of workers from a 'temporary' employment agency. This made the multi-skilling of workers appear less cost effective because future automation efforts would lead to the elimination of these temporary operators. The tendency to favour an un-skilled workforce, a trend noted by Perrow (1983), may also have been part of a larger corporate strategy to shift production to China – where this system is now based.

In the engine assembly case, the new line system had a team-based work organisation, originally a central element of sociotechnical design approaches (Eijnatten et al., 1993; Engström et al., 1995). In this case we observed improved co-worker support, an ergonomic benefit (Karasek and Theorell, 1990), over the OLD dock system where operators worked alone in their own 'dock' workstation until they reached their quota, itself a barrier to productivity. The team structure, along with 'runners' who moved along the line, was seen as necessary to overcome the systems losses inherent in serial flows. Job rotation within the teams provided some task enlargement (but not enrichment) and can distribute time-intensive loading across the workforce (Kuijer et al., 1999). Rotation may also expose more workers to hazardous peak load situations thus increasing a system's total risk level (Frazer et al., 2003).

4.5.5 Social and Technical Sub-System Interplay?

Taken together there appears to be a tendency for companies to use technical solutions to circumvent problems arising from the work organisation, and work organisational solutions to solve problems inherent in the technical sub-system. The extent to which the design of the technical system is influenced by the design of the social-subsystem is difficult to isolate, we observed simultaneous consideration of these issues in the design team. In practice this discussion can be inhibited by the lack of clear, unambiguous objectives for the work organisation (Wulff et al., 1999a; b). Medbo & Neumann (Medbo and Neumann, 2004) have demonstrated how the interaction of specific social and technical sub-system features can be examined using flow simulation - an application approach that appears to be novel. Further work is needed here to understand the complex interactions in these two domains.

4.6 Individual Factors

Individuals and normal life events had a great impact on the uptake of ergonomics into the organisation.

In paper 1 we demonstrated how individuals' workplace exposure to postural risk factors is associated with LBP risk. The larger OUBPS study suggests that workplace factors are generally more important than individual factors in determining risk (Kerr, 1997; Kerr et al., 2001). In Paper 4 we changed our focus from individual operators to individuals throughout the organisation. Here we observed how individual's situations can influence organisational change efforts. Of the many life events that were experienced by company personnel during the time of the project, it is primarily staff turnover that has been discussed in the change literature (e.g. Smith, 2003). For the practitioner trying to navigate ergonomics issues through the organisation it may be helpful to understand what is going on in peoples lives and careers. If the navigator (c.f. Broberg and Hermenud, 2004; Jensen, 2002) is experiencing resistance, understanding the contributing personal factors may help the navigator choose alternative approaches to moving the ergonomics agenda forwards. The human factors of organisational change appear to be important.

Model Issues: The studies here seem to support the need to consider ‘individuals’ beyond just the system operator, especially if one is trying to affect organisational change. The extent to which individuals’ acceptance of ergonomics objectives is affected by group membership, for example connection to the sub-culture of engineering, remains an interesting research issue. This is similar to the concept of ‘Clan’ control mechanisms in organisational theory (Hatch, 1997). The model presented does not explicitly include the presence of multiple overlapping group memberships although these could be mapped to better understand an individuals’ particular organisational circumstance.

Methodological Issues: While we have used primarily qualitative methods there exist many possibilities to use, for example, questionnaires to measures specific aspects of individual psychology. Reporting of individual factors can be quite sensitive, particularly in a case study scenario where individuals might be readily identified. If we believe there are certain ‘types’ of individuals with different knowledge sets, for example the “worked my way up engineer” as opposed to the “University trained engineer”, exploring the differences of these types would be better done with a broader survey, similar to Broberg ‘s (1997) approach to studying product and process engineers’ approach to ergonomics.

4.7 Organisational Factors

Organisational features can influence ergonomics due to the trend to separate human and technical aspects in the design process. Organisational boundaries can also inhibit the uptake of ergonomics into existing routines.

The action research study (paper 4) revealed organisational barriers to integrating ergonomcis into development processes. This analysis illustrated how the communication and responsibility barriers created by an organisational structure, such as the sub-division of the system design task, can lead to problems as the various pieces come together. Senge (1990), from an organisationl learning perspective, has discussed the kind of dysfunctional side effects that can emerge from the organisational design and the importance of alignment amongst stakeholders. In this case we observed the utility of Broberg & Hermenud's (2004) 'political reflective navigator' stance, in this case taken by the production manager (PM) acting as an internal agent with 'insider' knowledge to overcome setbacks and identify new approaches to integrating ergonomics into development. The program however remains vulnerable so long as the PM stands alone in the organisation supporting the initiative. Fortunately in this case the engineering department and company health and safety service both appear poised to take up this ongoing challenge.

> **"What faces those charged with bringing about changes in organisations is much more of a mess than a difficulty."** – *Saka 2003*

In paper 4 we were able to map how different organisational units participated in the development process (Figure 3.4.2). While other companies might have other developmental structures, the need to divide large design tasks amongst groups to ensure timely completion is quite common. Recent development in concurrent engineering, for example, appear to have potential for improved attention to human factors (Badham et al., 2000).

Model Issues: The model used does not explicitly include the many organisations that make up a companies "interorganisational network" in a particular supply chain (Hatch, 1997). This network structure could be incorporated in a particular formulation of this model when analysing a specific situation. The distribution of the design task amongst different groups, as was elaborated in Paper 4, may require elaboration in model applications.

Methodological Issues: The methods applied here were exploratory and qualitative. The extent to which the trends observed here apply to other cases may depend on their similarity and tools are needed in this area. Methodological issues here include sampling or recruitment strategies, and choices regarding breadth vs. depth implicit in for example quantified surveys vs. qualitative interview approaches. The slow rate of change of organisations creates a further time-frame problem when trying to evaluate the effects of an organisational change effort. The research and developmental challenges here are immense.

4.8 Societal Factors

While this dissertation is not focussed on social factors – understanding the role of society and cultural differences in the application of ergonomics is critical both to ensure that local action is appropriate and to ensure global trade is socially equitable.

In both cases of production redevelopment (Paper 2 & 3) the company was reacting to increased demand for their products from customers, and also wished to decrease product cost to improve their competitiveness in the global market. Neumann and Winkel (2004) have discussed how investor and customer demands place the organisation under competitive pressures. Rasmussen (1997) has described, and Woo and Vicente (2003) have illustrated, how the individuals in a complex system, reacting to pressures of competition by making changes (or cutting corners) in their own domain of authority, can drive the whole system into unsafe operational states. Paper 4 illustrated how risks can emerge when disparate development sub-systems, are combined. In the face of senior manage disinterest in human factors (Perrow, 1983), and the general absence of long term focus (Huzzard, 2003), it is easy to see how Rasmussen's (1997; 2000) osmosis into risk zones hypothesis might occur.

> **"In a culturally diverse and globally competitive world, scholars can only sit in discomfort in their own corners of the world pretending their patterns of change are the world's patterns of change"**
>
> \- Pettegrew, 2001

Pettegrew (Pettigrew et al., 2001) has pointed out that international comparative research on organisational change is an important priority. In paper 4 (engine assembly) we studied a situation in which a senior production manager, with a clear vision for human factors, demonstrated an unwavering resolution to achieve his goal. Perhaps this is a special individual who is the product of a special (Swedish) culture and is thus a social aberrant? Further research is needed here to understand the sociological determinants by which management will accept human factors agendas.

Model Issues: The model presents society as a single entity. While some might say technology has led to us to living in a 'Global Village' (McLuhan, 1968), this is not sufficient to understand how global societal forces can affect ergonomics. Better model resolution in social structures would be needed to study, for example, how consumer demand for cheap goods can lead to working conditions in foreign factories that the consumers themselves would consider unacceptable.

Methodological Issues: There is a very large range of approaches to studying social factors including qualitative and quantitative approaches applied on both micro and macro scales. Discussing these possible approaches is beyond the scope of this thesis. Paper 4 was not really able to isolate the external social forces that are said to influence change process (Bamford and Forrester, 2003).

4.9 Model Redevelopment

The studies conducted suggest an extension of the model would be helpful. Emphasising 'overall' corporate strategies and product development processes underlines the influence of these two aspects that are not considered in this thesis.

In light of the research presented and reflections discussed in this thesis, I propose a modification, or an extension of the original model (Figure 1) with increased emphasis on the strategic choices at the corporation and an explicit inclusion of the product development process (Figure 4.9).

The inclusion of product design has, similarly to process design, both strategic and design elements (levels 7 and 6 respectively). The importance of product development in defining the assembly task was discussed previously. As Broberg (1997) has pointed out: *"Design and production engineers have a great influence on ergonomics in manufacturing.*" since it is the product designer that defines the assembly task.

The inclusion of 'overall' corporate strategy (level 8) is an attempt to make explicit some of the larger forces in the organisation that are shaping behaviour. A decision to shift production to China (paper 2), for example, would be perhaps more of an 'overall corporate strategy', than a 'production strategy' per se. Corporate culture for example may be deliberately manifested in the form of value statements and visionary objectives (Hatch, 1997) as a strategy for anchoring employees to a desired behaviour pattern (Docherty, 2002). This model feature highlights the potential mechanisms by which corporate strategy can set the stage for developmental processes that can ultimately result in production operators suffering from MSDs. There is little research on how corporate strategy at this level affects ergonomics or on how ergonomics can contribute to the realisation of a particular company's strategic objectives.

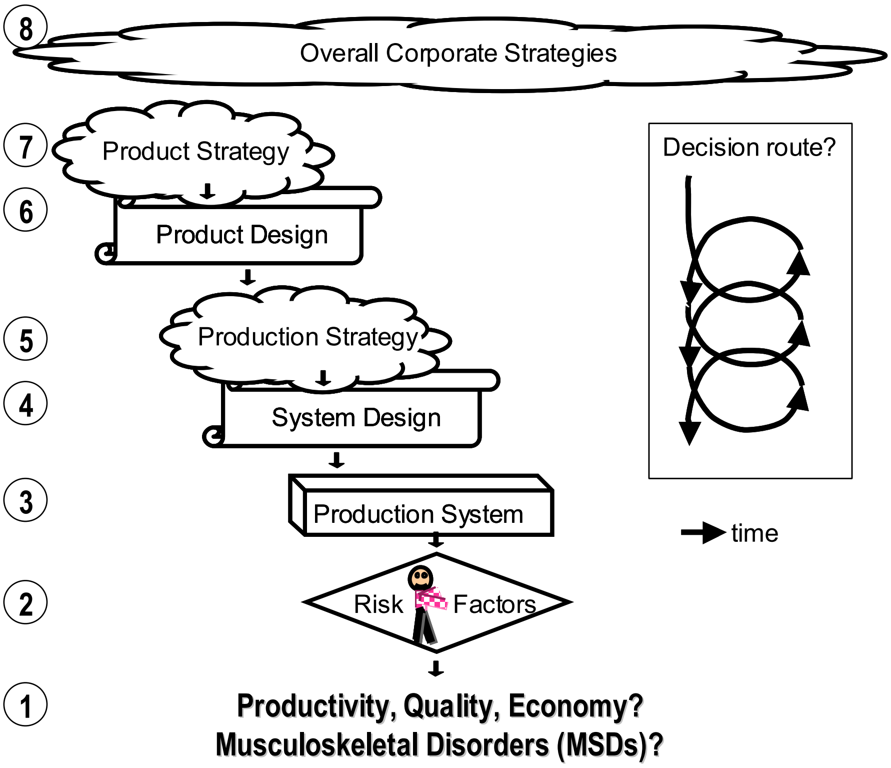

Figure 4.9: *Redeveloped process model in which 'overall' corporate strategies (8) set the stage for product development which has strategic and design decision elements (7&6) and defines the assembly task for production system development (5&4) this development will result in a production system (3) whose operators will be exposed to risk factors (2) as they run the system to generate outputs (1). If the risk factor profile (2) is disadvantageous then MSDs will result (1). Influence flow is generally downwards although decision pathways may be iterative and looping. Time flow is generally left to right with the extent of parallel development indicating the practice of concurrent engineering.*

The fuzzy border between "strategic" and "design" decisions, noted in the discussion (section 5.6), is further emphasised in the model (Figure 4.10) by the overlapping of these two concept bubbles in both the product (levels 7 & 6) and production system (levels 5 & 4) development processes. The principle that larger conceptual (strategic) choices set the stage for more specific design tasks remains useful to understand how certain aspects of production get "locked in" and are very difficult to change if they have negative consequences for ergonomics in the system. Design is a complex process with non-linear and iterative elements that can appear irrational (Broberg, 1997; Engström et al., 1998) despite the proliferation of apparently linear design models (Hammond et al., 2001; Jensen, 2002). This is emphasised by the circular 'decision route' spiral beside the model in Figure 4.9.

The lateral shifting of elements (flow from left to right) has been used to emphasize time aspects in the developmental process. In many organisations product and production process design are linked in parallel processes called concurrent engineering (Badham et al., 2000; Boujut and Laureillard, 2002; Luczak, 2000). In this model the extent of vertical overlap between design processes in a particular case will indicate concurrency in the engineering process. Concurrent engineering creates the potential to adjust the product design so as to improve ergonomics in production (Helander and Nagamachi, 1992).

> **"…the product development process is not a rational problem solving process and does not proceed in a sequential manner as described in engineering models. Instead it is a complex organisational process involving uncertainties, iterative elements and negotiation between key actors. "** - Broberg (1997)

This model should not be considered rigidly. Instead it can provide a flexible framework that can be adapted to local situation. Dynamics of a particular company with a particular developmental trajectory may require a changing adaptable approach over time. Every model is, by necessity, a simplification of reality. The point is not to build a model that reflects some absolute reality or represent a mythical 'general' firm (Toulmin and Gustavsen, 1996). Instead it should provide a *useful framework* to assist with the development of approaches to integrate ergonomics into a specific development situation.

4.10 Some Limitations of This Thesis

There are many limitations to this thesis. Application of any research findings should be done with the practitioners' eyes and mind wide open.

All texts, including this one, are 'coloured' by the readers and writers social contexts (Toulmin and Gustavsen, 1996). Hermeneutics suggests that misunderstanding, errors, or even new truths can emerge from the reading of a text (Wallén, 1996).

The Hazards of trandisciplinarity. Even the humble author of this thesis cannot be expert in all domains of relevance to the problem studied here. The role of researchers from other disciplines becomes critical. Similar to 'triangulation' approaches (Mergler, 1999; Nutt, 1998), this thesis strives for an interweaving of perspectives to provide a resilience which overcomes flaws in a single thread.

The case studies presented here can only illustrate the relationships in the model (Yin, 1994). Rather than 'prove' relationships in the classical positivistic sense, we attempt to understand of how system elements <u>can</u> interact to affect outputs. Further cases could help identify how common the findings in these cases are.

Attribution error poses a potential weakness in this thesis. Identifying which 'strategic' elements were associated with particular risks was an act of analysis in which quantified data, worker reports, supervisor comments and existing research evidence were all considered. Misattribution and overlapping effects remain a possibility. Presentations to and discussions with company stakeholders strengthen our confidence in the results.

4.11 Future Research & Development Priorities

Further work is needed if we are to benefit from the integration of human considerations into developmental processes. Attention is needed at the societal, organisational, and individual levels. Ideally this work would be coordinated across levels.

At the Society Level

- Can a society-wide trend to apply ergonomics in work system design be established? By what mechanisms?
- Are there social factors (e.g. attitudes, values, knowledge base) inhibiting uptake and application of ergonomics? Do these differ between countries?
- What groups are critical to success? Can customer and investor power be harnessed to foster good ergonomics? Can other groups be engaged?

At the Company Level

- How can companies be motivated to integrate ergonomics into development? Can the strategic and performance benefits of ergonomics be better demonstrated?
- If ergonomics *is* to be integrated into development work – how can this integration be best achieved?
- How do the organisational dynamics and patterns of risk emergence observed here play out in other companies? In smaller enterprises? In other sectors?

At the Individual Level

- How can individuals be helped to handle ergonomics in their development work? What knowledge, tools, or support is needed?
- Can knowledge about risk factor dose-response relationships be made more useful to system designers? How stable/linear are these relationships?
- How does integrating ergonomics into daily development work affect the individuals involved? Is there extra work? How does the individual's role change? Do we create new problems?

5 Conclusions

With regards to risk identification:

- It is possible to obtain reliable and accurate quantification of work related risk factors for MSD from video recordings: in this case posture and movements related to low back pain. MSD risk factors can be measured in existing systems and, by implication, could be predicted in planned systems to provide leading indicators of MSDs.

With regards to sources of risk in production system design:

- The early selection of technological solutions tended to lock in risk factors and could not be overcome by adjustments to the workstation layout. This highlights the ergonomic impact of early strategic decisions made by senior managers.

- While workstation layout (in conjunction with the material supply sub-system) determines operators' physical load amplitudes, the flow strategy and work organisation influence the pattern of physical loading. Psychosocial factors appear to be influenced by a combination of flow strategy, work organisation and, to a lesser extent, layout.

With regards to production strategies effects on ergonomics:

- The automation of repetitive assembly work (robots) increased productivity reduced system-wide operator exposure to manual assembly work, and thus system-wide MSD risk. The automation of transportation functions (to serial flow conveyors), however, contributed to starving and blocking losses, increased repetitive monotonous work, and hence increased MSD risk for remaining manual assembly workers. The ergonomics impact of automation appears to depend on the tasks automated and the tasks remaining to the operators.

- The performance of parallel flow systems can be compromised by the work organisation, such as the use of quotas, as well as inefficiencies in the kitting system.

- The serial line systems studied here showed increased risk of musculoskeletal disorders due to increased repetitiveness and physical monotony, as well as reduced job control with elements of machine pacing, and uneven load distribution across stations.

- Serial flow systems exhibit system and balance losses. While these reduce physical workload and movements, operators do not experience this forced waiting as a 'pause'.

- The use of team structures in the serial line system improved co-worker support, which implies a risk reduction. Teamwork also seemed to support productivity by reducing the impact of system disturbances.

With regards to integrating ergonomics into an organisations' development work:

- Integrating ergonomics into the organisation, even with strong support from production management, is a slow process marked by setbacks. Developmental barriers may be at organisational (e.g. inter-group barriers, communication gaps), or at individual levels (e.g. work overload, pending retirement, life events).

- 'Ergonomics' groups that are outside of regular development processes are vulnerable to disruption from, for example, reorganisation. Lack of engineering engagement in the initial process development can lead to barriers when engineering personnel became involved in the change effort.

- A deliberate process of 'political reflective navigation', taken on here by an internal stakeholder, supports the identification of new avenues for the integration of ergonomics into regular development practice.

- Workshops appear to be a good method to provide information, solicit support, and initiate dialogue with the engineering design team. Tools such as computer simulation appear to have good potential in providing designers with quantified or unambiguous indicators they can use to consider ergonomics simultaneously with other production concerns.

- The stakeholder map was a useful ‘navigational aid’ and helped us understand that not all design groups with relevant control over ergonomics have yet been reached by the process.

- Engineering teams work to the mandate given by senior managers – if innovative designs are to be developed senior managers must sanction them. Introducing innovations after key strategic choices may be too late to be taken up into the design process.

Taken together the results of this thesis suggest there are clear linkages between strategic choices made early in system design and musculoskeletal disorders. Each stage of the development process appears to have potential to contribute to or mitigate risk in the resulting system. Managing this risk implies changing roles for individuals and groups in the organisation. The change process to achieve this appears slow. Integrating human factors into work system design has potential to improve total system performance, but remains an under-utilised strategy for sustainable development.

6 Message to Practitioners

Based on the results of this thesis and on available information in the reviewed literature the following few suggestions, oriented to practitioners, seems appropriate:

1. Regarding risk factor quantification:
   a) Quantification of workplace risk factors, such as physical workload, can provide precise information related to MSD risk, and can support communication and build credibility for ergonomics.
   b) Risk factors can be used as leading indicators of MSDs and can help evaluate the ergonomic quality of existing or planned systems.
   c) Watch out that reducing risk factors in one area does not result in a shifting of risk to another risk factor. For example, reducing load amplitude may open the door to increased repetitiveness, while improving back postures may lead to increased shoulder loading. Would your measurement strategy catch this shift in risk?

2. Regarding automation:
   d) Consider not just what tasks are being automated but also what tasks remain for humans – removing repetitive work may decrease total risk but if variety-giving tasks are automated, risk at particular workstations may increase.
   e) Design managers should ensure that technological design is properly integrated with human factors in terms of physical load amplitude, loading pattern, and psychosocial conditions.
   f) Managers should encourage healthy scepticism as to the ease of reaping the benefits of technology systems.

3. Production system designers should establish ergonomic objectives and set the stage for work-related musculoskeletal disorders in their systems. Therefore ergonomics should be considered in all aspects of system design:
   g) Focus on the design <u>process</u> not just on the design problem.
   h) Tools estimating risk factor exposure, leading indicators of risk, should be applied at the earliest design stages possible.

i) Human factors requirements, specified as specifically as possible (ideally in reference to the tools!), should be set as design requirements. Consider here both psychosocial and physical working conditions.
j) Avoid design processes that isolate consideration of ergonomics issues from other productivity elements – ergonomic issues should be integrated into all design stages.
k) Chains of responsibility, linking decision makers to decision consequences, should be established and formalised. This accountability should begin with risk factor indicators and extend to pain and injury rates in operational systems (make engineering responsible for MSDs – not the Health and safety resource personnel). Ideally this performance will be connected to employee evaluation and remuneration processes.

4. Parallel flow, long-cycle assembly has both ergonomic and productivity advantages over short-cycle line assembly, particularly in multi-variant production environments. Nevertheless careful implementation, particularly of the material supply system, is needed to realise these benefits. A good kit can make even complex assembly fast and simple.

5. Making change to an organisation's development process takes years and can suffer setbacks. Don't get discouraged – adopt a reflexive stance. Consider what the current situation is and try to identify new courses of action with potential to further the ergonomics agenda. Think (micro) politically about how the organisation is structured, seek allies and build coalitions to support integrating human factors into regular development – it is, after all, the way to better performance.

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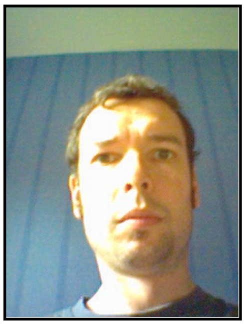
October, 2004.
-P.



Laptop's view of the author thanking you for reading this thesis!

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