2007:74

DOCTORAL THESIS

# Planning the Healthy Construction Workplace through Risk Assessment and Design Methods

Romuald Amitz Rwamamara

Luleå University of Technology
Department of Civil, Mining and Environmental Engineering
Division of Structural Engineering – Construction Engineering Management

2007:74 | ISSN: 1402-1544 | ISRN: LTU-DT -- 07/74 -- SE

LULEÅ UNIVERSITY OF TECHNOLOGY

**DOCTORAL THESIS**

# PLANNING THE HEALTHY CONSTRUCTION WORKPLACE THROUGH RISK ASSESSMENT AND DESIGN METHODS

**Romuald Amitz Rwamamara**

**Luleå 2007**

Division of Structural Engineering – Construction Engineering Management
Department of Civil and Environmental Engineering
Luleå University of Technology
SE - 971 87 LULEÅ
www.cee.ltu.se
construction.project.ltu.se

2007:74 | ISBN: 978-91-85685-11-0 | ISSN: 1402-1544 | ISRN: LTU-DT-- 07/74--SE

***This book is dedicated to the memory of my three mentors: my father and friend Charles and my friends Maisie Pillemer and Helen Kingsley whose earthly lives where taken respectively by the civil war violence, old age and cancer.***

Homer's eighth century BC Iliad declares that *"Death in ten thousand shapes hangs ever over our heads, and no man can elude him."* However

*“The brevity of life is not the most serious consequence of death.”* Dave Hunt

# Acknowledgements

I would like to thank the Lord my God who gives me the breath of life every morning, it would have been impossible for me to carry out and finish the work presented in this thesis without His gift of life everyday.

I am indebted to my family for letting me do my research work and thesis writing during some of our family evenings and holiday times. My wife Sarah, my daughter Channah, and my sons, Natan and Daniel, deserve a lot of credit for accepting my intense schedule requirements. Thank you Sarah for running things smoothly at home while I was focused on this project.

Sincere thanks are due to my main supervisor Professor Ove Lagerqvist and co-supervisor Professor Thomas Olofsson for their constant support and encouragement during my research studies at the Division of Structural Engineering. I am really grateful for these two men's patience and valuable advice while I was writing this thesis.

I am grateful to Assistant Professor Bo Johansson (who was my co-supervisor earlier in my research study), Peter Simonsson, Peter Holzmann and Håkan Norberg who along with my supervisors have been co-authors in the research papers appended to this thesis. Håkan, you are really outstanding in your knowledge and humility; I love learning science from men like you!

My invaluable gratitude goes to a number of construction project participants and the main contractors (Skanska, JM, Peab and NCC) in those projects which allowed me to conduct interviews pour through company documents and poke around their construction sites while I conducted the research for this thesis. I hope the time you invested will assist many other construction projects in becoming worksites that execute construction processes that are healthy and safe for construction workers.

The financial support has been provided by The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas), The Development Fund of the Swedish Construction Industry (SBUF), J.Gust. Richert Stiftelse, and Luleå University of Technology.

Finally, I would like to appreciate Associate Professor Milan Veljkovic and the steel group for having shown interest in my research work. Thank you for making me feel at home!

# Preface

This doctoral thesis is based on the research work carried out at Luleå University of Technology between 2003 and 2005 at the Division of Industrial Work Environment and from January 2006 to October 2007 at the Division of Structural Engineering, the Department of Civil and Environmental Engineering at Luleå University of Technology.

As early as autumn 2001 and under the supervision and encouragement of Professor Ove Lagerqvist I began to write down the research idea for a research proposal that eventually become a project that was geared towards identifying and describing best practices within Swedish construction projects that are used to reduce or eliminate work-related musculoskeletal disorders (WMSDs) among construction workers. This project was called "The Healthy Construction Workplace".

When "The healthy construction workplace" project came to term some of the conclusions indicated that poor planning was one of the main culprits for the occurrence of many health and safety problems including WMSDs. Professors Thomas Olofsson and Ove Lagerqvist saw a further opportunity to encourage me to research towards "the planning for the healthy construction workplace". I have endeavoured to accomplish this new task through the investigation of assessment methods and design methods that have the potential to contribute greatly to the planning of the healthy construction workplace.

Before I finish this preface I would like to introduce you to a song text that motivated me to start this whole research; the text stuck in my mind since I saw it the first time at the Gothenburg Maritime Museum.

| | |
|---|---|
| Vad kostar ett fartyg? | How much does a ship cost? |
| ”God morgon direktörn. Jag skulle vilja beställa en ångare på 1000 ton, är den dyr?” | "Good morning director. I would like to order a 1000- ton steamboat, is it expensive?" |
| ”Vi kan lova er en offert som inte ligger över våra engelska konkurrenter. Men bara ångmaskinen kostar 25 000 kronor.” | ”We can promise you an offer that is no more expensive than our English competitors. The steam engine only costs 25 000 crowns." |
| ”Nej jag menar inte så. Vad kostar hon egentligen? | ”No I don't mean that. How much does she actually cost? |
| Hur många skållade händer kostar hon? | How many burnt hands does she cost? |

Hur många krossade fötter kostar hon?

Hur många sönderslitna ryggar?

Hur många dödliga fall från dåligt stöttade och skrangliga ställningar kostar hon?

Hur många sothostor och förstörda lungor?

Hur många söndervärkta leder är priset på en vanlig ångbåt på 1 000 ton?

Hur många järnlungor, hur mycket gjutarfrossa, hur mycket magkräfta, hur mycket obotlig dövhet, hur många invalidiserande klämskador kostar en vanlig ångbåt?

Hur många stympade fingrar, hur mycket förlorad syn och blindhet kostar en kolångare?”

”Gud vilken märklig fråga! Här på varvet tar vi inte betalt för människor, bara för plåten.”

Karl-Axel Häglund (1927-1986)

How many crushed feet does she cost?

How many broken worn-out backs?

How many fatal falls from poorly supported and rickety scaffoldings does she cost?

How many sooty coughs and damaged lungs?

How many broken aching joints is the price of an ordinary 1000 ton steamboat?

How many iron lungs, how much vibration white finger, how much stomach cancer, how much incurable deafness, how many disabling pinch-related injuries does an ordinary steam boat cost?

How many maimed fingers, how much lost eyesight and blindness does a coal steamer cost?”

“What a strange question! Here at the shipyard we are not paid for people, only for the sheet metal.”

(English translation by R. Rwamamara)

Although this text illustrated the human cost in terms of health and safety at the shipyard this text was equally as good an illustration of the construction worksite then. Surely much has changed on construction sites since the time the text was written, yet there is much to be desired in the planning of a construction site that is healthy and safe for the work crews.

It is my goal, by highlighting the current best practices, the use of risk assessment and design methods, that practitioners both present and future will be equipped to reduce the number of work injuries especially work-related musculoskeletal disorders among construction industry workers.

Luleå, November 2007

Romuald Rwamamara

# Abstract

The construction industry is still one of the highest risk industries as far as work-related musculoskeletal disorders (WMSDs) are concerned. These disorders are the most frequently cited injury to workers, affecting many construction workers in Sweden. Work-related musculoskeletal disorders are also of immediate concern to the workers and their families who are adversely affected by these injuries. These injuries are a substantial source of economic drain to the construction industry. Sources of this drain include economic losses incurred from lost or decreased productivity as well as workers compensation costs. Therefore, it is within the best interests of the construction industry to prevent work-related musculoskeletal disorders from occurring, before they manifest into serious issues of medical, social and economic concern.

The purpose of the research presented in this thesis is to increase the understanding of how a healthy construction workplace can be realized through best practices, the risk assessment and design methods as prevention strategies. The main objective of this thesis is to identify tools used/usable in the construction industry to prevent work-related musculoskeletal disorders among construction workers.

In this doctoral research project, literature review and case studies have been conducted in order to investigate five research questions and thus fulfil the research purpose. The theoretical framework in this thesis is made of

occupational health and safety management, risk management of occupational health, construction planning, and design for health and safety. The common denominator shared by these theories is the planning of a healthy construction workplace.

The research presented in this thesis contributes both to theory and practice in five different areas:

The first area is benchmarking the good construction practices to promote musculoskeletal health; this consists of identifying and describing strategies and activities which have proved to be successful in the fight against the development of work-related musculoskeletal injuries in the construction industry; the results of this study allowed formulation of recommendations substantial to the injury prevention or reduction in the construction working environment.

The second area of contribution is the risk analysis of repetitive tasks in the industrialized house construction context; this study resulted in a critical look at risk assessment and analysis of workload in an industrialized construction process, using ergonomic tools, situations of high workload and risk for musculoskeletal injury are identified.

The third contribution area is a risk analysis of work tasks in a bridge construction process using prefabrication; the study highlights the benefits of using innovative construction methods such as prefabricated steel reinforcement components and self-compacting concrete; in terms of the construction site environment, improved manual material handling and elimination of vibration adverse effects were the benefits.

The fourth contribution area is in the form of a conceptual model which contributes to the theory of design as an injury prevention strategy in construction; this conceptual model is the result of the literature study and site observations perceived as insights for reducing work-related musculoskeletal injuries through designing health and safety in construction, the model presented is built on a participatory design process involving all key stakeholders working as an integrated team, risks can be eliminated or reduced by changes in design specification.

The last and fifth contribution of the thesis is practical ways to deal with the problem of planning for a healthy construction work environment; a case study on different construction projects sought to understand how potential health

and safety risks can be identified and their solutions or corrective measures implemented as a coordinated effort of all key stakeholders through design visualization tools.

The research results suggest that planning for a healthy construction workplace is possible through the implementation of the industry's best practices of the day, keeping up with the use of innovative construction methods such as prefabrication, yet not taking the health and safety benefits of these methods for granted, thus risk assessment and analysis of workload should remain a requirement in order to provide solutions and communicate them effectively between stakeholders through virtual design.

**Key words:** Best practices, Injury risk assessment, Virtual Design and construction site planning.

# Acronyms and atypical words

| | |
|---|---|
| ACS | Automatic Climbing System-Platform |
| AN/NZS | Australian Standards/New Zealand Standards |
| CAD | Computer Aided Design |
| 2D CAD | Two-dimensional Computer Aided Design |
| 3D CAD | Three-dimensional Computer Aided Design |
| CCOHS | Canadian National Center of Occupational Health and Safety |
| CDM | Construction Design Management |
| CPM | Critical Path Method |
| DfCS | Designing for Construction worker Safety |
| DTU | Danish Technical University |
| ECTP | European Construction Technology Platform |
| CEC | Council of the European Communities |
| CEE | European Economic Community |

| | |
|---|---|
| ErgoSAM | Ergo: identification and assessment of musculoskeletal disorders. SAM stands for a Sequence-based Activity and Method analysis. |
| EU | European Union |
| HSE | Health and Safety Executive |
| HVAC | Heating Ventilation Air-Conditioning |
| Foot profile | A database of a construction company’s workers feet anthropometry which allows the employer to purchase hard-toe shoes that are customer made. |
| FORMAS | The Swedish Research Council for Environment, Agricultural Sciences and spatial Planning |
| IT | Information Technology |
| MTM | Method Time Measurement system |
| OSHA | Occupational Safety and Health Administration |
| PPE | Personal Protective Equipment |
| QEC | Quick Exposure Check system for work-related musculoskeletal risks. |
| SBUF | Development Fund for the Swedish Construction Industry |
| SCC | Self-Compacting Concrete |
| SCB | Swedish Central Bureau for Statistics |
| SWEM | Systematic Work Environment Management |
| VR | Virtual Reality |
| WEP | Work Environment Plan |
| WMSDs | Work-related Musculoskeletal Disorders |

# Table of Contents

# 1 INTRODUCTION

## 1.1 Background

The construction sector represents a strategically important sector for the European Union, providing building and infrastructure on which all sectors of the economy depend. According to the European Foundation for the Improvement of Living and Working Conditions (2005), the construction sector is significant in terms of employment and provides constructed assets representing 49.6% of the gross fixed capital formation. The sector's productivity is low compared to other manufacturing sectors. Due to the nature of construction activities, the scope for mechanization and automation, and thus capital-intensive production, is limited. As a result, the construction sector is still very labour-intensive. In Sweden, while the total construction investments in 2004 totalled 19.51 billion Euros which amounts to 6.2% of the Swedish GDP, the construction industry employed 420,000 people, 10% of the total workforce (Flanagan et al, 2005).

Although, the construction industry is both economically and socially important, it has unfortunately one of the worst occupational safety and health records in the European Union countries, a problem that is estimated to cost businesses and tax payers nearly 75 billion Euros a year, not to mention human suffering (OSHA, 2004). In their study to estimate the work environment economic impact on companies and organizations, Rose and Örtengren (2000) estimated that 6% of the work environment-related injury costs for medium-sized construction firms represent the direct costs of sick leave pay, employers fees and workers compensations. However the remaining 94% are made up by costs related to production loss due to the work crew's reduced capacity.

In a SWOT analysis of the construction sector, problems with health and safety in terms of accidents and physical strain on employees, as well as low productivity and weak industry image among customers and potential new workers were part of the major weaknesses of the industry (Improvement of Living and Working Conditions, 2005). Among many facets of performance pertaining to a production process, safety is generally a more demanding aspect to forecast, manage, and deliver (Hessami, 2007).

In a project-based industry, accident and injury rates will vary from project to project. Each project is unique and has its own characteristics, methods of working, materials employed and techniques for construction. The fact that construction is a project-based industry is an important contextual issue. When attempting to manage a dynamic, changing work environment such as a construction site, it should be borne in mind that there needs to be an appropriate organization structure to deal with the changing nature of the project (Lingard and Rowlinson, 2005). Therefore, project planning is a critical task in the management and execution of construction projects. It involves the choice of construction methods, the definition of tasks, the estimation of the required resources, durations for the individual tasks, the identification and coordination of any interactions among the different work tasks and use of common resources (Clough et al., 2000).

The construction industry has been an industry with inadequate material utilization and thus efficiency is lost due to weaknesses in the work activities coordination. Therefore, the principles behind lean production should be highly applicable in the construction industry. The philosophy of lean production originates from Toyota Motor Company and Lean construction is its equivalent in the project-based construction industry. Major Lean principles are geared to making construction work efficient through the customer focus, workplace standardization, waste elimination and continuous improvement (Salem and Zimmer, 2005); briefly all these principles lead to the reduction of the number of mistakes and create value for the customer. Construction mistakes do not only cost the client's and the company's money, but it also tarnishes the construction industry reputation.

In the Swedish construction sector, where there have been debates concerning what can be done about the current low efficiency and the high levels of waste it has been more common to use lean construction principles as a way to solve problems of productivity and eliminate waste (Forsberg and Saukkoriipi, 2007). A study that sought to capture the amount of all types of waste in construction projects was done by Josephson and Saukkoriipi (2005). Their study inventories showed that the amount of waste was between 30-35% of a construction project's production cost, and the waste associated with work-related injuries and illnesses represented about 12% of the projects' production cost (Josephson & Saukkoriipi, 2005).

Occupational injuries such as Work-related Musculoskeletal Disorders (WMSDs) are unquestionably wasteful and non-value adding events in construction production systems. These events contribute to unreliable workflow, which in turn creates havoc on any construction project. As stated by Howell and Ballard (1994), achieving reliable workflow is possible when sources of variability are controlled. It follows then that safeguarding construction workers from occupational hazards is an integral part of the lean construction ideal of maintaining reliable workflow (Abdelhamid et al., 2003). Human-oriented work structuring will better the occupational health and safety of the construction workforce while simultaneously reducing workflow unreliability and enabling lean conversion efforts (Addelhamid and Everett, 2002).

Industrialization has been given credit for reducing health and safety problems such as WMSDs among construction workers. Industrialization describes and encompasses all three aspects of offsite construction work namely, modularization, prefabrication, and preassembly. It is widely used within the construction industry in Sweden (Rwamamara, 2005). The industrialization process can be defined as an investment in equipment, facilities, and technology with the intent of increasing output, decreasing manual labour, and improving quality (Warszawski 1990). It uses the concepts of manufacturing and applies them to construction. To some extent it implies the use of fully integrated and automated project processes.

Improving the health and safety of the construction site work environment has repeatedly been shown to save lives, time, and money. Occupational health and safety regulation compliance and exemplary safety practices are able to reduce injuries and accidents, but are unable to remove hazards inherent in a facility's design or required construction sequence. Due to this shortcoming of health and safety regulations, the concept of considering health and safety in design is slowly becoming familiar in the construction industry. The use of ergonomic redesign to reduce risk factors for work-related musculoskeletal disorders is a very good example of the application of this concept. Unfortunately, construction workers comprise one group of employees that has previously received limited benefit from safety through design. While architects and engineers clearly consider safety in their designs, the target of their efforts has traditionally been the end user of the facility rather than those who will construct it (Hecker and Gambatese, 2003).

The traditional separation between design and construct functions in construction has been a barrier to the improvement of health and safety of construction workers. The Commission of European Communities claims that over 60 per cent of all fatal construction accidents can be contributed to decisions made before construction work on the site (Commission of European Communities, 1993). According to Lingard and Rowlinson, 2005), this suggests that decisions made early in a project's life, particularly during design stages, may impact upon the health and safety of workers who must then construct the facility in accordance with design and specifications provided by the architect or design consultant. To strengthen this position further, 50 percent of the 71 contractors responding to a survey of the construction community in South Africa identified design as a factor that negatively affects health and safety (Smallwood, 1996).

Designer decisions made during the schematic and design development phases of a project directly impact the health and safety of the construction workers construction workplace. Many decisions also impact the safety of end users, maintenance and repair workers, and construction crews during renovation or deconstruction cycles. A safety analysis conducted during design phases is an effective means of identifying unnecessary hazards in the project design, many of which may be "designed out" through the use of alternative components, systems, or construction methods (Haas, 1999).

Assessments of the impact of addressing safety in design reveal considerable promise for the concept in reducing construction site injuries and fatalities (Weinstein et al., 2005). In a study of an intervention to prevent WMSDs to construction workers, antecedents in design, planning, scheduling, and material specifications were identified as probable contributors to working conditions that pose risks of such injuries during the actual construction process (Hecker et al., 2001). A number of studies have shown that a fairly large percentage of construction injuries could be eliminated, reduced, or avoided by making better choices in the design and planning stages of a project (Hecker et al., 2005; Gibb et al., 2004). Therefore, addressing construction health and safety in the design and planning phase, can have a considerable impact on reducing work-related musculoskeletal injuries and even the project delays costs caused by health and safety issues on the construction site.

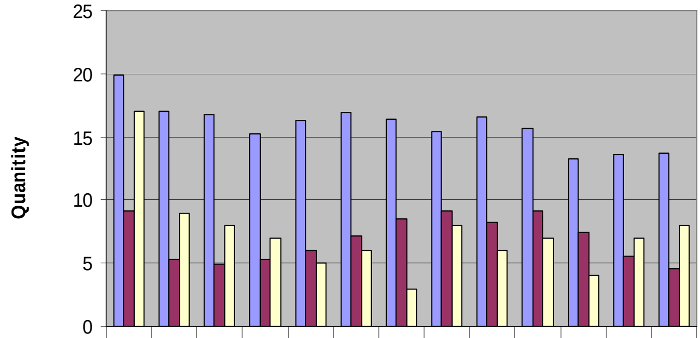
Current methods to represent construction planning information abstract the visual facility description into a textual description of construction activities; thus planners must visually conceptualise the sequence of construction, and subcontractors must interpret the construction because it lacks the necessary detail. During the construction planning process, visualizing a construction schedule helps planners to identify potential problems such as health and safety and constructability prior to actual building construction. Virtual design and simulation technologies should be used more to promote communication and interaction on work-related health and safety issues between the actors, such as designers, customers and contractors in the design process, in planning management of the building process. Visualization of construction projects allows construction workers, customers and users to get a look and feel for the construction before it is actually built. During the construction planning process, designs can be improved, and clashes and inconsistencies can be examined and eliminated. Furthermore, these technologies improve cooperation as non-technical staff and end-users can understand the project in a better way than simply looking at 2D drawings and designs (Improvement of Living and Working Conditions, 2005).

I am quite convinced that in our days of construction projects with their increasing complexity, the planning for a healthy and effective construction workplace does not only need alternative ergonomic methods to detect high musculoskeletal loads early in the design and planning processes, but also requires a visualization of construction work processes with the help of virtual design tools such as 3D CAD and 4D CAD models. This means that 3D CAD models are visualized in a 4-dimentional environment and allow project stakeholders to simulate and analyse what-if scenarios before commencing work execution on the construction site (Jongeling et al., 2005). In this research both ergonomic risk assessment methods and visual simulation technology are recognized to have the potential to contribute greatly to the reduction if not the elimination of WMSDs, thus promoting a healthy and effective construction workplace.

## 1.2 Observed problem - On-site work conditions

A total consensus among industry leading experts states that work conditions of the Swedish construction industry are very high compared to international standards. The building workers trade union and the employers' federation (the Swedish Construction Federation) have shown joint and immense commitment to issues related to health and safety of the construction workplace.

With reference to figure 1.1, the average frequency of occupational accidents between 1994 and 2006 is 17.2 per 1000 employees, while for the last five years this frequency has decreased to 14.6. Thus, there has been an improvement in the average value, but no continuous improvement can be traced. The average frequency of occupational sick-cases is 7.5 per 1000 employees for the years 1994 to 2006, and 7.0 for the last five years. Hence there has been an increase in sick-cases over the last years and the frequency has only improved a little since 1994. The average number of fatalities for the years 1994 to 2006 is 7.9 per year and for the last five years 6.4. Hence, there has been a slight improvement over the last few years, but nevertheless 6.4 fatalities per year makes the industry the most dangerous in the country.

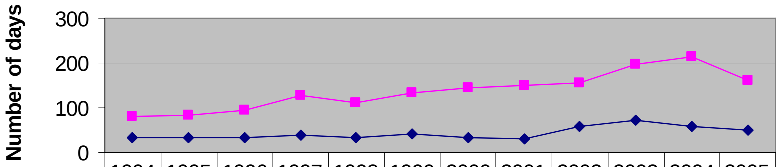



| | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Accidents per 1000 employees | 19.9 | 17 | 16.8 | 15.2 | 16.3 | 16.9 | 16.4 | 15.4 | 16.6 | 15.7 | 13.3 | 13.6 | 13.7 |
| Sick-cases per 1000 employees | 9.1 | 5.3 | 4.9 | 5.3 | 6 | 7.2 | 8.5 | 9.1 | 8.2 | 9.1 | 7.4 | 5.6 | 4.6 |
| Fatalities | 17 | 9 | 8 | 7 | 5 | 6 | 3 | 8 | 6 | 7 | 4 | 7 | 8 |

*Figure 1.1: Health and safety record of the Swedish construction industry 1994-2006.*

In the light of these statistics, the experts' opinions on the significant actions for improvement in health and safety are challenged by the hard data.

In the research presented in this thesis, the research focus has been on work-related musculoskeletal disorders (WMSDs) which constitute on the average 71.2% of all occupational diseases between 1999 and 2006. With reference to figure 1.2, when one looks at the average numbers of sick-days resulting from accidents and occupational diseases, employees are three times more often on sick-leave due to occupational diseases than due to occupational accidents. Therefore, more attention needs to be paid to the WMSDs which make the largest portion of occupational injuries that are the culprit for the majority of workers' absences from the construction site.




| | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average - Sick days/accident | 33.9 | 33.9 | 32.7 | 39.7 | 32.6 | 41.7 | 32.9 | 29.6 | 59.5 | 72.1 | 59 | 51 |
| Average - Sick days/sick-case | 81.4 | 83 | 93.1 | 129 | 113 | 135 | 143 | 149 | 154 | 198 | 213 | 160 |

*Figure 1.2: Sick leave records in the Swedish construction industry 1994-2005.*

## 1.3 Purpose of the research

The purpose of this research was to identify practical innovative and routine methods that are used or can be used in the construction industry for an effective planning of the healthy construction workplace. Furthermore, the scope of this research is to present tools that are able to identify WMSDs injury risk exposures as well as able to lead to the prevention or at least a significant reduction of WMSDs.

This research aims to investigate the risk assessment and virtual design methods as well as benchmark the best practices that the various construction industry stakeholders can employ in order to plan and provide a healthy construction site to the industry's workers.

## 1.4 Research questions

The research questions addressed in this research are related to four issues, namely the benchmarking of best practices to reduce WMSDs, identification of risk assessment methods usable at the construction planning stage, the impact of industrialization on the work environment and the virtual design and construction methods potential to plan for a healthy and effective construction work environment.

### Research question I

*What are the best practices which have proved to be successful in the fight against the development of work-related musculoskeletal injuries in the Swedish construction industry?*

This question aims at identifying and describing best practices which are defined as the processes, practices, and systems identified in the Swedish construction industry that performed exceptionally well and are widely recognized as improving the construction workplace's performance and efficiency in specific areas. Successfully identifying and applying best practices can reduce construction employers' expenses and improve organizational efficiency.

### Research question II

*How can the injury risk on construction workers be assessed in industrialized construction process?*

This question seeks to identify ergonomic tools capable of assessing WMSDs risks in an industrialized construction process and capable of being used in the planning stage prior to the actual construction.

### Research question III

*How does the use of prefabrication and innovative materials impact the construction workplace environment?*

This research question seeks to find out how increased prefabrication affects the construction process in terms of improved health and efficiency of the construction.

**Research question IV**

*How could design for safety concept improve construction health and safety?*

This question provides insights on the impact of assessing health and safety in design and what is necessary to design a healthy and effective construction workplace.

**Research question V**

*How does visualization impact the planning of a healthy construction workplace?*

This research question seeks to investigate the importance of virtual design tools in designing and planning for a healthy construction workplace.

## 1.5 Definitions

For the purpose of studying the healthy construction workplace planning, I used the following definitions:

**Work-related musculoskeletal injuries or WMSDs**

In this thesis when I use the term WMSDs or simply injuries, I am referring to those diseases that are chronic and their symptoms may appear after prolonged exposure to work-related risk factors, such as awkward postures, repetitive tasks, carrying heavy loads and applying force or pressure. According to Amel and Kumar (2002), general factors have been described as necessary for the development of an injury; including insufficient recovery time following task completion, high task repetition, as well as awkward posture and high force requirements of the task.

**Best practices**

Throughout this doctoral thesis, including two of the appended papers (Papers I and II), I refer to the strategies that key stakeholders in the construction industry have found to be successful in reducing work-related musculoskeletal disorders.

**Risk assessment**

By risk assessment, I refer to a careful examination of what could cause musculoskeletal injuries to construction workers in their workplace. A good risk assessment will help avoid risk factors to WMSDs, which can not only ruin lives, but can also increase costs to construction firms through lost output and compensation claims.

**Risk management**

Where I used the term risk management, I refer to the management of the working environment to control those aspects of work that will lead to undesirable health outcomes such as WMSDs in the case of the research presented in this thesis.

**Occupational accident**

In this thesis, the term occupational accident was used to refer to an accident at work which defined as an external, sudden, unexpected, unintended, and violent event, during the execution of work or arising out of it, which causes damage to the health of the employee.

**Occupational sick-cases or diseases**

Where occupational diseases or occupational sick-cases are used, I refer to the diseases caused by injurious influence, for example, musculoskeletal risk factors, chemical agents, noise, vibration as well as social or organizational conditions. Occupational sick-cases or occupational diseases are not of acute character.

**Biomechanics**

With the term biomechanics, I refer to an interdisciplinary field in which information from both the biological sciences and engineering mechanics is used to assess the function of the body.

## 1.6 Thesis outline

The ***first chapter*** of the thesis introduces the research, including the observed problem, the overall research purpose and the research questions.

The ***second chapter*** gives the overview of the research methodology, describes the research methods used and the outline of the thesis.

The ***third chapter*** describes the theory behind the main concepts of this research and related work.

The ***fourth chapter*** presents a detailed summary of papers with the individual papers results and knowledge contributions.

The ***fifth chapter*** of the thesis offers conclusions with a summary of the research contributions, discussions and recommendations for future research work.

The contents of this thesis are based on five appended papers briefly described in the following manner:

**<u>Paper I</u>**

Rwamamara, R., Lagerqvist, O., Olofsson, T. and Johansson, B. (2007) “Best practices for the prevention of musculoskeletal injuries in the construction industry”, *Submitted to Journal of Construction Management and Engineering*, ASCE (July 2007).

This First Paper identifies and describes strategies and activities, which have proved to be successful in the fight against the development of work-related musculoskeletal injuries in the construction industry. Furthermore, the paper formulates recommendations substantial to the musculoskeletal injuries prevention, specific to the construction work environment; and thus prepares a way for further research studies on identified problematic issues. This study presented in this paper was principally motivated by the fact that the problem of musculoskeletal disorders in construction work was found by both employees and employers organizations to be much more complex and that the problem could hardly be solved through individual efforts. I wrote this paper under the supervision of Professors Ove Lagerqvist, Thomas Olofsson and Assistant Professor Bo Johansson who all reviewed the work.

**Paper II**

Rwamamara, R. (2007) "Risk assessment and analysis of workload in an industrialised construction process", *Construction Information Quarterly*, CIOB, 9(2), 80-85.

Paper II presents risk exposure assessment ergonomic tools and their use in the assessment and analysis of workloads in industrialized construction work methods. The work presented in this paper was motivated by the need approved by the construction industry to investigate risk assessment tools for its increasingly industrialized processes. I wrote this paper and Professors Ove Lagerqvist and Thomas Olofsson have supervised and reviewed the work behind paper II. The paper was further double blind reviewed by two reviewers from the CIOB publisher of the paper.

**Paper III**

Simonsson, P., Rwamamara, R. (2007) "Consequence of Industrialised Construction Methods on the Working environment", *Proceedings IGLC-15*, July 2007, Michigan, USA, pp. 302-311.

Paper III presents an assessment of physical work environment risks in an industrialized construction setting where the lean construction tool, the Last Planner is involved in the planning of industrialized production process. The research presented in this paper was motivated by the use of risk assessment tool in order to prove the effectiveness of the work environment planning using a lean construction method. I wrote this paper together with a doctoral candidate colleague Peter Simonsson, and the paper was reviewed by both our supervisors, Professors Ove Lagerqvist and Mats Emborg and further a double blind review of the paper was provided by two anonymous reviewers from the publisher of the paper.

**Paper IV**

Rwamamara, R., Holzmann, P. (2007) "Reducing the Human Cost in Construction through Designing for Health and Safety – Development of a Conceptual Participatory Design Model", *2nd International Conference, World of Construction Project Management, WCPM 2007,* October 24-26, Delft, The Netherlands.

Paper IV is a conceptual paper exploring the emerging concept of designing for health and safety in construction. The writing of this paper was motivated by the need to review literature and use observations in order to find practical insights as a way forward in the process of planning for a healthy construction workplace with no or much less worker's injuries. This paper was written in cooperation with architect, researcher and practitioner in ergonomics, Doctor of Technology, Peter Holzmann, who has been a construction consultant both in Sweden and France. The paper was peer reviewed by an anonymous reviewer from the publisher.

**Paper V**

Rwamamara, R., Norberg, H., Olofsson, T. and Lagerqvist, O. (2007) "Using Visualisation Technologies for Design and Planning of a Healthy Construction Workplace", Submitted to *Construction Innovation* (November, 2007).

Paper V explores the use of virtual design impact on the planning of a healthy construction workplace. The research and writing of this paper was motivated by the need to know how virtual design using 3D and 4D CAD modelling is used to address worker's health issues in the planning process before the start of construction. This paper is written together with doctoral student Håkan Norberg, Professor Thomas Olofsson and Professor Ove Lagerqvist. The paper was reviewed by all these co-authors in addition to Doctor Rogier Jongeling.

# 2 RESEARCH APPROACH AND METHODS

This chapter reviews the research approach and methods. It gives a brief research agenda, the overview of the project methodology, describes the case study approach used and lays out the analysis plan.

## 2.1 Research agenda

This thesis is a contribution to a research agenda which seeks to provide concrete insights for a better and healthier construction work environment. AFA (2006) which is an umbrella organization of Swedish labour market insurance organizations realized that despite many years of hard work to create healthier and safer workplaces, accidents and injuries are still much too common due to the shortcomings in the work environment. Since the year 2006, AFA has initiated a prevention scheme which aims to develop a healthier and safer environment as an attractive workplace to employees on the labour market and for new personnel. Efforts are absolutely necessary to transform the working conditions for the workforce, to make the construction sector attractive to the most competent and skilled young people that it needs, as shortages in workforce are already a reality in Sweden.

## 2.2 Overview of the research methodology

An overview of the research methodology is illustrated in figure 2.1 to present the various methods used in the different parts of the research presented in this thesis.

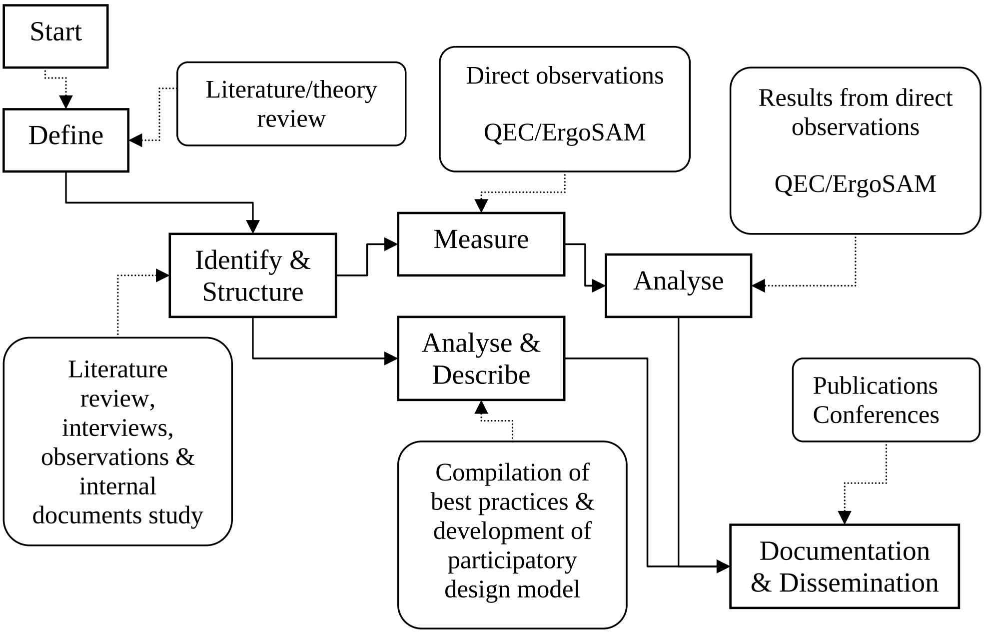



*Figure 2.1: An overview of the research project methodology*

The different methods used in this thesis research are presented in the methodology overview in terms of the functions they fulfilled as the research project advanced to achieve its aim through addressing the research questions.

## 2.3 Research methods

Research methods in the thesis concern the techniques which were actually employed in the research project presented here in this thesis. This section will give a brief description of the different methods used to address research questions already enumerated at the end of chapter 1 in this thesis.

### 2.3.1 Literature review

Firstly**,** a literature review was carried out during the whole research project period. An essential early stage of this research was to search for and to examine potentially relevant theory and literature. Through the reviewed literature, the researcher provides the reader of the research report with a summary of the 'state of the art', the extent of knowledge and the main issues regarding the topic which inform and provide rationale for the research which is being undertaken (Fellows and Liu, 2003).

For the purpose of the research work presented in this thesis, a literature review was done in areas of biomechanics, health and safety management, construction planning, industrialization and prefabrication, risk assessment, pre-build design as a prevention strategy and design visualization. All these issues have contributed to the understanding of the research topic concerned with the planning of the healthy construction workplace. Furthermore, reviewing these literature issues have allowed me as the author of this thesis to formulate a research process that I believe did lead to substantial results or rather answers to the research questions of the research project.

### 2.3.2 Case studies

Secondly, through case studies research, several construction projects were investigated for example to identify the best practices within the construction industry. Case studies were the main investigating tool in most of the research work presented in Paper I. In his classic book on case study research, Yin (1994) argues that case research and survey methods are better suited than other techniques for analyzing contemporary events. Case study research is superior to survey methods at answering “why’s” and “how’s” because the case analysis can explore more deeply into motivations and actions than structured surveys. Thus, this is the reason why the case studies were chosen above the survey approach.

### 2.3.3 Data collection methods

Because a single source of data cannot fully capture the complexities of a case study and although some sources might be more appropriate than others, using different sources of data (i.e., interviews, observations and internal documents study) was ideal. One of the preferred principles of data collection stated by Yin (1994) is the use of multiple sources of evidence. This is an important principle because different sources of evidence can present different aspects of the study, all of which will add to our understanding of the case. Moreover, multiple sources of evidence lead to an important element of data analysis in case study research, triangulation. In this research study, triangulation is important because when more than one source of evidence points out a certain interpretation of events, or certain key interactions or key facts, the quality of the data and the overall validity of the case studies are improved (Stake, 2000).

For these reasons, three data collection methods, namely interviews, direct observations and internal documents study were used in this research project.

**Interviews**

Interviews were one of the main sources of collecting primary data (in Papers I and V). The need for a representative sample is not as great for interviews as a questionnaire-based survey for example, as there is no statistical analysis of the results. Instead interviewees in key positions in construction projects can be targeted using sometimes different criteria. Using an interview-based approach for collecting data gives an opportunity to probe for more information during interviews. This allows for a more complex story to be told, and issues and topics that the researcher was unaware of at the design of the study could be incorporated.

**Direct observations**

Direct observations were also one of methods that were chosen for the research study. According to Stake (2000) the qualitative case study researcher spends the majority of the time personally in contact with the activities and operations of the case. Observational techniques are therefore very relevant for those using case studies research. During the fieldwork or investigation period, there was an overlap of data collection and analysis, and the reason for this was to speed up the analysis, but also it revealed useful adjustments for data collection. During the research project, guided work site visits were performed to directly observe and document the identified problematic jobs, tasks, job site organization, work practices, equipment and tools being used. During construction sites observations, photographs and video films were taken and consequently documenting interesting occurrences and solutions.

**Study of internal documents**

The study of relevant internal documents from various construction contractors involved in the projects I investigated, was employed in the research study reported in the Paper I of this thesis. Whenever possible, health and safety documentation on site was examined as corroboration of the information given in the interviews. The method allowed an additional tool of verification of the results obtained by means of interviews and direct observations.

### 2.3.4 Selection criteria

In the first study presented in Paper I, a total of thirteen large construction sites took part in this research project. The construction sites were selected on a convenience basis from the Swedish construction projects. Site managers and other key actors relevant who might have relevant information to this research were asked to participate in the research study.

As the subject of the study (in Paper I) was the search for best practices in the Swedish construction industry, the first criterion for participation was that construction projects/organizations had distinguished themselves in one or more areas affecting the musculoskeletal health of the construction worker, namely, planning, work organization, technical aspects, work tasks, and physical environment. A second criterion was the size of the construction project which had to be at least 20 workers at a time, and valued at no less than five million Swedish crowns, the reason for this criterion being that the research study was limited to medium and large construction workplaces. Thus, this criterion excluded very small construction projects.

### 2.3.5 Description of the sample of interviewees

In Paper I, a total of ninety-four semi-structured interviews with a range of people who worked with the different construction projects at their various stages, were conducted for the purpose of identifying and describing the best practices that are conducive to the reduction of construction-work related musculoskeletal disorders. The sample included developers/clients, site managers, sub-contractors managers, work supervisors, engineers, architects, health and safety representatives and foremen among eight construction trades namely carpenters, concrete workers, floor layers, HVAC (Heat, Ventilation and Air Conditioning) workers, electricians, roofers, scaffolding workers and machine operators.

In Paper V, interviews were conducted with five planners that are actively working with both or either of the virtual design tools 3D and 4D CAD models in the design of construction projects.

### 2.3.6 Analysis plan

The analysis of the data collected for the different studies presented in the papers in this thesis was done in the following manner:

**Analysis of qualitative data**

The interviews data were analysed by interpreting the information provided by the interviewee and relating it to the main objectives of the study (in Papers I and V). As the analyst of the interview data, I was actively involved in reorganizing the information and interpreting the interviews in meaningful ways. The analysis of data from interviews, site observations and documents study entailed drawing connections between different ideas and processes captured in these sources of data. Similarly, this may involve identifying patterns of associations or noting the relationship between what the interviewees said and the concepts and facts recorded in site observations and company's internal documents. In summary the analysis of these data sources is an attempt to interpret the content of these data sources in a way that relates the findings to the objectives of the study.

**Risk assessment methods**

Two risk assessment methods were investigated in this thesis (see Papers II and III), and they are both used to assess the risk for excessive musculoskeletal load by observing workers' task performance. Both Quick Exposure Check for Work-related Musculoskeletal risks (QEC System) and ErgoSAM (Ergonomic Sequence-based Activity and Method analysis) are among current techniques for assessing physical exposure for Work-related musculoskeletal risks.

The QEC system was developed by Li and Buckle (1998). This observational method includes the assessment of the back, shoulder/upper arm, wrist/hand and neck (the four body areas at the greatest risk to the most important risk factors for WMSDs), with respect to their postures and repetitive movement. Information about task duration, maximum weight handled, hand force exertion, vibration, visual demand and subjective responses to the work are obtained from the worker. QEC assessment encourages consideration of changes to workspaces, tools, equipment and working methods to eliminate, or at least to minimize, levels of exposure.

ErgoSAM is another risk assessment method considered in this thesis. It is one of the few methods for risk assessment of a task in a planned but not yet existing workplace (Laring et al., 2005), although ErgoSAM can still be used to identify risk in a task during production (Rwamamara, 2007). ErgoSAM is based on SAM (Christmansson et al., 2000), a higher-level method-time-measurement (MTM) system. The SAM system is systemised description of the method with which a work task is being or is to be carried out. Each step is described in SAM code complemented with two more types of data in ErgoSAM. The two additional data are the weight of the handled object or the force exerted by the hand(s) and whether the upper arm is held at an angle inside or outside of 30º outwards from the body or turned from the normal anatomical posture. This information together with the time and movement information in the SAM system is the basis for a Cube model analysis that can be plotted along the timeline of the SAM analysis (see figure 2.2).

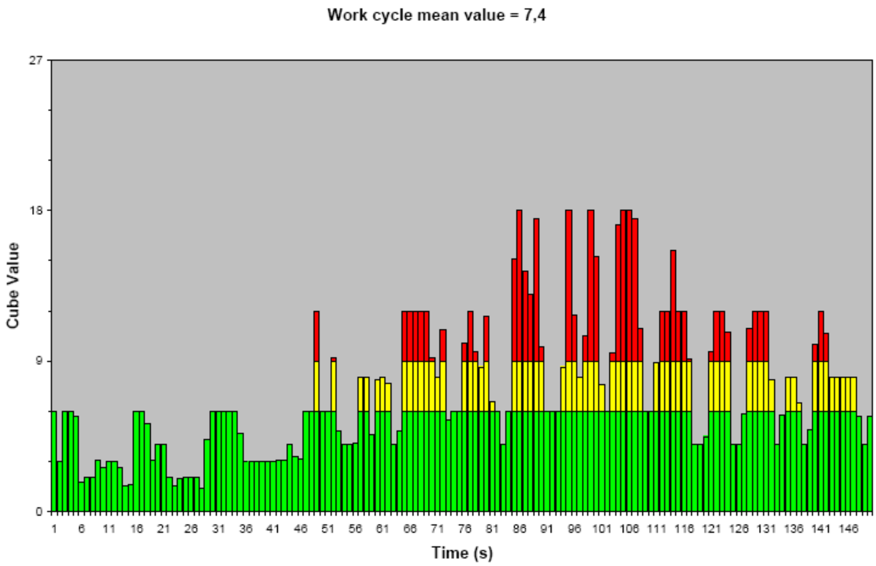



*Figure 2.2: An example of ErgoSAM diagram, where the Cube value is plotted along the timeline of SAM.*

The mathematical Cube Model is based on the observation that in many situations, the risk to acquire WMSDs can be assessed biomechanically based on combinations of variables in three dimensions: force, work posture, and repetitivity. For a specific working task, and for each dimension separately, demand levels may be defined as low, medium, or high, where the demand criteria are chosen so as to discriminate between good or poor work ergonomics, and assigned weight factors 1, 2, and 3 respectively. Combinations of demands are evaluated by multiplication of the three weight factors, and this product determines the acceptability of the task (Sperling, 1993). Combinations of these demands will largely decide whether a work situation is entails risks of strain injuries or work-related musculoskeletal disorbers.

### 2.3.7 Validity and reliability

According to Svensson (1996), validity and reliability are central to the evaluation. Validity and reliability are more or less integrated in case studies,

Validity has to do with trustworthiness, that there is empirical evidence, and the researcher has made reasonable interpretation of the evidence, and that the result is useful in some context (Yin, 1994; Miles and Huberman, 1994). Validity issues are concerned with the design of the study, methods for data collection, the analysis and the results. The design guides the process of collecting, analyzing and interpreting the observations, and therefore, validity has to be taken into consideration when designing, therefore, validity has to be taken into consideration when designing the study. The results of a case study depend on multiple sources of evidence with data needing to converge in a triangulation (Yin, 1994). Triangulation is a common technique to eliminate validity threats in a case study (Yin, 1994; Denzin, 1989). Further, Denzin (1989) remarked that triangulation is very important in the research act if one wants to find evidence for, explain, predict, or understand certain empirical phenomena.

Reliability is whether the same result would be obtained if the study is repeated. Svensson (1996) says that it is important to remember that each event of interviews and observations are unique. It is impossible to recreate the very moment of an interaction. The uniqueness of the moment requires that each occasion be validated on its own. This uniqueness also means that my conclusions of the case studies performed in this thesis research are only valid for the cases studied at the time I studied them.

# 3 THEORY

This chapter briefly reviews the theory related to the biomechanical basis of WMSDs, health and safety management, risk management, construction planning, risk assessment, industrialization and prefabrication, pre-build design as a prevention strategy and design visualization.

## 3.1 Biomechanics approach

A major assumption in occupational biomechanics (which is the portion of biomechanics dealing with ergonomics issues) is that the body behaves according to the laws of Newtonian mechanics (Kroemer, 1987). The object of interest in a work environment context is most often a quantitative assessment of mechanical loading that occurs within the musculoskeletal system.

The approach to biomechanical assessment is to characterise the human-work system situation through a mathematical representation or model. The idea behind such models is to represent the various underlying biomechanical concepts through a series of rules or equations in a system that help us understand how the human would be affected by exposure to work (Marras, 2006). An advantage of representing the worker in a biomechanical model is that the model permits one to quantitatively consider the trade-offs associated with risk to various parts of the body in the design of a workplace. When one considers the biomechanical rationale, one finds that it is difficult to accommodate all parts of the body in an ideal biomechanical environment. Trade-offs considerations are necessary because it is often the case that a situation that is advantageous to one part of the body is disadvantageous for another part of the body. Thus, designing an ergonomic workplace requires one to make various trade-offs and rationales for various design options.

### 3.1.1 Biomechanical loading concepts

The biomechanical exposure has several concepts that define it, however it mainly depends on three concepts namely the load, the body posture and the time. With regard to biomechanical loading, the exposure quantity depends on the amplitude of the load, its variability (i.e. the frequency content or repetitiveness) and the exposure duration (Winkel, 1999).

The fundamental concept in the application of occupational biomechanics to ergonomics is that one should design workplaces so that the load imposed upon a structure does not exceed the tolerance of the structure (Marras, 2006). Figure 3.1 illustrates the realistic scenario of biomechanical risk. The fact that repetitive loading of the structure tissue may decrease over time to the point where it is more likely that the structure loading will exceed the structure tolerance and result in injury.

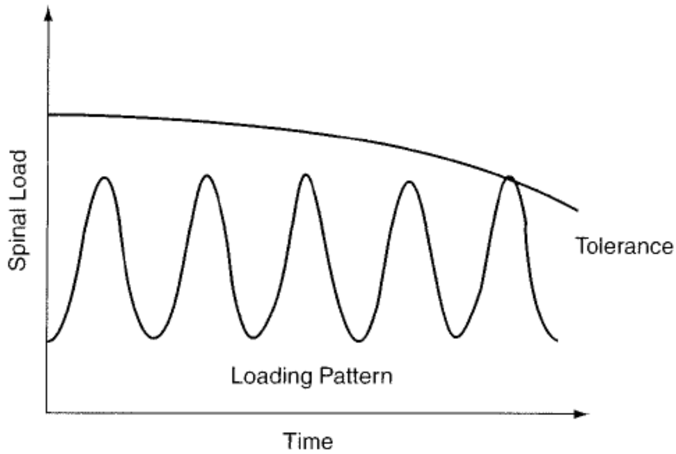



*Figure 3.1: Realistic scenario of biomechanical risk (adapted from Marras, 2006).*

## 3.2 Health and Safety management

The aim of an occupational health and safety management system is to ensure that the productive work of a company is designed and performed with workers' occupational health and safety in mind, that managers make decisions following a systematic evaluation of health and safety risks, and the work is adequately planned, resourced and controlled so as to prevent occupational injuries or illnesses (Lingard and Rowlinson, 2005).

Health and Safety Executive (HSE) (2000) guidebook "Successful Health and Safety Management" outlined five key elements to a successful safety and health management (see figure 3.2). Many industrially developed countries, have also favoured the systematic approach in managing the workplace's health and safety (OSHA, 1989; AS/NZS 4804:1997; CCOHS, 1998). Although their key system elements were not identical, they basically fell into the same categories as proposed by HSE. The systematic identification and control of risks were the fundamental core elements of all health and safety management systems.

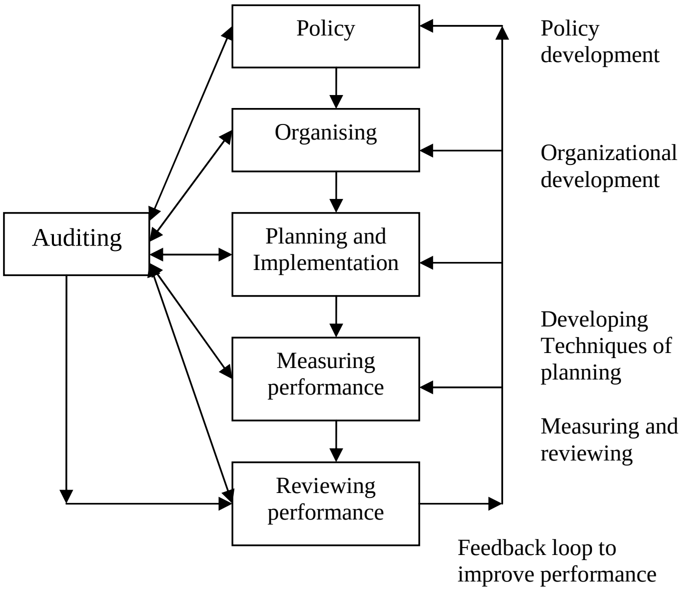



*Figure 3.2: Key elements of successful health and safety management (adapted from HSE, 2000).*

The necessary management activities for successful occupational health and safety management require clearly a defined policy, well-defined plans incorporating specific objectives, strong management commitment, the provision of sufficient resources, a systematic training program, effective monitoring and reporting of performance and a process for reviewing performance and making improvements (Lingard and Rowlinson, 2005).

According to Health and Safety Executive (2000), defining a corporate healthy and safety policy is the first step in the occupational health and safety management process. Policy should be established following a detailed analysis of an organization’s current situation with regard to health and safety. Events causing injuries and illness may also damage property and interrupt production. Identifying hazards and assessing risks, putting precautions in place and checking they are protects people and safeguards production. Health and safety policy should influence the selection of people, equipment and materials, the way work is done and how goods and services are provided. A written statement on the arrangements for implementing and monitoring policy shows that hazards have been identified and risks assessed, eliminated and controlled.

To make a health and safety policy effective, the next step in the management of health and safety is creating an organization in which roles, responsibilities and relationships support the systematic planning and control of health and safety. Various construction project stakeholders must be involved and committed to making it work. This is often referred to as a 'positive health and safety culture', of which the following five 'C's are the essential aspects:

- Commitment in being clear about your intent to achieve excellence in health and safety.
- Competence: to ensure that the workforce is competent to fulfil their health and safety responsibilities, the training needs of different groups of employees must be considered.
- Control: monitor staff knowledge and awareness.
- Consultation: involve the workers in the reviewing of problems and procedures.
- Communication: occupational health and safety information needs to flow effectively within the organization and people outside it.

Planning and implementation is the third step for a successful occupational health and safety management. Planning is the key to ensuring that your health and safety efforts really work. Planning for health and safety involves setting objectives, identifying hazards, assessing risks, implementing standards of performance and developing a positive culture.

Planning should provide for:

- Identifying hazards and assessing risks, and deciding how they can be eliminated or controlled;
- Complying with the health and safety laws that apply to your business;
- Agreeing health and safety targets with managers and supervisors;
- A purchasing and supply policy which takes health and safety into account;
- Design of tasks, processes, equipment, products and services, safe systems of work;
- Procedures to deal with serious and imminent danger;
- Co-operation with workers, managers, contractors and/or subcontractors;
- Setting standards against which performance can be measured.

Standards help to build a positive culture and control risks. They set out what people in the organization will do to deliver the policy and control risk. They should identify who does what, when and with what result. These standards should be measurable, achievable and realistic.

As in other areas it is necessary to measure health and safety performance to judge success. The fourth step for a successful health and safety management is measuring and monitoring health and safety performance which is a key activity in making sure that the organization is achieving its health and safety policy, objectives and targets.

The measurement of occupational health and safety performance involves a number of functions (HSE, 2000; Lingard and Rolinson, 2005). These include:

- Providing an indication of how the organization is performing in health and safety;
- Identifying problem areas in which improvements are needed;
- Providing the ability to track performance over time and evaluate the effectiveness of health and safety improvement strategies; and
- Providing data that can be used in benchmarking or comparative performance assessments, for example between construction projects.

As for monitoring, there are two key components to effective monitoring. Active monitoring, before things go wrong, involves regular inspection and checking to ensure that your standards are being implemented and management controls are working. Reactive monitoring, after things go wrong, involves learning from your mistakes, whether they have resulted in injuries and illness, property damage or near misses.  Information from active and reactive monitoring is used to identify situations that create risks, and do something about them. Priority should be given where risks are greatest, and looking closely at serious events and those with potential for serious harm. Both require understanding of the immediate and the underlying causes of events. The information is thereafter referred to the people with authority to take remedial action, including organizational and policy changes.

Monitoring provides the information needed to review activities and decide how to improve performance. Audits by the company own employees or outsiders, complement monitoring activities by looking to see if the policy, organization and systems are actually achieving the right results. Audits will indicate whether the health and safety policy have been reliable and effective. While reviewing the effectiveness of a health and safety policy, attention needs to be paid to:

- the degree of compliance with health and safety performance standards (including legislation);
- areas where standards are absent or inadequate;
- achievement of stated objectives within given time-scales;
- Injury, illness and incident data - analyses of immediate and underlying causes, trends and common features.

## 3.3 Construction planning

Construction planning is a fundamental and challenging activity in the management and execution of construction projects. It involves the choice of technology, the definition of work tasks, the estimation of the required resources and durations for individual tasks, and the identification of any interactions among the different work tasks. A good construction plan is the basis for developing the budget and the schedule for work. Developing the construction plan is a critical task in the management of construction (Hendrickson, 2000). Construction planning is not an activity which is restricted to the period after the award of a contract for construction. It should be an essential activity during the facility design. Also, if problems arise during construction, re-planning is required. The construction planner working for the contractor is usually a person with much experience in building construction who knows how to estimate the required labour and equipment from a building design. This knowledge is used to create a construction plan as the leading schedule for other derived plans such as safety, transport and measurement.

### 3.3.1 Choice of technology

According to Hendrickson (2000), in the development of appropriate alternatives for facility design, choices of appropriate technology and methods for construction are often ill-structured yet critical ingredients in the success of the project. In selecting among alternative methods and technologies, it may be necessary to formulate a number of construction plans based on alternative methods or assumptions. Once the full plan is available, the review of impacts of alternative approaches is possible, and this examination of several alternatives is often made explicit in the tendering process in which several alternative designs may be proposed.

In forming a construction plan, Hendrickson (2000) states that a useful approach is to simulate the construction process either in the imagination of the planner or with a formal computer based simulation technique. Due to the critical factor of the planning, a lot of research efforts have been directed to simulation of the building process based on planning, to visually search for conflicts and errors (de Vries and Harink, 2007). Three and four dimensional geometric models in a computer aided design (CAD) system may be helpful in simulating space and time requirements for operations and for identifying any interference. Similarly, problems in resource availability identified during the simulation of the construction process might be effectively forestalled by providing additional resources as part of the construction plan.

### 3.3.2 Work tasks definition

A parallel step to the choice of technology in the planning process is to define the various work tasks that must be accomplished. These work tasks represent the necessary framework to allow the scheduling of construction activities, along with the estimation of the resources required by the individual work tasks, and any necessary precedence or required sequence among the tasks. The terms work "tasks" or "activities" are often used interchangeably in construction plans to refer to specific, defined items of work. The scheduling problem is to determine an appropriate set of activity start time, resource allocations and completion times that will result in completion of the project in a timely and efficient fashion (Hendrickson, 2000). Construction planning is the necessary fore-runner to scheduling. In this planning, defining work tasks, technology and construction method is typically done either simultaneously or in a series of iterations.

The definition of appropriate work tasks can be a long and a tedious process, yet it represents the necessary information for application of formal scheduling procedures. Since construction projects can involve thousands of individual work tasks, this definition phase can also be expensive and time consuming (Hendrickson, 2000). Fortunately, many tasks may be repeated in different parts of the facility or past facility construction plans can be used as general models for new projects.

The set of activities defined for a project should be completely exhaustive so that all necessary work tasks are included in one or more activities. Typically, each design element in the planned facility will have one or more associated project activities. Execution of an activity requires time and resources, including manpower and equipment. The extent of work involved in any one activity can vary tremendously in construction project plans. Indeed, it is common to begin with fairly coarse definitions of activities and then to further sub-divide tasks as the plan becomes better defined.

### 3.3.3 Defining precedence relationships among activities

Once work activities have been defined, the relationships among the activities can be specified. Precedence relations between activities signify that the activities must take place in a particular sequence. Numerous natural sequences exist for construction activities due to requirements for structural integrity, regulations, and other technical requirements (Hendrickson, 2000).

## 3.4 Risk management in occupational health and safety

Emmett and Hickling (1995) defined risk management as: “the management of the working environment to control those aspects of work that will lead to undesirable health and safety outcomes. It involves an explicit analysis and determination of an acceptable level of risk”. The principle in risk management is to identify, assess and control risks before they could have any adverse effect on the working environment (Loflin and Kipp, 1997).

Risk management is not a linear process that is undertaken once. The cyclical nature of risk management is particularly important in the constantly changing construction environment in which new or emergent risks must be often assessed and controlled. It is critical that risk be assessed at every stage in the life of a construction project, and that the input of key stakeholders and project participants is sought (Lingard and Rowlinson, 2005). An effective risk management process should be managed by a cross-disciplinary team, and be supported by free and open communication and consultation between the project stakeholders.

### 3.4.1 Traditional approach

The cyclical nature of risk management process is opposed to the traditional approach shown in figure 3.3 and where its main characteristics are the separation of the design and construction processes, the lack of integration across the boundary and the employment of a whole series of consultants to design the project, with an independent contractor to take charge of the construction process. Typically, the project team is led by an architect with the responsibility for both design and project, where other consultants such as structural engineers and quantity surveyors will come in later in the design. In this case, the contractor’s input to the design process will be minimal, and often none. The design and construction processes and their sub-tasks are seen as sequential and independent.

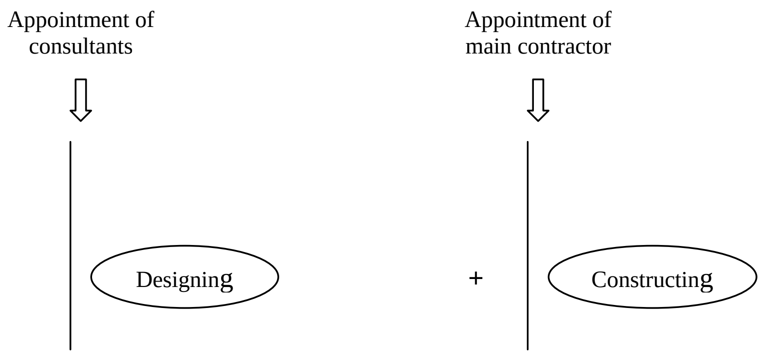



*Figure 3.3: The traditional approach (adapted after Austen and Neale, 1984).*

Important characteristics of the traditional approach are the level of differentiation among process participants, and the fragmentation in the tasks accomplished in order to complete the project. This approach has an effect on the health and safety system implemented on a construction project. Lingard and Rowlinson (2005) argue that the high level of differentiation and specialization leads to a situation where health and safety is not considered during the early phases of the project. As a consequence, worker's health and safety issues are not built into the design process, and the designers of a project have very little influence on the construction process, methods and materials used.

Lingard and Rowlinson (2005) state that due to the traditional process in which there is a divorce between design and construction, there is a heavier reliance on contract documentation and legislation to ensure that the risk assessments are produced and presented to the client or client's representative, and no very detailed analysis takes place based on construction methods or the risk in context.

### 3.4.2 Risk assessment

Risk assessment determines the degree of risk employees face from exposure to health and safety hazards at work and can help establish what is necessary to control the risk and to protect health. Broadening risk assessment to identify specific short and long term health hazards could be the way forward for the construction industry, driving targeted and effective health management. However, it must always be remembered that construction workers have a key part to play in the management of their own health, facilitated by the provision of education and training as part of the health management system (Gyi et al., 1998).

The risk management process is an iterative process involving a continuous cycle of risk identification, assessment and treatment or control. The assessment of risks informs risk control decisions, the implementation of which is monitored and reviewed to ensure that risk is controlled and remains within tolerable limits (Lingard and Rowlinson, 2005).

In general, in order to provide a practical guidance for the risk prevention, the assessment along with the identification and control of risks arising from tasks undertaken in the workplace which involve either or both the repetitive or forceful movement and maintenance of constrained or awkward postures should be performed.

Because of the dynamic nature of the construction work environment, Lingard and Rowlinson (2005) argue that it is critical that risk be assessed at every stage in the life of a construction project, and that the input of key stakeholders and project participants are consulted. These authors further state that involving designers in health and safety risk assessment exercises can provide opportunities to “design out” features of a building or structure that pose a threat to health and safety of crews during the construction phase.

### 3.4.3 Ergonomic workplace assessment

Ergonomic workplace assessment addresses an operator’s work assignment from the perspective of whether that operator or worker is physically capable of performing the assigned tasks, possibly within a specified time.

Apart from Schneider, Griffin and Chowdhury (1998) who performed a detailed analysis of ergonomic exposures of construction workers; research work done in the area of quantifying ergonomic injury exposures in the construction industry is quasi absent.

From a comprehensive review of epidemiological evidence for work-related musculoskeletal disorders (WMSDs), Bernard (1997) concluded that there is evidence of an association between musculoskeletal injuries and certain work-related factors when there is a high exposure to more than one physical factor; for instance, repetition, frequency, duration, intensity and posture. The results suggest that, while exposure to a single risk factor alone may cause injury, injuries are more likely where multiple risk factors occur.

In construction work, many of these physical risk factors are present and construction’s job-related activities that increase the risk of WMSDs are hereby identified by Schneider et al. (1995):

- The frequency or repetition with which the task is performed;
- The amount of physical force that is used;
- The need for lifting or moving heavy loads;
- The amount of prolonged static muscular tension;
- Working posture and position;
- Vibration from tools or machinery; and
- Need for working overhead and extreme ranges of movement.

An optimal approach to reducing WMSDs among construction workers requires a holistic assessment of all elements of the work system so that optimal solutions can be achieved. This requires a full range of generic issues to be considered, such as work task/workplace design, worker/equipment interface, work organization, organizational culture, individual variation and legal requirements.

### 3.5 Industrialization and prefabrication

Industrialization is a term used to attempt to describe and encompass the three aspects of offsite construction work: modularization, prefabrication and preassembly. Warszawski (1990) defines the industrialization process as an investment in equipment, facilities, and technology with the intent of increasing output, decreasing manual labour and improving quality. It uses the concepts of manufacturing and applies them to construction.

Prefabrication normally involves one skill or trade, such as electrical, piping, or steel rebar (Hass et al., 2000). Here, prefabrication does not seem to include concrete casting, which could be classified as an industrialization method when it is for example self-compacting concrete casting. Prefabrication can be defined as “a manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of a final of installation” (Tatum, 1987). These prefabricated components often only involve the work of a single craft. Any component that is manufactured offsite and is not a complete system can be considered to be prefabricated (Hass et al., 2000).

Industrialization of the construction processes in which industrialization changes from an on-site construction process to a more controlled factory-like construction process has been encouraged for reasons such as the attractiveness of workplaces that will strongly be enhanced by vigilant organization, new manufacturing methods, new architectural typology based on 2D and 3D components, new components, new connections and interfaces, and new on-site assembly methods (ECTP, 2005).

Increased use of off-site production furthers the industrialization of the construction process. Transferring as many as possible on-site activities into the factory is probably one of the most promising approaches in regard to the improvement of health and safety on the construction site (Wright et al., 2003; Gibb et al., 2004; McKay et al., 2005; Blismas et al., 2006).

## 3.6 Pre-build design as a prevention strategy

Although theoretically and practically it is impossible to prevent all injuries and illnesses from occurring, because of the fact that zero-risk can never be achieved, a significant reduction in disabling injuries and illnesses is attainable, and all other incidents can be managed through a comprehensive, multifaceted approach (Kumar, 1994). This holds particularly true for work-related musculoskeletal disorders (WMSDs).

Prevention through design, the concept that significant reductions in injuries can occur when safety is designed into a product, service or process, has been established within the general occupational health and safety field for many decades (Manuele, 1997). The most appropriate method of dealing with detrimental workload and preventing injuries would be to design the future task within the limitations of the worker to significantly decrease the risk of incident (Abdelhamid and Everett, 2002).

Ergonomics and human factors design principles may be employed as prevention strategies. Ergonomics and human factors employ the optimal design of workspaces, tools, equipment, environment, and processes with respect to health and safety. With knowledge of the physical and physiological limitations of the worker, as well as the organizational environment, the design principles may be employed during the planning and construction of the workspace, equipment, or job task as means of primary prevention (Amell and Kumar, 2001). Such significant front-end thought, input and planning into designing for the worker is desired.

## 3.7 Design for health

Designing for health and safety is based on the premise that many health and safety hazards exist because they are designed into the permanent features of the project. That is, features of the permanent facility influence the health and safety of those who build it (Gambatese et al., 2005). The concept of designing for safety is consistent with the traditional hierarchy of controls approach used by health and safety professionals. This hierarchy calls for eliminating or minimizing a workplace hazard before relying on personal protective equipment or administrative or temporary controls to protect workers (Manuele 1997).

Conventionally the role of design consultants has been to design a building, facility, or a structure such as it conforms to the accepted engineering practices, local building codes, and fulfils public safety regulations. The construction workers’ health and safety issues are relegated to the main constructor (Lingard and Rowlinson, 2005). However, design professionals can influence construction safety by making better choices in the design and planning stages of a project. This will result in fewer site decisions that have to be made by contractors and workers that can potentially lead to injuries and accidents (Mroszczyk, 2006) as a result of basic root causes such as lack of proper training, deficient enforcement of safety, unsafe equipment, unsafe methods or sequencing, unsafe site conditions, not using the available safety equipment and a poor attitude towards safety (Toole, 2002).

Gambatese (2003) in his study which aimed to investigate designing for health and safety as a prospective intervention for improving health and safety of construction workers, views the concept of designing for construction safety as a viable intervention to improve worker health and safety. This point of view is supported by the belief that there is a greater ability to influence safety of a project earlier in the project as illustrated by the time/safety influence curve shown in Figure 3.4 (Szymberski, 1997).

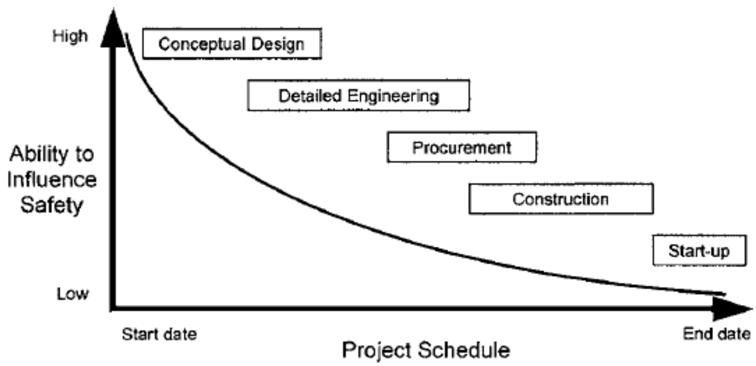



*Figure 3.4: The ability to influence safety decreases as schedule moves towards start-up (adapted from Szymberski, 1997)*

According to Szymberski (1997), the ideal situation is for construction safety to be a prime consideration in the conceptual and preliminary design phases; thus a significant portion of the ability to influence construction safety is lost when its consideration remains absent until the construction phase begins. There is a possibility to eliminate occupational health and safety problems and even improve project constructability when works contractors' experience and knowledge are incorporated at the design stage (Hinze and Gambatese, 1994; Behm, 2005).

## 3.8 Designing for construction worker health and safety

To follow up the rationale of influencing health and safety from the conceptual design stage, Gambatese et al. (1997) has introduced the concept of Designing for Construction Worker Safety (and health) (DfCS). Designing for safety (DFS) is the formal process that incorporates health and safety hazards analysis at the beginning of a design (Hagan et al., 2001). This process starts with the identification of hazards. Engineering measures are then applied to eliminate hazards or reduce risks.

The hierarchy of design measures starts with eliminating the hazard by engineering design. If the hazards cannot be eliminated by engineering design, then safety devices are incorporated. If the risk of injury cannot be eliminated by engineering design, or reduced by incorporating a safety device, then warnings, instruction, and training are the last resort (Mroszczyk, 2006). This process has been applied in manufacturing industry during the design process of products, equipment, machines, facilities and work tasks.

Designing for Construction Worker Safety (DfCS) is an extension of the DFS process for construction projects. The DfCS process applies to the design of permanent facilities or structures. The process does not address methods to make construction safer, but to make a project safer to build. DfCS process requires the ability to identify potential health and safety hazards associated with construction and maintenance workers in the design stage of a project. The skill of the design professional is then applied to eliminate the hazard or significantly reduce the risk by incorporating the appropriate design features (Mroszczyk, 2006).

The most essential feature of this process is the input of the site health and safety knowledge into design decisions. A number of reviews would ensure that health and safety issues are taken into consideration throughout the design process. At the end of the process, the drawing or virtual models and specifications would reflect a design that is conducive to a healthy and safe construction work environment.

## 3.9 Design visualization

Computer-aided design (CAD) software is a useful tool for addressing health and safety in the design of a project. CAD systems are commonly used throughout the design and construction industry, and they facilitate visualizing the design in the three dimensions to expose design conflicts and space issues. Incorporating the sequencing of activities of the construction work into the CAD drawings is especially helpful for determining the impact of the construction process on health and safety during different stages of the work. Designers can electronically proceed step-by-step through the construction sequencing to visualize the working conditions impacted by the design as it is being constructed (Gambatese, 2004).

### 3.9.1 Current construction design techniques

The communication of the construction schedule and execution strategy of work activities among the project team members is a unique construction problem that takes place at almost all construction sites. In addition, the built facility generates complex shapes of occupied workspaces by the executed construction processes, the analyses and communications of the execution space becomes more difficult and critical. Current space-time planning techniques involve mainly textual description, hand sketches with site layout templates, bar charts, network diagrams, and 2D/3D scaled visualization models. Current construction planning techniques like Gantt chart, network diagrams, and CPM are proven to be inadequate for construction execution space planning (Jongeling and Olofsson, 2007; Dawood, 2006).

The traditional technique for coordination of activities and resources in construction projects is the CPM-scheduling, which has been the predominant scheduling method since it was introduced in the late 1950s. Over the years, CPM has proven to be a very powerful technique for planning, scheduling and controlling projects. However, there is criticism raised on the CPM method, specifically in the case of construction projects, for deficient management of construction work and discontinuous flow of resources.

Construction projects usually involve a large number of direct and indirect stakeholders. Current methods of information exchange and communicating building design information among them can lead to various types of problems, including incomplete understanding of the planned construction, functional inefficiencies, and impediments called information filtering and information disconnects (Wakefield, O’Brien, and Beliveau, 2001).

### 3.9.2 Emerging virtual design tools

**3D modelling**

By visualizing construction processes in 3D, operational concepts can be validated and verified, design interferences checked, and construction operations reviewed. Also, by using visual representations of planned or completed construction activities, communication and information exchange among different stakeholders can be improved (see figure 3.5).

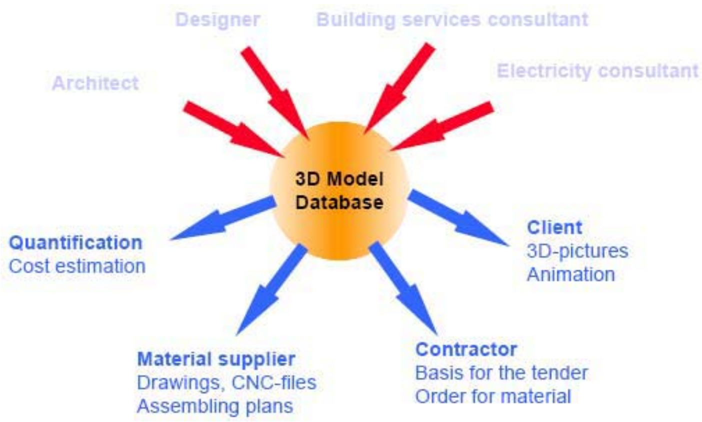



*Figure 3.5: The 3D database model for construction (Bergsten, 2001)*

The 3D modelling is extensively used for information sharing. The 3D model which is based on sharing a common database provides the last versions of drawings and information available from the database to all different players in the construction process. This database usually produced by professional designers through consultation with building and electrical consultants, provides a very useful resource for key stakeholders such as the client, the contractor, the material supplier and quantity surveyors. Material specifications and drawings obtained from the 3D model database are used for manufacturing and assembling prefabricated building components.

There are many advantages that 3D modelling holds for the project stakeholders. Rischmoller et al. (2006) state that the utilization of 3D CAD models to resolve interferences between 3D model objects during the project design stage avoids errors and problems that can represent high costs and delays if detected late during the project execution, extending the benefits of CAD utilization to the construction stage. Bergsten (2001) states however, that the 3D model is a static model, built in the computer for representing the physical building. This could be seen as a drawback for the construction process since the construction process is a dynamic process and needs a dynamic presentation. This is a problem when it comes to health and safety management at the design phase, 3D is not a model where workers and sub-contractors could contribute optimally as the 3D model does not allow the visualisation of a dynamic construction workplace that the construction worksite always is.

**Virtual reality (VR)**

In addition to 3D CAD, virtual reality technology can be utilised to further enhance the visualisation results. Taking the technological solutions to present-day limits, the use of virtual reality is becoming very important as a future mechanism for improving construction site health and safety. Hadikusumo and Rowlinsson (2002) and Rowlinsson (2003) discuss the use of VR systems to assist in construction layout and safety analysis. These authors argue that the issue is addressed through a visualisation that allows the representation of virtual product and the process data. A simple VR system can be used to represent a 3D object that supports a ‘what-you-see-is-what-you-get’ environment. This advantage can be used to eliminate the problem of interpreting 2D drawings as 3D mental objects, since all construction objects can be represented as 3D objects in a VR world (Lingard and Rowlinson, 2005).

**4D CAD simulation**

Both in the construction industry and educational institutions there has been a tradition of analysing the designs for building and infrastructure projects and planning their construction by reviewing 2D project design drawings and by developing construction cost estimates and schedules. For example, educators in construction engineering tend to use 2D drawings and Critical Path Method (CPM) schedules to discuss project planning. These traditional design and construction planning tools do not support the timely and integrated decision making necessary to move projects forward safely and quickly. Although 2D drawings and CPM schedules are to a degree visualization tools, they limit their users' ability to comprehend the impact of design and planning decisions on projects.

CAD systems that include the time element are becoming more available in the industry and easier to use. There is a growing interest to improve construction planning through the use of virtual reality and 4D CAD modelling (3D CAD with schedule time as the $4^{th}$ dimension) of construction processes and projects (Heesom and Lamine, 2004).

In recent years, a number of civil and architectural programs are assessing the educational value of having students develop 4D CAD models for building projects (Messner et al., 2003). 4D CAD software supports linking of 3D (CAD) geometry to one or more schedule activities, as reflected in Figure 3.6.

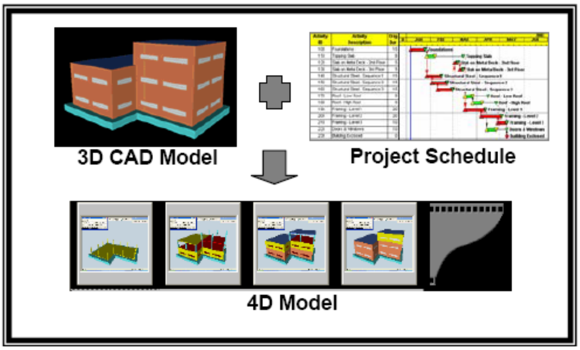



*Figure 3.6: 4D CAD Model development (Messner et al., 2003)*

The result of an established link of 3D geometry representing building elements and schedule activities is a simulation of the planned building process. The simulation enables analysis and communication of a schedule. Cory (2001), states that 4D CAD focuses on the integration of the technical design information into the design and construction phases. Dawood et al., (2003) agree that 4D CAD planning consists of systems "where the process is visualised by building the 3D product model through time according to the critical path method". 3D CAD is thus converted to "virtual reality" simulation. 4D construction simulation or visualization is described by Chau et al., (2003) as being "generated automatically via integrating the 3D geometrical model with the associated activity schedule". As far as health and safety management of the construction workplace, the 4D modelling offers a dynamic construction work environment through simulation, and thus enabling design decisions related to health and safety to be taken earlier at design start.

### 3.10 Conclusions on theories

Occupational biomechanics provides us with an assessment able to quantitatively describe the musculoskeletal loading that occurs during work so that one can derive an appreciation for the degree of risk associated with work tasks. Different theories of health and safety management indicate the traditional separation between design and construction which contributes to the difficulty of planning for a healthy workplace for construction workers. Risk management could be controlled partly through industrialisation and prefabrication, however to be certain that the preventive effort will be efficient in reducing injury, established risk assessment methods should test the current working environment in order to establish the best practices within the construction industry. Furthermore, addressing health and safety issues early on in the design stage shows the potential of being more beneficial than dealing with these issues later on in the production phase. Virtual design tools could potentially help improve communication over issues or concerns between construction project participants in the early design where there are still many opportunities to modify a design or simulate what if scenarios in order to evaluate the impact of different designs on workers' health and safety. Planning for the healthy construction workplace requires the capacity to communicate the construction design information adequately among the project stakeholders including subcontractors and work crews who would be the greatest contributors in planning for a healthy construction workplace.

# 4 SUMMARIES OF PAPERS

This thesis chapter includes brief summaries of the five papers. The summary outline of each paper includes: the title of the paper, the author or authors of the paper, publication status, which research question the paper addresses, the paper's key words, the background, methods, results and contributions of the paper.

The five papers demonstrate a line of reasoning that shows how planning for a healthy construction workplace is done through the identification and implementation of the best practices of the day, the workload risk assessment and the use of 3D and 4D CAD visualisation of construction projects designs in order to address work-related health risks (i.e. WMSDs) through a multidisciplinary participation.

The first three papers deal with benchmarking best practices in WMSDs reduction and workload risk assessment of carpenters and concrete workers working with innovative construction methods. The last two papers pave the way theoretically and practically for how to design healthy construction workplaces (see figure 4.1.).

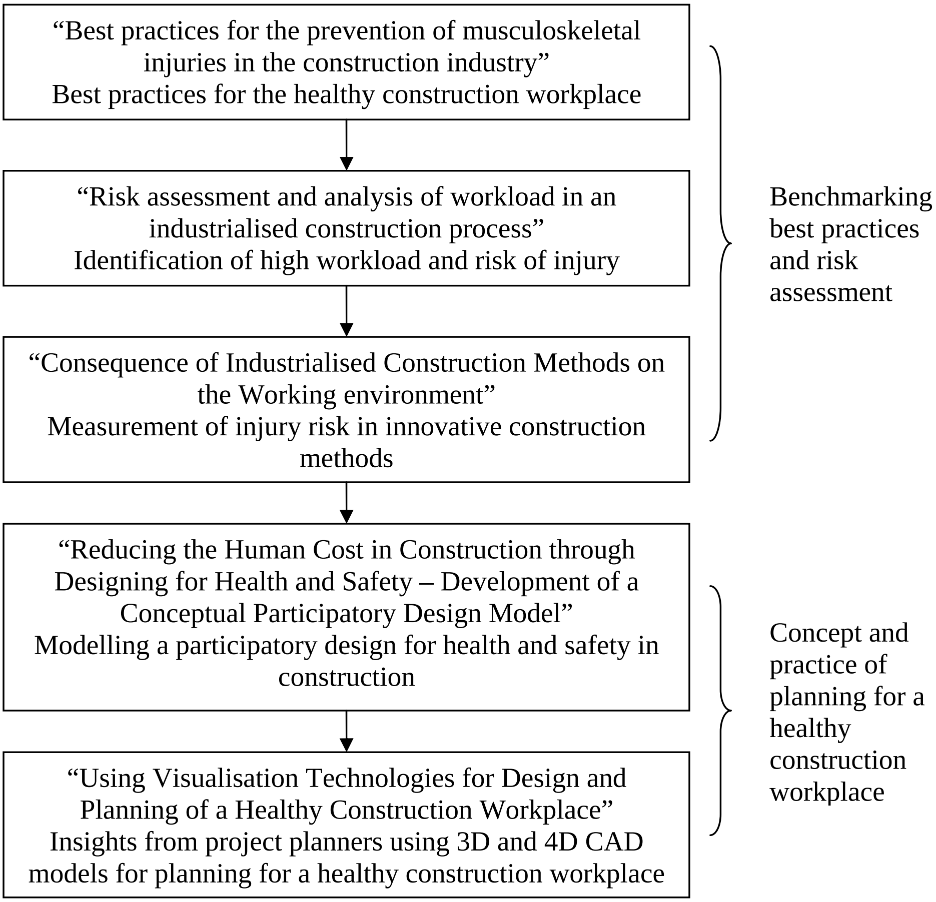



*Figure 4.1: A flow diagram of the thesis papers*

## 4.1 Summary of Paper I

**Title:**

Best practices for the prevention of musculoskeletal injuries in the construction industry

**Authors:**

Romuald Rwamamara, Ove Lagerqvist, Thomas Olofsson and Bo Jahansson

**Publication status:**

Submitted in 2007 to the *Journal of Construction Engineering and Management*

**Which research question of the thesis is addressed?**

Research question I: What are the best practices which have proved to be successful in the fight against the development of work-related musculoskeletal injuries in the Swedish construction industry?

**Key words:**

Construction management, injuries, Occupational health, working conditions

**Background:**

The work environment alone cannot account for the large number of long-term sick leaves due musculoskeletal disorders among construction workers, but it is one of several factors involved, and improvements in the workplace are seen to be the most important single measure for reducing the incidence of ill-health. In the absence of literature that gives enough information about good industry practices promoting musculoskeletal health, benchmarking best practices in construction activities from the construction planning to the construction production process was employed in research to show how different activities impact a healthy construction workplace.

**Purpose:**

To identify and describe strategies and activities which have proved to be successful in the fight against the development of work-related musculoskeletal disorders in the construction industry.

**Methods:**

Empirical data concerning the construction projects' best practices conducive to the reduction of Work-related Musculoskeletal Disorders (WMSDs) were obtained through a triangulation of interviews, site observations and company documents.

**Research results:**

The results have shown that there are numerous best practices both in design/planning and production stages of the thirteen construction projects investigated in the research study. Although best practices were identified in the different areas of the construction workplace system, there seems to be a significant need for good practices in Systematic Work Environment Management (SWEM) and the implications of some payment methods on the production schedule had a negative effect as far as construction workers' work-related musculoskeletal health is concerned. Poor planning of work tasks done on the construction site was often seen as the main culprit for musculoskeletal injuries.

**Contributions to knowledge:**

The main theoretical contribution is the construction workplace system being used an empirical basis to identify the construction workplace best practices conducive to the reduction of WMSDs. Based on the empirical results in this paper, specific practical recommendations were offered to the construction industry, for example the need for client involvement in the implementation of a work environment plan, and consideration of a broader consultation of construction project key stakeholders (including work crews representatives) at the design and planning stage. Furthermore, Paper I brought to attention the need for planning for a dynamic construction site in order to contribute to the health of its workers.

## 4.2 Summary of Paper II

**Title:**

Risk assessment and analysis of workload in an industrialised construction process

**Author:**

Romuald Rwamamara

**Publication Status:**

Published in 2007 in the scientific journal of *Construction Information Quarterly*, CIOB, 9(2)

**Which research question of the thesis is addressed?**

Research question II: How can the injury risk on construction workers be assessed in industrialized construction process?

**Key words:**

Industrialised process, exposure assessment, health and safety design, best practices

**Background:**

Industrialization of the construction processes in which industrialization changes from an on-site construction process to a more controlled factory-like construction process has been encouraged in construction projects for reasons such as the attractiveness of the workplace in terms of health. However, awkward and repetitive postures are still observed despite the benefits of industrialization, for example the use of prefabricated components on construction sites. Therefore there is a need for assessment tools that are able to predict the risk of future WMSDs so that the monetary costs and human suffering can be averted.

**Purpose:**

To measure the workload associated with the assembly/building of inner walls using prefabricated components or gypsum wall panels and its affects on musculoskeletal system of construction workers.

**Methods:**

Using video recordings, two risk analysis methods, ErgoSAM based on SAM (a sequence-based activity method), a higher-level method-time-measurement (MTM) system and QEC (a Quick Exposure Check) were used in the study to measure potential exposure to risk factors for WMSDs. Work risks measurements were limited to the inner walls assembly work tasks.

**Research results:**

The study presented in this paper revealed that the installation of inner walls using prefabricated components entails a number of work tasks that are physically demanding due to awkward work postures and lifting of heavy gypsum panels. The use of the methods ErgoSAM and QEC to analyse the impact of an industrialised system (i.e. use of prefabricated components) has a lot of potential in identifying WMSDs risks and thus providing a basis on which these injury risks can be planned out in the design of an effective and healthy construction workplace. Recommendations for consideration in the selection of ergonomically designed tools are drawn from best practices publications.

**Contributions to knowledge:**

ErgoSAM method which has been traditionally a manufacturing pre-production risk assessment tool has been shown for the first time in this paper as an adequate tool to assess and analyse the risk for musculoskeletal injury in the construction activities during production phase. Further, the paper suggests that the health and safety benefits from industrialization cannot be taken for granted as the paper has identified situations of high workload and risk for musculoskeletal injury. The paper has also linked the problematic work tasks to corrective measures found in the best practices tools available in the construction industry publications.

## 4.3 Summary of Paper III

**Title:**

Consequence of Industrialised Construction Methods on the Working environment

**Authors:**

Peter Simonsson and Romuald Rwamamara

**Publication status:**

Published in 2007 in *Proceedings of the 15$^{th}$ International Group for Lean Construction Conference* (IGLC15)

**Which research question of the thesis is addressed?**

Research question III: How does the use of prefabrication and innovative materials impact the construction workplace environment?

**Key words:**

Working environment, Steel reinforcement, Concrete casting, Industrialization, Lean construction

**Background:**

The industrialization of the construction process reflects the use of technology to change the sector's work environment for the better. Industrialised construction methods such as the use of the prefabricated steel reinforcement and the Self Compacting Concrete (SCC) have been introduced into the construction workplace for among other reasons the improvement of the work environment.

**Purpose:**

To investigate how different traditional production methods are from the industrialised ones in terms of their impact on the concrete workers during steel reinforcement and concrete casting work tasks.

**Methods:**

Empirical data were collected through construction site observations along with video filming and informal interviews. With a sequence-based activity method ErgoSAM, an ergonomic risk analysis was conducted on work tasks recorded on video films.

**Results:**

The paper showed that the use of prefabrication and innovative materials industrialised construction methods reduced ergonomic workload on concrete workers. The paper indicates that industrialization of the production process through the introduction of innovative construction methods has improved the construction workplace environment in terms of reducing the injury risks due to WMSDs among workers (i.e., concrete workers). With the use of these industrialised construction methods, not only manual material handling tasks are noticeably reduced, but the adverse affect on health due to handling vibrating tools is eliminated.

**Contributions to knowledge:**

Based on empirical results, the paper presents important differences in injury exposures between the use of conventional and the use of industrialised methods on the construction site.

### 4.4 Summary of Paper IV

**Title:**

Reducing the Human Cost in Construction through Designing for Health and Safety – Development of a Conceptual Participatory Design Model

**Authors:**

Romuald Rwamamara, Peter Holzmann

**Publication status:**

Published in 2007 in *Proceedings of 2nd International Conference, World of Construction Project Management, WCPM 2007.*

**Which research question of the thesis is addressed?**

Research question IV: How could design for health and safety concept improve construction workers health and safety?

**Key words:**

Health and safety, design, construction, building planning, virtual design

**Background:**

Due to the persistent human cost related to WMSDs caused by risk factors engendered by construction work activities, both the industry production loss and construction workers ill health are the result of a problem yet to be solved. Prevention through design is being introduced in the construction industry as a concept that could be used to significantly reduce injuries occurrence through designing health and safety into a product, service or process.

**Purpose:**

To develop a conceptual model based on the participation of key stakeholders in construction projects and as well as based on consideration of identified areas of construction design influences on work-related musculoskeletal injury occurrence.

**Methods:**

Review of literature and sites observations.

**Results:**

The developed model is concerned with breaking down the traditional separation of design and construction functions and considers inputs of various key stakeholders in a construction project. The participation of the project stakeholders in designing for health and safety in construction will form a participatory health design which takes account of the design originating factors for WMSDs.

**Contributions to knowledge:**

The developed model pulls together the knowledge of various stakeholders in design and construction to plan for construction workers health and safety from the planning stage to the maintenance of the building facility or infrastructure. The participatory nature of the model gives weight to the necessity of partnership in the vital task of planning for construction workers health. Practically, this model can be used by planners to design healthy construction workplaces.

## 4.5 Summary of Paper V

**Title:**

Using Visualisation Technologies for Design and Planning of a Healthy Construction Workplace

**Authors:**

Romuald Rwamamara, Håkan Norberg, Thomas Olofsson and Ove Lagerqvist

**Publication status:**

Submitted in 2007 to the Journal of *Construction Innovation*

**Which research question of the thesis is addressed?**

Research question V: How does visualization impact the planning of a healthy construction workplace?

**Key words:**

Design visualization, effective planning, healthy and safety, construction workplace

**Background:**

Virtual tools such as 3D and 4D models are renowned for being capable and innovative communication tools, and that is mainly why there is a growing trend in the construction industry to use these tools for visualization of construction information. The primary or nascent use of 3D and 4D modelling has been essentially viewed as a means to increase the quality of production through decreasing the number of potential design mistakes and increasing buildability. However, with a constantly growing number of work injuries due to poor planning a robust tool for visual communication of construction activities and their potential health consequences is required.

**Purpose:**

To identify the advantages of the virtual tools namely 3D and 4D models in terms of their ability to communicate design details and their impact on the healthy construction workplace planning

**Methods:**

Interviews were performed with planning engineers using 3D and 4D models as planning tools in their current construction projects. Observations were also made on a 4D model of one of the three construction projects investigated in this paper’s research study.

**Results:**

The paper results indicate that through 3D and 4D virtual models the construction process becomes efficient for all key stakeholders in the project. The study presented in the paper points out that the 3D and 4D models are also a powerful tool for a clear and tangible communication on workers health and safety issues during the design and healthy construction site planning.

**Contributions to knowledge:**

The contribution of this paper is the use of the virtual models to identify health and safety problems early in the design phase, and thereafter addressing these problems in the design and planning of a project. The paper presents how useful simulations of the production process through 4D CAD are in regard to construction work methods and work tasks planning. Through simulations logical sequencing of tasks can be performed to avoid work space congestion and work crews overlapping and an efficient planning of lifting aid devices can occur already in the early stages of design.

# 5 CONCLUSIONS

In general the purpose of the research presented in this thesis is to enhance the knowledge of how the planning for a healthy construction workplace could be achieved through best practices benchmarking, risk identification and participatory health and safety design facilitated by visualization tools during the design phase. This purpose was essentially fulfilled through the identification of good practices employed in the Swedish construction industry to eliminate or reduce WMSDs, the risk assessment of industry's current construction methods, the development of a conceptual participatory design model and the empirical evidence and practical use of virtual tools to facilitate the participation of key stakeholders through tangible and clear communication. The stepping stones of the overall purpose of this thesis research were specified through the formulation of five research questions already mentioned in two of the previous chapters. This concluding chapter contains a summary of how the research questions were addressed as well as the scientific and practical contributions, and finally this chapter will include suggestions for future research.

## 5.1 Addressing research questions

The research questions are addressed through the research results obtained in the five papers that are part of this thesis. The research gives answers to the following five research questions:

**Question I:** What are the best practices which have proved to be successful in the fight against the development of work-related musculoskeletal injuries in the Swedish construction industry?

This research question is addressed in Paper I, where different best practices were recognized and identified by the interviewees from different occupational groups with various functions in the design/planning and construction production along the entire construction process. As a way of managing work-related musculoskeletal disorders (WMSDs) in construction work activities, a number of best practices were constantly identified in the empirical data gathered from the interviews records, site observations and construction companies' health and safety related internal documents. The identified best practices in the 13 construction projects investigated in the research study were categorized in 6 interrelated areas, namely the planning, the work organization, production technology, the physical work environment, work tasks and the individual worker characteristics. Briefly the good practices in regard to reducing WMSDs are comprised of a planning in which trade workers representatives and subcontractors are invited to give their opinion on the design in regard to workers health and safety issues and specifically in terms of building materials and work methods to be used; the work organization in construction projects which is hierarchically flat and streamlined allows the workers and their representatives to raise the health issues in weekly meetings with their managers and supervisors who are offered training on how to recognize and deal with these issues; in terms of technology aspects, production methods have improved to accommodate more work processes that involve less manual material handling and much more off-site construction; the construction site is getting physically bearable in a sense that it is becoming less weather dependant when sites are managed under a production hall or weather shields. Finally, the work tasks and individual characteristics have contributed to best practices in terms of tasks being performed with ergonomically designed tools and personal protective equipment meant that work postures with which work tasks are performed do change for the better thus reducing risks of WMSDs.

**Question II:** How can the injury risk on construction workers be assessed in the industrialized construction process?

This research question is addressed in the Paper II, where an injury risk assessment was carried out on carpenters working in an industrialized situation using prefabricated building components. The risk assessment was performed through two methods ErgoSAM and QEC; both these assessment tools are quite meticulous, in particular due to their original use in the manufacturing industry where work tasks at stationary workstations are analysed. The risk exposure assessment methods are both based on well-established WMSDs risk factors, namely force, posture and frequency which are found in the epidemiological research studies on the origins of WMSDs. Based on work tasks observation and information from workers on their own work activities and its risk factors, a predictive WMSDs risks assessment could be made more accurately during production or before production at the design stage if work tasks execution details could be available perhaps through experienced and methodical construction workers.

**Question III:** How does the use of prefabrication and innovative materials impact the construction workplace environment?

This research question is addressed in Paper III, by empirically investigating a case study project where innovation in construction work methods was highly employed in a bridge construction project. Innovation in this project consisted of the use of prefabricated steel reinforcement and self-compacting concrete (SCC) casting. Through a sequence-based activity method, an ergonomic analysis was performed on work tasks entailed in steel reinforcement and concrete casting work activities. A performed comparison between the traditional or conventional performance and the innovative performance of these construction activities revealed a large difference in injury risk exposures. The new construction methods i.e. the use of prefabricated steel structures and SCC showed a much lesser impact on the construction site work environment in terms of reduced WMSDs risk exposure among concrete workers who are usually exposed to risk factors such as heavy lifting, awkward postures, repetitive movements and even vibration when their tasks are performed in the conventional manner.

**Question IV:** How could the design for health and safety concept improve construction workers health and safety?

This research question was addressed in Paper IV, by developing a conceptual model for designing health and safety in construction. The development of this conceptual participatory design model which is based on different injury influencing factors in the construction design, shows that a close interaction and active partnership between various key stakeholders in a construction project are necessary to achieve a participatory health and safety design through the different key stakeholders inputs materials, equipment and tools optimal design and through permanent works and work tasks design. Furthermore, paper IV points out that the participatory health design for a healthy construction workplace must be facilitated by a robust communication namely the design visualization tools such as the 3D and 4D CAD models which are potentially useful for addressing health and safety in the design of a construction project.

**Question V:** How does visualization impact the planning of a healthy construction workplace?

This research question was addressed in Paper V, by investigating three construction projects that have used virtual design tools in the planning of the work activities in the production process. Interviews results in Paper V showed that visualization through 3D and 4D CAD models allows representation of the virtual building object and the process data. Interviews with the users of 3D and 4D models in construction planning indicate that through visualization various stakeholders in a construction project are able to communicate easily about their health and safety concerns and thus solutions. According to interview results, the use of 3D and 4D CAD models, allowed different people involved in a construction project to see virtually real construction objects easily since they are represented as 3D objects, this situation improves the health and safety process by removing the difficult mental interpretation process of imagining 2D architectural drawings as 3D mental objects. Finally, the interviews with the planners using 3D and 4D models indicated that these models made it easier to conduct risks assessment in the virtual building object before the project design had been completed, allowing significant contributions to be made to the health and safety planning of the construction workplace.

## 5.2 Concluding discussion

In addition to providing the specific answers addressing the research questions examined in the research presented in this thesis; the research has through its findings contributed to theory and practice as well as practical implications vis-à-vis the industry’s practitioners, workforce and society. Therefore the following section will provide a description of the scientific and practical contributions of this thesis research work.

### 5.2.1 Scientific contribution

In the research presented in this thesis, there are four chief areas where contributions to theory and practice have been made. The first area of contribution is found in Paper I where the identification of best practices conducive to the reduction of WMSDs is provided through a model of the construction work system made up of various interacting aspects (i.e. planning, work organization, production technology, physical workplace, work tasks, and individual worker characteristics) whose balance determine whether construction workers are exposed to WMSDs risk factors or not. The research study presented in Paper I contributes to the research body of knowledge by pointing out those aspects of the construction work system that are causal factors of the work-related musculoskeletal health or the absence of it.

The second area of contribution is offered in Papers II and III where the risk assessment of work tasks is shown to be imperative to determine the potential WMSDs and risk exposure level whether a construction process uses industrialized or traditional construction methods. Both risk assessment methods employed in Paper II originate from the manufacturing industry world, and for the first time in this thesis research they have been used to assess injury risk exposure in construction work tasks. I hope many other researchers are going to go ahead and do further experiment with these risk assessment methods in future construction work tasks studies.

The third area of contribution is presented in the Paper IV where a model was built on existing theories and existing past research studies; this model needs to be tested to prove its practical applicability, however if the model for the health and safety participatory design is proved through future research studies to be worth using to improve the planning of the construction site's health and safety, then I would say that this model has been one of the stepping stones towards an optimal health and safety design for the construction workplace.

The fourth area of contribution is found in Paper V, where this paper indicates the potential of 3D and 4D visualization to improve the design for health and safety and easy identification of injury risks. In order to solve these occupational injuries such as WMSDs, the crucial benefit of adequate information communication provided through 3D and 4D models was shown to be a great advantage in the quest of planning a healthy constriction workplace.

### 5.2.2 Practical contributions

The research findings presented in this thesis have various practical implications for different construction stakeholders. I believe the common interest between stakeholders for this kind of research is the tools for the improvement of work-related health and specifically the reduction of WMSDs among construction workers. There is no doubt that any reduction of these injuries would reduce the individual, company and societal costs associated to them and would increase the image of the construction industry as a whole, thus making the construction worksite an attractive place to work for a young aspiring workforce.

For trade workers and engineers who are plagued by WMSDs, the study in Paper I identified current best practices that the industry employs to reduce WMSDs. Paper I suggests recommendations in regard to areas that need improvement in order to contribute effectively to the musculoskeletal health of workers. The areas such as ineffective worker consultation and involvement and inadequate planning of health issues were addressed in Papers IV and V through visualization design tools (i.e., 3D and 4D models) embedded in the conceptual participatory health design model that strongly advocates consulting key stakeholders which include workers as they are the ones who know the job or work tasks better in order to design out potential injury risks.

The research findings in Paper II contribute to the understanding of contractors and clients that prefabrication is not always free of injury risk exposure especially if the prefabricated elements have not been specified meticulously in the factory in order to avoid adjustments that generate unplanned repetitive work tasks before the prefabricated components are finally installed on-site. Both ErgoSAM and QEC as risk analysis methods have great potential in the production planning, especially where assembly work is required.

The research findings on the innovative construction methods in Paper III come as an encouragement to the clients and contractors as its benefits in terms of health and safety on constriction site were highlighted. The main benefit was specifically the reduction of WMSDs risks exposure that was significant when working with innovative building materials such as the prefabricated steel reinforcement and the self-compacting concrete. The use of these methods not only reduces injury risks to construction workers, but does also reduce the costs associated with material waste.

Finally, the research findings have practical implications on partnerships between key project stakeholders (including subcontractors and trade workers) that have to be improved in order to communicate effectively on health issues. The research in this thesis shows those involved in construction projects that there is a huge potential through visual simulation of work processes using 3D and 4D models that enable adequate planning, communication and analysis capabilities that create a healthy construction workplace.

In summary, while I believe that I have not presented the final solution to planning the healthy work environment, this work can be considered a significant step on the way towards such a solution.

### 5.2.3 Limitations and future research

In this closing section of the thesis, encountered limitations and future research work are discussed.

**Research limitations**

The research presented in this thesis has some limitations without which this research may have been more accurate and perhaps more beneficial to different stakeholders in this research, namely the society, the industry, and the scientific community.

Time is often the main limitation when doing PhD research and this case was no exception. The conceptual model presented in Paper IV would have been more beneficial if it had been tested in a real case study to check the extent of its applicability in a real construction project. To do such a case study would have involved a large amount of time and commitment on behalf of all key stakeholders; furthermore additional time would have been required of the investigator or researcher to follow-up and evaluate the success or absence of it as far as the participatory health design model being tested is concerned.

In Papers II and III, limitations are not time-related but they are rather due to the restriction of the case studies to quantitative ergonomic risk methods, where subjective assessments such as interviews with workers would have perhaps added a necessary confirmation to the results obtained through risk assessment methods. In Papers II and III where ErgoSAM method, the method proved to be an easy tool to analyse a workplace by assessing the physical workload; however the method does not take into account all ergonomic parameters (static loading for example). Furthermore, unlike QEC method which is relatively easy to use, ErgoSAM method is time consuming (1 minute of video film analysis could take up to an hour). In addition, the accuracy of ErgoSAM analysis of construction work tasks may be affected due to the use of the limited parameters in the SAM database defined in a different industry.

Paper I identified best practices which were best at the time when the research was done, the research is limited in a sense that it is difficult to measure the shelf-life of these best practices. What is best today might not be best tomorrow. Furthermore, the best practices presented in Paper I were identified only from thirteen construction projects, which means that it will be difficult to generalise that the good practices are typical for all of the Swedish construction industry.

### Future research work

The next step is to test the proposed model for health and safety participatory design. Investigate further the impact of visual simulation of construction work processes on designing for a healthy construction workplace. Furthermore, location and time-independent interaction and partnership among the multidisciplinary team of stakeholders in the construction industry at the early design stage could highly influence the level of health and safety on the construction site. Construction projects are highly project oriented in nature, which results in different teams being formed at a very dynamic and fast pace, thus leading to the possibility of an inefficient partnership among the project team members. How does one develop a mechanism that can provide an efficient health and safety partnership among key stakeholders at early stages of a building project?

Further improvements to be investigated include construction tasks modelling using visualization tools that adapt tangible products and processes to human capabilities during the design process to improve the task performance, the physical comfort and the health and safety of construction workers. Therefore, to incorporate ergonomic considerations in a purely digital (CAD) phase, early in the design process, a designer will need digital representations of the future users namely avatars in the 3 and 4D models.

# References


Abdelhamid, T.S. and Everett, J.G. (2002) Physical demands of construction work: A source of workflow unreliability. *Proceedings of the 10th Conference of International Group for Lean Construction,* Gramado, Brazil, August.

Abdelhamid, T. S., Patel, B., Howell, G. A., and Mitropoulos, P. (2003). “SignalDetection Theory: Enabling Work Near The Edge”. *Proceedings of the 11th Annual Conference for Lean Construction*, 22-24 July 2003, Blacksburg, Virginia, 243-256.

Amell, T. and Kumar, S. (2001) Work-Related Musculoskeletal Disorders: Design as a Prevention Strategy. A Review. *Journal of Occupational Rehabilitation,* 11, 4, 255-265.

AS/NZS 4804:1997 (1997) *Occupational Health and Safety Management Systems – General Guidelines on Principles, Systems and Supporting Techniques*, jointly published by Standards Australia, Homebush, Australia, and Standards New Zealand, Wellington, New Zealand.

Ballard, G. and Howell, G. (1998) Shielding Production: Essential Step in Production Control. *Journal of Construction Engineering and Management,* ASCE, 124 (1).

Behm, M. (2007) Linking construction fatalities to the design for construction safety concept. *Safety Science*, 43, 589-611.

Bergsten, S. (2001) 4D CAD- An efficient Tool to Improve the Production Method for Integration of Apartments in Existing Buildings. Construction Informatics Digital Library. http://itc.scix.net/paper w78-2001-2.content

Bernard, B.P. (1997) *Musculoskeletal Disorders (MSDs) and Workplace Factors, 2nd printing,* US Department of Health and Human Services.

Blismas, N.G., Gibb, A.G.F. & Pasquire, C.L. (2006) Benefit evaluation for offsite production in construction, *Construction Management and Economics*,.24 (2), pp. 121-130, ISSN 0144 6193

Canadian Centre for Occupational Health & Safety (CCOHS) (1998) *A Basic Occupational Health and Safety Program*, Canadian Centre for Occupational Health & Safety, 1998. Available: http://www.ccohs.ca/oshanswers/hsprograms/basic.html

Christmansson, M., Falck, A.-C., Amprazis, J., Forsman, M., Rasmusson, L. and Kadefors, R. (2000) Modified method time measurements for ergonomic planning of production systems in the manufacturing industry, Ind. J. Prod. Res., 38, 17, pp. 4051-4059.

Clough, R.H, Sears, G.A. and Sears, S.K. (2000) *Construction Project Management,* Fourth Edition, John Wiley & Sons, New York, USA.

Dawood, N. and Mallasi, Z. (2006) Construction Workspace Planning: Assignment and Analysis Utilising 4D Visualisation Technologies. *Computer-Aided Civil and Infrastructure Engineering*, 21, 498-513.

Denzin, N.K. (1989). The Research Act. A theoretical Introduction to Sociological Methods. Third Edition. Prentice Hall, Englewood Cliffs, NJ.

De Vries, B. and Harink, J.M.J. (2007) Generation of a construction planning from a 3D CAD model. *Automation in Construction 16, 13-18.*

ECTP (European Construction Technology Platform) (2005) Strategic Research Agenda for the Construction Sector, Achieving sustainable and competitive construction by 2030. http://www.ectp.org/documentation/ECTP-SRA-2005_12_23.pdf, (accessed 4th July 2006)

Emmett, E. and Hickling, C. (1995) Integrating Management Systems and Risk Management Approaches, *Journal of Occupational Health and Safety*, Australia and New Zealand, 11 (6), 617-624.

European Foundation for the Improvement of Living and Working Conditions (2005) Trends and drivers of change in the European construction sector: Mapping report. http://www.eurofound.europa.eu/emcc/publications/2005/ef04149en.pdf (last accessed 29th June 2007).

Fellows, R. and Liu, A. (2003) Research Methods in Construction. Blackwell Science Ltd, Oxford, UK.

Flanagan, R.; Jewell, C.; Ericsson, S.; Henricsson, P. (2005) Measuring Construction Competitiveness in Selected Countries. Final Report. http://n.1asphost.com/competitiveness/ last accessed on June 15, 2007.

Forsberg, A. and Saukkoriipi, L. (2007) Measurement of waste and productivity in relation to Lean thinking. *Proceedings of the 15th Conference of International Group for Lean Construction*, July 2007, Michigan, USA.

Gambatese, J. (2003) Investigation of the viability of designing for safety. The Center to Protect Workers' Rights, Rockville, MD, USA.

Gambatese, J. (2004). An Overview of Design-for-Safety Tools and Technologies. In S. Hecker, J. Gambatese and M. Weinstein (eds). Designing for Safety and Health in Construction. *Proceedings from a Research and Practice Symposium*. University of Oregon Labor Education and Research Center, University of Oregon Press.

Gambatese, J., Behm, M., Hinze, J.W. (2005) Viability of Designing for Construction Worker Safety. *Journal of Construction Engineering and Management*, September 2005, 1029—1036.

Gibb, A., Haslam, R., Hide, S., and Gyi, D. (2004) "The role of design in accident causality." In: S. Hecker, J. Gambatese, and M. Weinstein (Eds.) Designing for Safety and Health in Construction.

Gibb A.G.F, Pavitt, T.C., & McKay, L.M., (2004) Designing or health and safety in cladding installation – implications from preassembly, *Proceedings of International Conference on Building Envelope Systems and Technologies* (ICBEST 2004), Sydney, Australia, p 1-7.

Gyi, D.E., Haslam, R.A. and Gibb, A.G.F. (1998) Case Report. Case studies of occupational health management in the engineering construction industry. *Occupational Medecine*, 48 (4), 263-271.

Haas, C.T., O'Connor, J.T., Tucker, R.L., Eickmann, J.A. and Fagerlund, W.R. (2000) *Prefabrication and Preassembly Trends and Effects on the Construction Workforce.* Center for Construction Industry Studies, Report No. 14. The University of Texas at Austin.

Haas, C. (1999) "Design for Safety. The Field Systems and Construction Automation." Group at University of Texas, Austin, USA. August.

Hadikusumo, B.H.W. and Rowlinsson, S.M. (2002) Integration of virtually real construction model and design-for-safety-process database, *Automation in Construction*, Elsevier Science B.V., 11, 501-509.

Hecker, S., Gibbons, B., and Barsotti, A. (2001) "Making ergonomic changes in construction: worksite training and task interventions." *Applied Ergonomics,* D. Alexander and R. Rabourn, eds., Taylor & Francis, London, 162-189.

Hecker, S. and Gambatese, J.A. (2003) 'Safety in Design: A Proactive Approach to Construction Worker Safety and Health', *Applied Occupational Health & Environment*, 18:5, 339 - 342

Hecker, S., Gambatese, J., and Weinstein, M. (2005) "Designing for Worker Safety", *Professional Safety,* September 2005, 32-44.

Heesom, D. and Mahdjoubi, L. (2004) Trends of 4D CAD applications for construction planning. *Construction Management and Economics, 22, 171-182*.

Hendrickson, C. (2000) Project Management for Construction – Fundamental Concepts for Owners, Engineers, Architects and Builders, 2nd edition, available at http:/www.ce.cme.edu/ pmbook/, last accessed 9 August 2003.

Hessami, A.G. (2007) Safety management of complex technology. Neural Comput & Applic., 16: 21-25.

Hinze, J. and Gambatese; J.A. (1994) Design decisions that impact construction worker safety, in *Proceedings of the 5th Annual Rinker International Conference on Construction Safety and Loss Control*, University of Florida, Gainsville.

Howell, G and Ballard, G (1994). Lean Production Theory: Moving Beyond 'Can-Do. *Proceedings of the 8th Conference of the International Group for Lean Construction, Santiago, Chile, September.*

HSE (Health and Safety Executive) (2000) *Successful Health and Safety Management*, HMSO, London.

Jongeling, R. and Olofsson, T. (2007) A method for planning of work-flow by combined use of location-based scheduling and 4D CAD. *Automation in Construction*, 16, 2, 189-198.

Jongeling, R., Emborg, E., Asp, M., and Olofsson, T. (2005) “Modelling and Simulations of Cast in Place Concrete Construction Using N-Dimensions” Research Report 2005:18, Department of Civil and Environmental Engineering, Luleå University of Technology, Luleå, Sweden.

Winkel, J. (1999) "Ergonomics programs and rationalisation". International Seminar on Corporates Initiatives in Ergonomics, Stockholm, 19-20 March 1999.

Kroemer, K.E. (1987) Biomechanics of the Human Body, In G. Salvendy ed., Handbook of Human Factors. John Wiley and Sons, Inc., New York.

Kumar, S. (1994) A conceptual model of overexertion, safety and risk of injury in occupational settings. *Human Factors,* 36, 2, 197-209.

Laring, J., Christmansson, M., Kadefors, R. and Örtengren, R. (2005) ErgoSAM: A preproduction Risk Identification Tool. *Human Factors and Ergonomics in Manufacturing,* Vol. 15 (3), pp. 309-325.

Lingard, H. and Rowlinson, S. (2005) *Occupational health and safety in construction project management,* Spon Press, New York.

Li, G. and Buckle, P. (1998) The development of a practical method for the exposure assessment of risks to work-related musculoskeletal disorders. General report to the HSE (Contract No. R3408), Robens Centre for Health Ergonomics, European Institute of Health and Medical Sciences, University of Surrey.

Loflin, M.E. and Kipp, J.O. (1997) Incorporating Risk Management into Emergency Incident Operations, *Professional Safety*, July, 42 (7), 32-35.

McKay, L.., Gibb, A.G.F., Haslam, R.A. & Pendlebury, M.C. (2005) Health and safety management of offsite construction – how close are we to production manufacturing?, 4th Triennial International Conference - cib W99, Rethinking and Revitalizing Construction Safety, Health, Environment and Quality, Port Elizabeth, South Africa, Smallwood & Haupt (eds), pp. 432-441, ISBN 0-620-33919-5.

Manuele, F.A. (1997) *On the Practice of Safety.* New York: John Wiley and Sons, Inc.

Marras, W.S. (2006) *Biomechanical Basis for Ergonomics.* In W.S. Marras and W. Karwowski (eds.) (2006) "The Occupational Ergonomics Handbook" Fundamentals and Assessment Tools for Occupational Ergonomics, 2nd ed., CRC Press, Taylor & Francis Group.

Messner, J., Yerrapathruni, S.C.M., Baratta, A.J. (2003) Using Virtual Reality to Improve Construction Engineering Education. *Proceedings of the 2003 American Society of Engineering Education Annual Conference & Exposition.*

Miles, M.B. and Huberman, A.M. (1994) Qualitative Data Analysis. Second Edition.Sage Publications, Inc. Thousand Oaks, CA.

Mrosczyzk, J. (2006) Designing for construction worker safety." ASSE *Blueprints*. 5(3):1, 3-4, 11.

Occupational Safety & Health Administration (OSHA) (1989) *Safety and Health Program Management Guidelines; Issuance of Voluntary Guidelines - 54:3904-3916*, Occupational Safety & Health Administration, U.S. Department of Labor, Washington DC, 1989. http://www.osha-slc.gov/FedReg_osha_data/FED19890126.html, accessed on 25 September 2007.

OSHA, (2004) Building in Safety. Construction: Campaign, Background, Information. *European Agency for Safety and Health at Work 18-22 October 2004.*

Rischmoller, L., Alarcon, L.F. and Koskela, L. (2006) Improving Value Generation in the Design Process of Industrial Projects Using CAVT. *Journal of management in Engineering*, April 2006, pp.52-60.

Rose, L. and Örtengren, R. (2000) Personal injury risk management in companies. *Proceedings of the International Seminar on Risk Management & Human Reliability in Social Context*, European Safety, Reliability & Data Association, Karlstad, June 15-16.

Rowlinsson, S. (2003) Virtually real construction components and processes for design-for-safety-process (DFSP), in M. Phair (ed.), *Developments and Applications: The Visual Construction Enterprise*, Printice-Hall, pp.211-222.

Rwamamara R. (2005) Impact of the Industrialised construction work on the Construction Workplace. *The First International Conference of Lifestyle, Health and Technology*, Luleå University of Technology, Luleå¬ 1-3 June, 2005.

Rwamamara, R. (2007) Risk assessment and analysis of workload in an industrialized construction process. Construction Information Quarterly, CIOB, 9(2), 80-85.

Salem, O. and Zimmer, E. (2005) Review - Application of Lean Manufacturing Principles to construction. *Lean Construction Journal*, 2, 2 October 2005. www.leanconstructionjournal.org ISSN:1555-1369.

Schneider, S., Griffin, M. and Chowdhury, R. (1998) Ergonomic exposures of construction workers: An analysis of the US Department of Labor Employment and Training Administration database on job demands, *Applied Occupation Environment and Hygiene*, 13, 238-241.

Schneider, S., Punnett, L. and Cook, T.M. (1995) Ergonomics: Applying what we know, *Occupational Medicine*, 10, 385-394.

Smallwood, J.J. (1996) The influence of designers on occupational safety and health. *Proceedings of the First International Conference of CIB Working Commission W99*, Implementation of Safety and Health on Construction Sites, Lisbon, Portugal, September 4-7, 1996, 203-213.

Sperling, L., Dahlman, S., Kilbom, Å. and Kadefors, R. (1993) A Cube Model for theclassification of work with hand tools and the formulation of functional requirements. *Applied Ergonomics,* 24, 212-220

Stake, R.E. (2000) Case Studies. In: Handbook of Qualitative Research, Denzin, N.K.and Lincoln, Y.S. (eds). Sage Publications, Inc., London.

Svensson, P-G. (1996) "Förståelse, trovärdighet eller validitet", In Svensson, P-G. and Starrin, B. (1996). Kvalitativa studier i teori och praktik, Studentlitteratur, Lund.

Szymberski, R. (1997) Construction Project Safety Planning. TAPPI Journal 80 (11), 69–74.

Tatum, C. B., Vanegas, J. A., and Williams, J. M. (1987) *Constructability Improvement Using Prefabrication, Preassembly, and Modularization*, Construction Industry Institute, The University of Texas at Austin.

Thomassen, M.A. (2002) *Lean Construction and Safety*, Presentation at the 4th Annual Lean Project Congress, August 2nd, 2002 - Berkeley

Thomassen, M.A., Sander, D., Barnes, K.A. and Nielsen, A. (2003) *Experience and Results from Implementing Lean Construction in a Large Danish Contracting Firm* , IGLC 11, Blacksburg VA, USA

Toole, T. (2002) Construction Site Safety Roles. *Journal of Construction Engineering and Management*, May/June 2002, pp. 203-210.

Warszawski, A. (1990) *Industrialization and Robotics in Building Construction a Management Approach*. Reading, MA, U.S.A. Addison-Wesley Educational Publishers, Incorporated.

Weinstein, W., Gambatese, J. and Hecker, S. (2005) Can Design Improve Construction Safety?: Assessing the Impact of a Collaborative Safety-in-Design Process. *Journal of Construction Engineering and Management*, ASCE, 131(10): 1125-1134.

Wright, M; Pavitt, T.C.; Gibb, A.G.F. & Bendig, M. (2003) The case for CDM: better, safer design – a pilot study, HSE Contract Research Report RR148, 2003, Greenstreet Berman, Health and Safety Executive, HSE Books, 76 pp, ISBN 0 7176 2733 0, www.hse.gov.uk/research/rrpdf/rr148.pdf

Yin, R.K. (1994) Case Study Research: Design and Methods; 2nd Edition, Sages Publications. Thousands, Inc., Oaks.

# PUBLICATIONS

## Appended papers

The following papers for journals and conference proceedings papers are appended to this thesis:

Paper I

Rwamamara, R., Lagerqvist, O., Olofsson, T. and Johansson, B. (2007) “Best practices for the prevention of musculoskeletal injuries in the construction industry”, *Submitted to Journal of Construction Management and Engineering*, ASCE.

Paper II

Rwamamara, R. (2007) “Risk assessment and analysis of workload in an industrialised construction process”, *Construction Information Quarterly*, CIOB, 9(2), 80-85.

Paper III

Simonsson, P., Rwamamara, R. (2007) “Consequence of Industrialised Construction Methods on the Working environment”, *Proceedings IGLC-15*, July 2007, Michigan, USA, pp. 302-311.

Paper IV

Rwamamara, R., Holzmann, P. (2007) “Reducing the Human Cost in Construction through Designing for Health and Safety – Development of a Conceptual Participatory Design Model”, *2nd International Conference, World of Construction Project Management, WCPM 2007,* October 24-26, Delft, The Netherlands.

Paper V

Rwamamara, R., Norberg, H., Olofsson, T. and Lagerqvist, O. (2007) “Using Visualisation Technologies for Design and Planning of a Healthy Construction Workplace”, S*ubmitted to Construction Innovation.*

**Articles and reports**

Rwamamara R. (2005) Design and Construction Process. Book of Abstracts, Design and Health, *The 4th World Congress on Design and Health, Frankfurt,* 6-10 July, 2005.

Rwamamara R. (2005) Impact of the Industrialised construction work on the Construction Workplace. *The First International Conference of Lifestyle, Health and Technology,* Luleå University of Technology, Luleå 1-3 June, 2005.

Rwamamara R.A. (2005) *The Healthy Construction Workplace: Best Practices in the Swedish Construction Industry to prevent work-related musculoskeletal disorders among construction workers*. Licenciate Thesis, Luleå University of Technology.

Rwamamara, R. (2006) Successful strategies for the prevention of work-related musculoskeletal disorders among construction workers. *16th World Congress on Ergonomics, Maastricht,* 10-14 July, 2006.

Rwamamara, R. and Holzmann, P. (2007) Reducing the Human Cost in Construction through Design. *39th International Conference of Nordic Ergonomics Society, Lysekil,* 1-3 October.

# APPENDIX A

Appendix A contains some data collection tools information regarding Paper I. The appendix firstly includes the introductory words about the research project prior to the interviews session and secondly shows the interview guide used in the research study.

**Den hälsosamma byggarbetsplatsen**

Projektet behandlar problemet med en tydligt ökande arbetsrelaterade ohälsa inom byggbranschen och vad som kan och bör göras att vända den negativa utvecklingen så att istället hälsosamma byggarbetsplatser kan skapas.

**Syftet** med projektet är att

1. Identifiera och beskriva strategier och aktiviteter som visat sig vara framgångsrika i kampen mot utveckling av arbetsrelaterade belastnings-sjukdomar inom byggbranschen.

2. Sprida kunskap om de strategier och aktiviteter som bidrar till att skapa den hälsosamma byggarbetsplatsen till byggnadsindustrin för att därigenom skapa förutsättningar för en utveckling av hälsosamma byggarbetsplatser på bred basis.

Projektet fokuserar på det muskel och skelett belastningsområdet. Projektet fokuseras också på följande yrkesgrupper: ställningsbyggare, betongarbetare, snickare, golvläggare, takläggare, el- och VVS-installatörer samt maskinförare.

Fallstudier vid större byggprojekt ska ha genomförts via observationer, dokumentation och intervjuer med olika byggherrar, entreprenörer (inklusive underentreprenörer), konsulter (t.ex.arkitekter), projektledare samt byggarbetare.

Kontakt person: Romuald A. Rwamamara, Luleå tekniska universitet

Tel. 0920-49 30 39; E-mail: rorw@ltu.se

The following is the interview guide used in the study presented in Paper I. The order followed in the interview guide may differ from the one in the Paper.

**1. Planering**

- Beskriv hur ni arbetar med lång- och kortsiktigt planering i er del av byggprocessen. På vilket sätt beaktas hälsofrågorna i planeringen?
- Hur planeras arbetsplatsen med avseende på arbetarnas belastning av muskler och skelett?
- Hur planerar ni med avseende på val av byggprodukter, konstruktioner, installationer och deras placering för:
    - ställningsbyggare,
    - betongarbetare,
    - snickare,
    - golvläggare,
    - takläggare,
    - el- och VVS-installatörer samt
    - maskinförare
- Medverkar dessa yrkesgrupper i planeringsarbetet inför byggstart? På vilket sätt?

**2. Organisation**

- Beskriv i grova drag organisationen av hela byggarbetsplatsen (parter, uppgifter, ansvar, befogenheter, resurser, kompetens mm). Vilka företag ingår och hur samverkar de? Hur är företagens samarbete med avseende på arbetsmiljö- och hälsofrågor?
- Varför har ni organiserat er på detta sätt?
- Vilka för- och nackdelar finns det med ert sätt att organisera er?
- Har ni den bemanning som ni önskar er?
- Hur kommer ni att utveckla er organisation?
- Har ni någon speciell organisation för arbetsmiljöarbete? Hur fungerar den?
- Vilka fördelar och nackdelar finns det med ert sätt att organisera arbetsmiljöarbetet?
- Vilken lönepolicy har ni och vilket lönesystem tillämpas på arbetsplatsen? Varför?
- Vilka förmåner finns utöver traditionell lön?
- Vilken löneform bedöms vara bäst för yrkesarbetarna? Varför?
- Vilken inverkan har arbetstiderna på yrkesarbetarnas belastning av muskler och skelett? Varför?
- Hur fungerar information och kommunikation på byggarbetsplatsen?
- Vilka möjligheter har yrkesarbetarna till kompetens- och kunskapsutveckling i arbetsmiljö- och hälsofrågor?
- Vilka möjligheter har yrkesarbetarna att påverka organisationen då det gäller frågor som påverkar deras hälsa?

**3. Teknik**

- Vilken produktionsteknik är utmärkande för er verksamhet? Finns det något som tekniskt skiljer er väsentligt från andra byggarbetsplatser?
- Använder ni någon speciell produktionsteknik som tydligt minskar belastningar på muskler och skelett?
- Vilka speciella hjälpmedel och verktyg finns idag på arbetsplatsen för att minska belastningar på muskler och skelett? Hur används de?
- Vilken ny teknik utvecklas för de olika yrkesgrupperna?
- Hur inför och använder ni ny produktionsteknik? Hur påverkar den nya tekniken belastningar av muskler och skelett?

**4. Fysisk arbetsmiljö**

- Beskriv arbetsplatsens fysiska arbetsmiljö (utformning, rbetsutrymmen, nivåskillnader, underlag, ordning, vibrationer). Hur påverkar den fysiska arbetsmiljön belastningen av muskler och skelett?
- Hur påverkar klimatet (vädret) belastningen av muskler och skelett?

**5. Arbetsuppgift**

- Vilka huvudsakliga arbetsuppgifter har de olika yrkesgrupperna?
- Vilka möjligheter har yrkesarbetarna att utveckla sina arbetsuppgifter?
- Bidrar arbetsuppgifterna till att främja arbetarnas hälsa? Varför?
- Vilka belastningar av muskler och skelett innebär arbetet (för olika yrkesgrupper) och hur hanteras/klaras de?
- Hur är balansen mellan krav, kontroll och resurser?
- Hur påverkas hälsan av följande faktorer i arbetet?
    - arbetsställningar
    - hanterade vikter
    - variation
    - arbetscyklernas längd
    - arbetstakt
    - handlingsutrymme
    - precisionskrav
    - kompetenskrav
    - arbetsobjektens utformning

**6. Individ/personal**

- Hur pass god är personalens hälsa? Varför?
- Hur pass god muskelstyrka, kondition och kroppskontroll har personalen?
- Hur stor är sjukfrånvaron? Hur stor andel av sjukfrånvaron beror på besvär och skador i muskler och skelett?
- Hur är ålders- och könsfördelningen inom respektive yrkesgrupp?
- Gör personalen något på arbetstid för att vara i god kondition för krävande arbetsuppgifter?
- Har personalen kunskap om lämplig arbetsteknik? Används lämplig arbetsteknik?

- Gör personalen något på fritiden för att vara i god kondition för krävande arbetsuppgifter?
- Hur viktig är personlig utrustning (kläder, skor etc) och hjälpmedel? Används utrustning och hjälpmedel?

# APPENDIX B

Appendix B contains information on data collection tools used in Paper V. This appendix includes firstly a brief introduction of the research study to the interview respondents, and secondly the interview guide is presented.

## *Planering av den hälsosamma byggarbetsplatsen*

Målet med projektet är att utveckla förbättrade planerings- och simuleringsverktyg som också beaktar hälsorisker, t.ex val arbetsmetoder i trånga arbetsutrymmen, delade ytor för material och utrustning på byggarbetsplatsen. Angående projektet kommer vi att fortsätta studera metoder för att minska riskerna för arbetsrelaterade förslitningsskador.

Resultatet kommer att vara en praktisk metod att integrera produktions och arbetsmiljö-planering. Planeringsresultatet kommer att kunna kommuniceras till byggherrar, huvudentreprenörer, underentreprenörer, byggnadsarbetare m.fl.

Romuald Rwamamara

Avdelningen för byggkonstruktion

Institution för Samhällsbyggnad

Luleå tekniska universitet

Tel. 0920 492353

e-post: romuald.rwamamara@ltu.se

The following is the interview guide used in the study presented in the Paper V:

## *Praktisk 3D/4D teknologi användningen från hälso- och säkerhet perspektiv*

### Intervju mallen

***Intresse i hälso- och säkerhetsinriktad byggnadsdesign***

1. Har någon tidigare frågat efter din åsikt om byggarbetarnas hälsa och säkerhet?
2. Känner du dig bekväm med att prata om byggarbetarna hälsa och säkerhetsfrågor?

***Allmän 3D/4D användning inom hälso- och säkerhetsdesign***

1. Använder du 3D/4D CAD i byggprojektet design?
2. Vad erbjuder 3D/4D modellering till olika aktörer i byggprojekt.
3. Kan byggarbetarnas hälsa och säkerhet förbättras genom 3D/4D modellering av byggprocessen?
4. Vad ser du för fördelar med 3D/4D teknologi när det gäller hälsa och säkerhet?
5. Vilka typer av hälso- och säkerhetsfrågor kan man identifiera genom användning av 4D modellering i byggprojekt?
6. Finns det någon speciell information som borde finnas med i 3D/4D modeller för att leverera en optimal design för hälsa och säkerhet?

***Mindre detaljerad 3D/4D användning inom hälso- och säkerhetsriskbedömning***

1. Hur bra tror du den simulerade inomhusarbetsmiljön senare stämmer överens med den verkliga på arbetsplatsen?
2. Hur bra tror du den simulerade utomhusarbetsmiljön senare stämmer överens med den verkliga på arbetsplatsen?
3. Tror du att du kommer ha möjlighet att ta tidiga beslut angående byggarbetsmiljön och säkerhet genom att använda dig av 4D modellering?
4. Hur kan 3D/4D modellering hjälpa olika aktörer under designprocessen när det gäller hälso- och säkerhetsfrågor?
    a. Beställare/Byggherre
    b. Huvudentreprenör
    c. Underentreprenör
    d. Byggarbetare
    e. Tillverkare och leverantörer (av t.ex. verktyg, material etc.)
    f. Underhållskonsulter
5. Hur kan olyckor och sjukdomar elimineras och reduceras med hjälp av 3D/4D modell ering under designfasen?
6. Är det möjigt att ge information om kvarvarande risker med hjälp av 3D/4D modellering? Om ja, hur?

***Mer detaljerade 3D/4D modeller för simulering av arbetsmiljö***

1. Tror du att 3D/4D modeller kommer att kunna stödja aktivitetsplanering på byggarbetsplatsen vad gäller hälsa och säkerhet?
2. Hur kan 3D/4D modeller stödja analyser av hälso- och säkerhetsfrågor i designskedet innan produktionsstart?
    a. Anbudsskedet
    b. Design review
    c. Produktionsplanering
3. Vilka av följande fem aspekter när det gäller arbetsplatssäkerhet kan upptäckas genom 3D/4D modellering och hur kan de upptäckas?
    a. Upptäcka hälso- och säkerhetsmetoder
    b. Sätta en säker arbetstakt
    c. Upptäcka vilka säkerhetshjälpmedel som kan behövas
    d. Upptäcka säkerhetsbrister
    e. Upptäcka osäkra arbetsaktiviteter
4. Hur kan 3D/4D modeller användas när det gäller följande dataflöden?
    a. Bygghandlingar
    b. Arbetsgenomförande
    c. What-if händelser
    d. Framtagande av tidplaner/Resursplanering
    e. Uppföljning
    f. Brister i designen
    g. Dagliga rapporter och prognoser

# APPENDIX C

The Appendix C contains information about some of the Paper III results. Figure C.1 and Figure C.2 which show respectively ErgoSAM analysis diagrams for short work cycles of conventional steel reinforcement and conventional concrete casting on construction site.

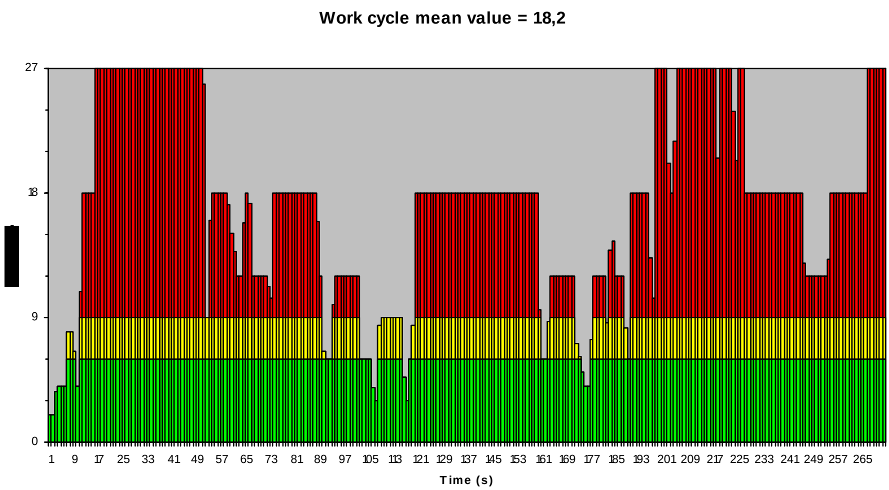



*Figure C.1: ErgoSAM analysis of a short work cycle of a concrete worker working with conventional steel reinforcement method. A cube value or work cycle mean value under 6 is acceptable, 6 to under 9 is conditionally acceptable and 9 and above is unacceptable.*

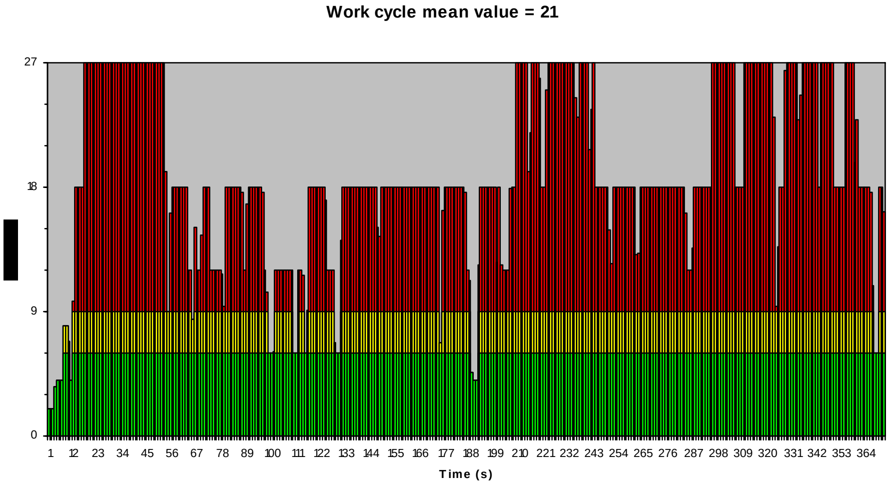



*Figure C.2: ErgoSAM analysis of concrete worker's short work cycle during traditional concrete casting and vibration. A cube value or work cycle mean value under 6 is acceptable, 6 to under 9 is conditionally acceptable and 9 and above is unacceptable.*

I

*“When you build a new house, then you shall make a parapet for your roof, that you may not bring guilt of bloodshed on your household if anyone falls from it.”* Old Testament (Deuteronomy 22:8)

# BEST PRACTICES FOR THE PREVENTION OF WORK-RELATED MUSCULOSKELETAL DISORDERS IN THE CONSTRUCTION INDUSTRY

**Authors**

R.A. Rwamamara[1], O. Lagerqvist[1], T. Olofsson[1], B. Johansson[2]

**Affiliation**

*[1]Division of Structural Engineering, Department of Civil and Environmental Engineering Luleå University of Technology, SE-971 87 Luleå, Sweden*

*[2]Division of Industrial Production Environment, Department of Human Work Sciences Luleå University of Technology, SE-971 87 Luleå, Sweden*

Submitted in 2007 to the Journal of Construction Engineering and Management

**Abstract**

Many construction work tasks are physically very strenuous, and the incidence of work-related musculoskeletal disorders (WMSDs) among construction workers is considerably higher than that in most other occupations. The aim of the study presented in this paper was to contribute to an understanding of a healthy construction site brought about by the best practices implemented by medium and large construction sites to prevent WMSDs. A triangulation method made of interviews, site observations and company's documents study was used to identify the best practices in 13 construction projects A range of best practices both in pre-construction and construction phases of projects were identified in six different areas of the construction workplace system balance; however there seems to be a significant need for good practices in the systematic work environment management. It has now been established that the Swedish construction industry has several best practices to protect work-related musculoskeletal health. However, the inadequate worker participation and the neglect of health and safety issues by designers in the planning process and the implications of some remuneration methods on the production schedule were perceived as detrimental to musculoskeletal health of construction workers.

**Key words**

Construction management, injuries, Occupational health, working conditions

## Introduction

The Swedish construction work environment is regarded as the safest in the world [Flanagan et al., 2001] as far as the working conditions and musculoskeletal health are concerned. Nevertheless, there are still work environment related health problems to be tackled. Public debate in recent years has focused increasingly on work environment issues. Although this alone cannot account for the large number of long-term sick leaves, it is surely one of several factors involved, and a multi-aspects improvement of the workplace is seen to be the most important single measure for reducing the incidence of ill-health such as musculoskeletal disorders and thus reducing the number of sick leaves they cause. According to the Swedish Social Insurance Agency [2004] which administers the various types of insurance and benefits which make up social insurance in Sweden; musculoskeletal disorders are among the most compensated illness among male workers, for example back pain accounts for 17 percent of all sickness compensations. The average of the total back pain illness compensation per case for men (focusing on men who constitute 92 % of the construction industry's workforce) is about 5,727 US dollars; this cost denotes 56 US dollars per sick leave day.

In the Swedish construction industry, Samuelsson and Lundholm [2006] report that out of all 1582 cases of sick leaves caused by occupational illnesses reported in the year 2004, 1342 cases of sick leaves were caused by ergonomic risk factors. Work-related musculoskeletal disorders (WMSDs) are described as a whole range of disorders which are not typically the result of an acute or instantaneous event, but which are the result of a chronic development. Various risk factors, including personal characteristics (for example physical limitations) as well as societal factors may contribute to the development of these disorders [Armstrong, et al., 1993].

WMSDs affect a wide variety of construction occupations, and are not specific to any type of job or work activity. Different construction trades are exposed to various kinds of physical workload, involving different parts of the body [Holmström et al., 1995] and the incidence of WMSDs is considerably higher than in most other occupations [Schneider, 2001]. Risk factors which can cause or which may have an association with WMSDs include repetitive, forceful or prolonged exertions of the hands, frequent or heavy lifting, pushing, pulling or carrying of heavy objects and prolonged awkward postures. High physical work demands such as these are considered the primary risk factor for work-related musculoskeletal complaints [Marras et al. 2000; Hoozemans et al. 2002; Lotters et al. 2003]. According to Djupsjöbacka et al. [2004], physical risk factors encompass work postures, heavy dynamic work, light repetitive work, static work, vibrations, temperature, lighting and noise; whereas psychological factors include work demands (time pressure, difficult work tasks), influence, social support, salary and rewards, work times and role allocation/ambiguity. Many types of musculoskeletal disorders have a considerable work-related component [Hagberg et al., 1995; NIOSH, 1997; Punnett and Bergqvist, 1997]. This is particularly true where there is a high exposure level and where there are combinations of difficult conditions, for instance lifting loads with outstretched arms at a high frequency is stressful for the shoulder region. There is also strong evidence that low back disorders are associated with lifting, high exertion and awkward back postures [Punnett et al., 1991; Marras et al., 1993]. Construction constitutes a substantial part of the economy of most countries, employing large numbers of workers. In Sweden, there are 234 869 construction workers (SCB, 2006).

Large numbers of construction workers are still leaving the industry before the retirement age due to WMSDs [Samuelsson and Andersson, 2002]. Construction workers are exposed to physical workload such as heavy burdens, extreme working postures like stooping, kneeling, work with hands above shoulder level, and vibration. With respect to physical exposure, it varies between occupational groups, and it seems that significantly increased prevalence of WMSDs within a trade often corresponds to its physical exposure [Holmström and Engström, 2003]. There is however an emerging hope in this industry's workplace, as it was recently reported [Byggnads Arbetaren, Jan 16, 2006] that the number of WMSDs in the construction sector continued to drop for the third year in a row. Between 2003 and 2005, the number of reported work-related diseases, WMSDs being accountable for the majority of them, has fallen 30 percent. Bengtsson et al. [2002] attribute this improvement partly to the emerging construction workplace culture of health promotion which focuses on a number of the surrounding and individual-related factors. Menckel and Österblom [2004] explained that health promotion focuses more on creating supportive environments and conditions for a better health for all at the workplace.

In summary, although it is observed through the review of literature that the physical work demands which form the main cause of musculoskeletal injuries are high for the construction workers, findings of scientific studies have identified physical, organisational, and individual occupational risk factors for the development of work-related musculoskeletal disorders. Thus, the response appealed to for this multifactorial problem of WMSDs, should be a multi-aspects improvement [Morray, 2000] of the construction workplace in the effort to prevent or at least reduce these construction injuries.

**Study Objectives**

There were two general objectives underlying this research study. In the absence of enough information about good industry practices promoting musculoskeletal health, the first objective consisted of identifying and describing strategies and activities (i.e. best practices1), which have proven to be successful in the fight against the development of work-related musculoskeletal injuries in the construction industry. The second objective was to formulate recommendations significant to WMSDs prevention and specific to the construction work environment; in order to bring about immediate actions or to guide further research studies on identified issues.

**Study Boundaries**

The research study focused on the issue of WMSDs in the construction industry, because these injuries still constitute a large portion, approximately 73 percent of all work-related diseases reported among construction workers [Samuelsson and Lundholm, 2002]. Other than developers, professional designers, site managers and contractors, the focal point of this study was on eight construction trades (Table 2). In Sweden, these specific trades have been most affected by musculoskeletal injuries and with a higher average of sick leave days due to WMSDs [Samuelsson and Lundholm, 2002; 2003]. This study was further limited to housing construction projects.

**Research Methodology and Data Sources**

The methodology for data collection has used a triangulation method (Yin, 1994), that is three complementary sources of information in an effort to increase accuracy, reliability, and representativeness of the data: detailed site observations of construction processes; interviews; company documents studies.

Semi-structured interviews were conducted with a sample of 94 respondents from eight construction trades (crew leaders were selected due to their long work experience), contractors, sub-contractors, designers and developers working with specific construction projects were selected for the study. The respondents came from varying sizes of construction firms with 48.9% of the sample working with large construction organizations with over 2000 employees and with an annual turnover that exceeds 1 billion dollars. The rest of the respondents were from companies that employed less than 100 people. With the help of an interview guide with 39 questions within the framework of six different aspects influencing musculoskeletal health (see figure 1), the interviews were conversational and open-ended, typically varying between 45 and 90 minutes in duration. Interviews were all conducted by the same interviewer who is a civil engineer. Altogether, three investigative tools interviews, site observations and companies' documents study were performed, with the objective of identifying the best practices that are conducive to the musculoskeletal health of construction workers.

Thirteen large construction sites in different regions of Sweden were chosen. Construction workplaces were selected on a convenience basis from the Swedish construction industry and were invited via telephone or e-mail to participate in the study. A criterion for participation was that construction projects/organisations had distinguished themselves in one or more areas, namely, planning, work organisation, technical aspects, work tasks, and physical environment. Another selection criterion was the size of the construction workplace, because the research study was limited to construction sites with at least fifty construction workers.

The data collected for this study was analyzed by sorting the data material into the different best practices and relating them to the various aspects affecting the musculoskeletal health of the construction worker, as depicted in the model for the construction workplace system balance (see Fig. 1). Belle [2000] asserted that to improve performance, benchmarking should single out those practices that have proved to be the best in a given area.

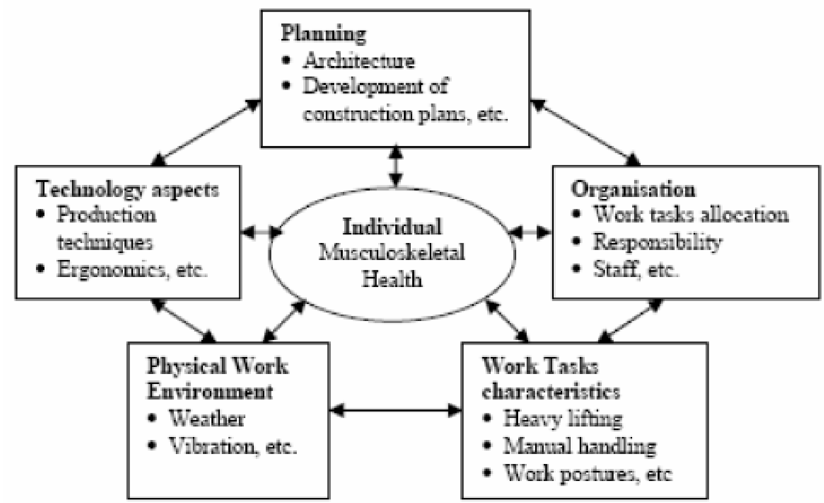



**Fig 1.** Six aspects affecting work-related musculoskeletal health of the construction worker [Rwamamara, 2005].

According to the model in Fig. 1, every construction workplace can be characterized by the planning carried out, by the organization performed, the technology used, the work tasks performed, the physical work environment as well as those individuals that carry out various work tasks. If these various aspects or components are not balanced, then problems in various forms emerge, for example low productivity, injuries and other ill health among the personnel. However, through a good balance of these components, a corresponding positive result could be attained [Rwamamara, 2005]. The model in figure 1 takes into account external influence exerted on the individual musculoskeletal health through the various aspects, which interact. All interaction relationships between various aspects of the construction workplace system balance are not shown in this simplified model in figure 1, and these relationships vary in strength and direction depending on which workplace is being studied. The model considers the planning aspect which is important to the construction workplace's health because planning is very much linked to production tasks to be performed. Hendrickson and Au [2000] stated that construction planning is a fundamental and challenging activity in the management and execution of construction projects. In addition to the planning component, the model takes into consideration four more aspects namely work tasks, production technology, physical work environment and work organization that affect the individual construction worker's musculoskeletal health. Karasek and Theorell [1996] and a number of other authors have outlined principles for designing healthy work tasks for human-machine systems. The ability to accomplish tasks and the load on the individual accomplishing the tasks are often determined by the technology being used by the worker. Carriere et al. [1998] examined the relationship between the introduction of new technologies and health and safety system, and found that health minded and effective companies adopted new technologies faster. Work environment refers to the work conditions that may affect individual workers in the workplace. Typically this includes the cold weather, the vibration emissions, and mechanical environments [Smith and Sainfort, 1989]. Manuele [1997] noted that a work organization's culture determines the level of safety attained, and management's commitment or non-commitment to safety is an outward sign of that culture. All individual workers enter the construction work environment with a variety of strengths and weaknesses. These include age, general health status, motivation, skill level, performance knowledge of the required work expectations, and ways of interacting with co-workers, supervisors and management. A healthy work environment builds on those strengths and motivations to develop a continuous learning and sharing work environment that rewards creativity, problem-solving initiative, responsibility, and teamwork. Open communication and participation are integral to a supportive work environment [Jaffe, 1995].

## Results

A three year investigation of 13 construction projects (Table 1) has yielded the results presented in this paper which are the product of the analysis of site observations, documents study, and as well as interviews with 94 participants of whom, 70 have at least 15 years of work experience in the construction industry, and the rest had worked at least 3 years in the industry (Table 2). Best practices were identified from other practices through an analysis that matched simultaneously those practices recurring over and over in the results of our observations, interviews (Table 3) and documents study.

**Table 1.** Description of the construction projects and characteristics of the sites and workers involved

| Construction work ( Building firm) | Construction period (month/year) | Contract value | Procurement | Site visit period | Number of subcontractors in the construction project | Number of salaried employees/ trade workers in the project |
|---|---|---|---|---|---|---|
| Office & Residential building Turning Torso/ Malmö (NCC) | 02/00- 05/05 | 180,832,000 US $ | Shared contract | Spring 2004 | 45 | 100/500 |
| Office buildings/ Malmö (PEAB) | 09/02-05/04 | 17,404,000 US$ | Design-build contract | Autumn 2003 | 18 | 5/100 |
| Refuse Incinerator Plant/ Linköping (NCC) | 10/02-02/05 | 21,486,000 US$ | Design-build contract | Autumn 2003 | 50 | 15/200 |
| Office building/Staffanstorp (NCC) | 03/02- 11/03 | 6,446,000 US$ | Design-build contract | Autumn 2002 | 20 (40 indiv.) | 4/60 |
| Apartments buildings/Bromma-Stockholm (SKANSKA) | 04/03-10/05 | 20,995,000 US$ | Performance-based contract | Summer 2004 | 45 | 6/22 |
| Senior citizen homes/ Vindeln-Umeå (PEAB) | 06/03-08/04 | 6,546,000 US$ | Design-build contract | Spring 2004 | 5 | 2/15 |
| Office building renovation/Lidingö (JM) | 01/03-03/05 | 9,633,000 US$ | General contract | Summer 2004 | 20 (60 indiv.) | 4/16 |
| Multiple apartments building Diamanten/Lund (NCC) | 12/03-03/05 | Confidential | General contract & Shared contract | Winter 2003 | 24 | 6/60 |
| Apartments building/Örebro (PEAB) | 10/02-01/04 | 5,586,000 US$ | Divided contractor | Summer 2004 | 12 | 4/50 |
| Apartments building/Filmstaden-Stockholm (SKANSKA) | 05/04-12/05 | 15,912,000 US$ | Design-build contract | Spring 2004 | 15 | 13/30 |
| House building/Luleå (PEAB) | 10/03- 02/04 | 683,000 US$ | General contract | Autumn 2003 | 8 | 4/10 |
| Swimming pool building renovation/ Gammalstad-Luleå (PEAB) | 04/03-01/04 | 2,704,000 US$ | General contract | Winter 2003 | 10 | 3/10 |
| University offices & facilities /Luleå (NCC) | 03/03-12/05 | 4,114,000 US$ | General contract | Summer 2004 | 30 | 2/25 |

**Table 2.** Respondents' details

| Occupational group | Number of interviewees (N=94) | Gender | | Average of occupational experience (years) | Occupational experience (in years) | |
|---|---|---|---|---|---|---|
| | | Male | Female | | Minimum | Maximum |
| Developers | 5 | 5 | 0 | 22 | 15 | 25 |
| Designers (architects + Structural engineers) | 9 | 8 | 1 | 18 | 3 | 27 |
| Site managers/ supervisors | 19 | 19 | 0 | 15 | 6 | 25 |
| Concrete workers | 11 | 11 | 0 | 21 | 12 | 26 |
| Carpenters | 12 | 12 | 0 | 25 | 15 | 35 |
| Sub-contractor managers | 3 | 3 | 0 | 12 | 9 | 15 |
| Electricians | 7 | 7 | 0 | 15 | 6 | 25 |
| Plumbers/HAC | 6 | 6 | 0 | 12 | 5 | 20 |
| Scaffolding workers | 6 | 6 | 0 | 15 | 10 | 20 |
| Roofers | 5 | 5 | 0 | 20 | 10 | 25 |
| Floor layers | 6 | 6 | 0 | 10 | 7 | 13 |
| Machine operators | 5 | 5 | 0 | 12 | 5 | 16 |

**Table 3.** Percentages of respondents that have identified the best practices as highly effective to reduce WMSDs

| Best practices / Respondents | Planning | Work Organisation | Production Technology | Physical Work Environment | Work tasks characteristics | Individual factors |
|---|---|---|---|---|---|---|
| Developers | 60% | 100% | 80% | 100% | 80% | 60% |
| Designers (architects + Structural engineers) | 89% | 55.5% | 89% | 100% | 22% | 22% |
| Site managers/ supervisors | 63% | 63% | 95% | 100% | 79% | 53% |
| Concrete workers | 100% | 89% | 91% | 82% | 82% | 73% |
| Carpenters | 100% | 58% | 83% | 75% | 75% | 58% |
| Sub-contractor managers | 100% | 100% | 100% | 100% | 100% | 67% |
| Electricians | 100% | 100% | 57% | 100% | 57% | 43% |
| Plumbers/HAC | 100% | 67% | 83% | 67% | 100% | 50% |
| Scaffolding workers | 100% | 83% | 100% | 83% | 83% | 67% |
| Roofers | 100% | 80% | 100% | 100% | 100% | 60% |
| Floor layers | 100% | 100% | 83% | 100% | 100% | 50% |
| Machine operators | 60% | 80% | 100% | 100% | 100% | 80% |

### *Identified best practices*

*Planning*

At every construction workplace, a compulsory Work Environment Plan (WEP) (AFS 1999:3) which consists of three important aspects; the regulations to be applied on the construction site, a description of how the work environment work is to be organized and a description of how certain work environment recommendations are to be implemented during the construction phase; is laid down by the developer although the implementation of WEP is delegated to the principal contractor.

A long term planning of health issues starts with the preliminary hazard analysis of construction activities. This risk analysis makes it easier to schedule and select appropriate mechanical aids such as cranes and personnel and material hoists. A high level master schedule maintained throughout the project is coordinated with the short-term/look-ahead schedules to manage detailed flow. A common requirement during planning and scheduling is to match the product, the process, work methods and the promotion of health issues at the workplace.

In planning for industrialized construction, which is more often the case in large Swedish construction workplaces, more attention is paid to the building components design and ease of installation, thus prefabrication is preferred to the traditional construction which entails heavy lifting, awkward postures and repetitive tasks. Although professional designers, especially architects admitted their little knowledge about health and safety issues affecting construction workers, thus little consideration of these issues in their design; they expressed that there is a growing dialogue between designers and contractors on designing for workers health. During the pre-production planning stage of preventive measures, worker’s views and risks from previous projects are taken into account.

*Work and workplace organization*

Depending on how large the construction workplace is, the management is made up of the site manager and the supervisors. The organization is a flat hierarchy and site managers are not only responsible for the production matters but also for economic and work environment issues. Construction workplaces currently have a more streamlined organisation with a system of cooperation based on negotiation.

Healthy organizations included regular meetings between various groups e.g. the main contractor and subcontractors and a good flow of information on different health and safety issues between for example work supervisors and construction workers. This was made easier by the flat organizational system. For more effectiveness in dealing with WMSDs issues, worker representatives and work team leaders are offered regular training through health and safety courses which provide updated knowledge about health promotion and WMSDs prevention measures. At the worksites where it was practiced, the consultation of construction workers was of a paramount importance as a number of site managers asserted that workers are resourceful and well worth listening to when dealing with health issues pertaining to the workers’ musculoskeletal health.

*Production technology*

Special production techniques were discussed in the interviews and were observed on construction sites; some of these techniques are not commonly available in all construction workplaces. During discussions with both the management and construction workers; production halls, Automatic Climbing System (ACS) scaffoldings (Fig. 2) and off-site pre-assembly of bathrooms and ventilation modules (Fig. 3), were identified as special production techniques that contributed to the reduction of WMSDs risk factors.

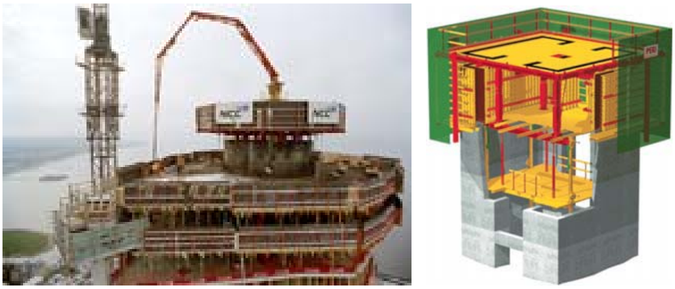


**Fig. 2.** Automatic climbing system (ACS) scaffolding (Courtesy of HSB and PERI)

At construction sites where ACS scaffolding systems were used along with multiple cranes that could serve every corner of the building site, the traditional scaffolding system was replaced effectively, thus eliminating the risk of WMSDs due to heavy lifting and repetitive tasks often related to scaffolding assembly tasks, in addition to avoiding workers the risk of slip and fall injuries.

**Fig. 3.** Prefabricated bathroom and ventilation room modules lifted into a building site.

An automatic climbing system (ACS) scaffolding installation allows concreting of the core ring wall at any one level to proceed at the same time as the tightening of the internal elevator walls on the floor below.

**Fig. 4.** Off-site steel reinforcement in production hall with a traverse for lifting heavy structures.

Use of these innovative production techniques such as producing steel reinforcement, bathroom and ventilation modules in a controlled work environment such as a factory or a production hall minimizes risks of heavy manual material handling, repetitive tasks, awkward work postures and slips and falls; thus eliminating the exposure to some of the WMSDs risk factors. Other aids include remote-controlled concrete pumps (Fig. 5) and traverses (used in production halls) (see Fig. 4), personnel and material hoists, carrying aids such as automatic scissor lifts (Fig. 6).

**Fig. 5.** Concrete cast with a remote-controlled pump


**Fig. 6.** Personnel and material hoist, and a scissor lift

Other than the mechanical aids, large Swedish construction workplaces have invested a lot in ergonomically-designed and light hand tools, in order to reduce vibration and awkward postures. Newly developed building products such as self-compacting concrete (SCC) (Fig. 7) has huge musculoskeletal health benefits for concrete workers.

SCC is a concrete to which no additional inner or outer vibration is necessary for the compaction. SCC compacts itself alone due to its self-weight and is de-aerated almost completely while flowing in the formwork. Traditional or conventional concrete casting produces high noise levels and the vibrating tools used for compaction of the concrete often lead to unhealthy and repetitive working postures. When SCC is used, concrete workers don’t need to compact the concrete, therefore those work tasks related to lifting and using a vibrator disappear and thus the likelihood of workers suffering vibration white finger will not occur.

Furthermore, the use of prefabricated building concrete components such as slabs, walls, and stairs has reduced the number of work tasks which were traditionally performed on site, thus minimizing the awkward work postures occurrence.

**Fig. 7.** Self-Compacting Concrete Casting (photo on the left) with no need to use a compacting vibrator (as seen in photo on the right).

*Work tasks*

When it comes to improving work tasks by eliminating WMSDs risk factors using mechanical aids, personal protective equipment (PPE), and work rotation within a work group, team work and working with an upright work posture are the common preventive measures. Among the eight trades investigated, only plumbers, electricians and carpenters were found to have several work tasks done above shoulder level; however the management often solves this problem by minimizing the risk exposure level.

*Physical work environment*

During interviews, many construction workplace managers and construction workers have affirmed that good lighting, good house keeping and having enough work space contribute to a reduction of work-related injuries. The use of new or improved building materials and hand tools has considerably reduced the vibration emissions at the construction workplace. To accommodate different working heights, the use of lifts and access ramps is very common on construction sites, thus making it easier for workers to perform their tasks and transport materials without undue strain. Performing production tasks in the production hall (Fig. 8) where buildings up to five-stories can be built, or working underneath a large tent or under weather cover sheets are considerably changing construction activities into weather independent ones, and consequently cutting down WMSDs related to cold, windy or snowy weather.

**Fig. 8.** A weather independent production hall with safe lifting with a traverse.

*Individual factors*

Although, the Swedish construction workforce is an aging one; construction workers indicated that their health was generally good and that they liked their occupations despite the risk factors involved in their jobs. Workers understand the importance of using PPE, applying adequate work methods as well as having good physical fitness in order to minimize risk for WMDS.

Besides regular physical fitness, pre-work stretching sessions on sites which focus on loosening up ligaments, tendons and muscles are considered to have contributed to the reduction of WMSDs especially during winter time where workers need to warm up before lifting and carrying building materials between 20 and 30 kilograms. A typical pre-work stretching session emphasizes stretching the body from the neck down to the ankles. The stretches in the ten-minute session include chin tucks, shoulder shrugs, wrist flexion, hamstring stretch, calf stretch, and even a seated back stretch. Through massage and naprapath therapy, the number of those who stayed at home because of muscular pain has reduced. During interviews, the management expressed its satisfaction with the worker's foot anthropometry profile system that takes into account the characteristics of individual workers and has been used to equip their workers with custom-made safety footwear, thus reducing some of their workers' musculoskeletal problems of the knees and the back.

***Recommendations and conclusions***

The recommendations in this paper constitute a proposal on areas where good practices need to be developed in consideration of work-related musculoskeletal health issues.

*Planning*

The study showed that developers had very little involvement in the implementation of the WEP. Constant cooperation between developers and general contractors is necessary not only on designing the work environment plan but also on implementing it. A broader worker participation in the preproduction planning should be desired for an optimal input about the potential risks and controls. Furthermore, general contractors should encourage sub-contractors to take part in the pre-production planning to present the identified health risks. Furthermore, due to the ignorance expressed by designers in regard to health and safety issues and their consideration in design; educational courses on health and safety design in construction should be recommended for civil engineering programmes in architecture as it is also suggested by Gambatese (2004).

*Work organisation*

An effective solution to reduce WMSDs among construction workers should not ignore issues of leadership, remuneration system, employment types and worker involvement. Training workers in health and safety issues provides a basis for consistent awareness, identification, analysis, targeting and control of WMSDs. Therefore, construction companies should consider providing training to workers, supervisors and site managers through participating in the musculoskeletal disorders control program. Both the management and the workers need more training to improve their knowledge in Systematic Work Environment management (SWEM) (See fig.8). Features that distinguish SWEM are similar to those of the EU-directive 89/391 (EU, 1989) which requires a policy, risk analysis, information, division of work tasks regarding the work environment, registration of work-related accidents etc. The Swedish regulation however, is more far-reaching than the EU-directive 89/391/EEC.


**Fig. 9.** Schematic description of SWEM (AFS 2001:1)

*Technical aspects*

A greater level of industrialized production and use of assembling techniques for prefabricated modules is recommended to construction companies in their endeavour to prevent WMSDs. Furthermore, the availability of mechanical aids on the site should depend on the nature of the work tasks to be performed. Construction employers should do an evaluation of cost-effectiveness of the positive effects generated by the accessibility of mechanical aids.

*Work tasks*

To reduce production pressures, the principal contractor and his subcontractors should consider providing enough manual labour. By estimating reduced costs for sick leaves due to reduced workload, the employer should be able to support his staffing strategy. Employers and workers in partnership should continue addressing these risk factors by both administrative (e.g., management systems) and engineering (e.g., mechanical aids and ergonomic tools) controls. Further, the study showed there is a need for an efficient planning that will make the mechanical aids and necessary work tools promptly and readily available to workers to help them perform their work tasks.

*Physical work environment*

Findings indicated that a poor and inadequate planning was the first contributor to a bad physical work environment. A dynamic and thorough site layout should be considered in order to accommodate a constantly changing construction workplace. This point is supported by Anumba and Bishop [1997] who state that site layout and organization are essential management functions which should, ideally, be given full consideration early in the construction planning stage of the construction process. The study indicated there is a lack of coordination of housekeeping. Housekeeping responsibilities should be spelt out in contracts and tender documents. These documents should define the responsibilities and contractors should discuss details. In line with the study findings it would be reasonable to suggest that the more construction activities are performed in a production hall, the less WMSDs risk factors workers will be exposed to, especially during winter. This suggestion is also supported by Rundgren and Östlund’s [2002] study on how to make the production hall more efficient.

*Individual factors*

The study showed that workers have different physical work capacities due to their age and muscular strength. Therefore, it is important to consider mapping out individual workers’ capacities and limitations. Other beneficial measures include workers foot profile system and physical training during work hours. The benefits of physical fitness or the consequence of the lack of it have been shown for example in studies by Hildebrandt [2000] and Merlino et al. [2003].

### *A final conclusion*

In summary, all these best practices formulated into practical recommendations are part of a quest after an optimal solution which can be achieved. As stated by Morray [2000], a range of generic issues or aspects should be considered, such as task design (at the planning stage), worker/equipment interface, and individual variation, training needs, work organization and legal requirement. To create that health-yielding balance between all these aspects affecting work-related musculoskeletal health is a challenge but achievable. In regard to the occupational groups investigated in this study, observations performed in the study showed that these trade groups were representative of those performing the same work tasks throughout Sweden as the study looked at 13 construction projects located in different regions of the country.

## Limitations of the Study

Limitations in this study were mainly those difficulties encountered during interviews. At many occasions, interviewees found it difficult to identify and describe examples of best practices at hand in their construction workplaces. Furthermore, it is possible that this study could have given perhaps better results if there had been a fair participation of the designers and the developers of the different construction projects investigated in the research study. This low participation in the study was generally due to the designers and developers' lack of time. The participation of subcontractors' managers in this study was also unexpectedly low. Although several telephone and e-mail contacts were made with contractors, inviting them to participate in the study, these invitations were often not responded to or declined on several occasions. Another limitation of the study was the cultural attitude of interview respondents who did not often think that they had anything better than another construction workplace. This typically Swedish "unassuming nature" made it hard to get some examples of *best* practices out of the interview participants.

## Future Research

The following areas require more attention and future research will focus on finding answers to these issues:

- Develop improved planning methods that also consider working methods, work space allocation including dynamic site plans of shared construction site areas and equipment with the objective to minimize the risk of WMSDs.
- Investigate ways to have a greater and adequate worker participation in the pre-production planning.

## Acknowledgments

The writers wish to acknowledge all the industrial partners in the research project reported in this paper. This work was principally funded by the Development Fund of the Swedish Construction Industry (SBUF).

**References**

AFS 1999:3 Building and Civil Engineering Work. Provisions of the Swedish National Board of Occupational Safety and Health on Building and Civil Engineering Work with General Recommendations on the Implementation of the Provisions. Solna, Sweden. http://www.av.se

AFS 2001:1 Systematic Work Environment Management Guidelines. The Swedish Work Environment Authority. http://www.av.se

Anumba C. and Bishop G. (1997) Importance of safety considerations in site layout and organisation. Can. J. Civ. Eng. 24: 229-236 (19979.

Armstrong TJ, Buckle P, Fine LJ, Hagberg M, Jonsson B, Kilbom A, Kuorinka IA, Silverstein BA, Sjogaard G, Viikari-Juntura ER. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scandinavian Journal of Work Environment Health, (1993) Apr;19(2):73-84.*

Belle R A. (2000). Benchmarking and enhancing best practices in engineering and construction sector. *J. Management in Engineering*, Vol.16, No.1, pp. 40-47.

Bengtsson S, Blomqvist A-C, Edvardsson A, Rälg, I. (2002) *Kokbok för friskare arbetsliv. En socialpsykologisk studie av hälsofrämjande strategier i arbetslivet.* Växjö Universitet, Institutionen för samhällsvetenskap.

Byggnads Arbetaren (16 January 2006)

Carriere JB, Dionne-Prouix J, Beauchamp Y. (1998). Strategic management of new technologies and prevention of industrial accidents: Theoretical framework and empirical analysis. *Human Factors and Ergonomicsin Manufacturing*, vol. 8, no.1, p.1-22.

Djupsjöbacka M, Stenberg L and Gellerstedt S. Muskelvärk? Långvarig muskelsmärta vid arbete – risker, uppkomst och åtgärder, Belastningsskadecentrum, Högskolan i Gävle, (2004).

EU (1989). Council Directive of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work (89/391/EEC). Luxembourg.

Flanagan F, Jewell C, Larsson B and Sfeir C. “Vision 2020: Building Sweden’s future”, Department of Building Economics and Management, Chalmers University of Technology, Sweden. (2001).

Gambatese, J. (2004) Safety Emphasis in University Engineering and Construction Programs. In S.Hecker, J. Gambatese and M. Weinstein (eds) Designing for Safety and Health in Construction. *Proceedings from a Research and Practice Symposium.* University of Oregon Press.

Hagberg M., Silverstein B., Wells R., Smith R., Carayon P., Hendrick H., Perusse M., Kourinka I., and Forcier L. (eds). 1995. Work-related Musculoskeletal Disorders (WMSD): A handbook for Prevention, Taylor and Francis, London.

Hendrickson C., Au T. (2000). Project Management for Construction – Fundamental Concepts for Owners, Engineers, Architects and Builders. http://www.ce.cmu.edu/pmbook/. (2004-01-25)

Hildebrandt VH, Bongers PM, Dul J et al. (2000). The Relationship Between Leisure Time, Physical Activities and Musculoskeletal Symptoms and Disability inWorker

Populations. Int Arch Environ Health 73:507–518.

Holmström E, Moritz U, Engholm G, (1995) Musculoskeletal Disorders in construction workers. *OCCUPATIONAL MEDICINE: State of the Art Reviews*, vol.10, no.2, p.295-311.

Hoozemans MJM, van der Beek AJ, Frings- Dresen MHW, van der Woude LHV, van Dijk JH.(2002) Low-back and shoulder complaints among workers with pushing and pulling tasks. *Scandinavian Journal of Work, Environment & Health* 28, 293-303.

Jaffe DT. (1995). The healthy company: Research paradigms for personal and organisational health. In, S.L. Sauter and L.R. Murphy (eds), *Organisational Risk Factors for Job Stress* (pp. 13-39). Washington, D.C.: American Psychological Association.

Karasek R., Theorell L. (1996). Current issues relating to psychological job strain and cardiovascular disease research*. Journal of Occupational Health Psychology,* vol. 1, p. 9-26.

Lotters F, Burdorf A, Kuiper J, Miedema H. (2003) Model for the work-relatedness of low-back pain. *Scandinavian Journal of Work, Environment & Health,* 29, 431-440.

Manuelle FA. (1997). A causation model of hazardous incidents. *OccupationalHazards*, vol. 59, p. 160-164.

Marras W S, Lavender S A, Leurgans S E, Rajulu S L, Allread W G, Fathallah F A, Fergusson, S A. (1993). The role of dynamic three-dimensional trunk motion in occupational-related low back disorders: the effects of workplace factors trunk position and trunk motion characteristics on risk of injury. *Spine.* (18(5): 617-628.

Marras WS, Allread WG, Burr DL, Fathallah FA. (2000) Prospective validation of a low-back disorder risk model and assessment of ergonomic interventions associated with manual materials handling tasks. *Ergonomics* 43, 1866-1886.

Menckel E and Österblom L. Ledningssystem för hälsosamma arbetsplatser. I red. B. Johansson, K. Frick och J. Johansson, (2004). Framtidens arbetsmiljö- och tillsynsarbete. Studentlitteratur, Lund. (In Swedish).

Merlino LA, Rosecrance JC, Anton D and Cook MC. (2003). Symptoms of Musculoskeletal Disorders Among Apprentice Construction Workers. Applied Occupational and Environmental Hygiene 18(1): 57-64, 2003.

Morray N. (2000) Culture, politics and ergonomics. *Ergonomics*, 43:858-868.

NIOSH. (1997) Musculoskeletal disorders (MSDs) and workplace factors. A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. US Department of Health and Human Services, Cincinnati, OH.

Punnett L and Bergqvist U. (1997). Visual display work and upper extremity musculoskeletal disorders: A review of epidemiological findings, national Institute for Working Life- Ergonomic Expert Committee Document No.1.

Punnet L, Fine L J, Keyserling, W M, Herrin G D, and Chaffin D B. (1991) Back disorders and non-neutral trunk postures of automobile assembly workers. Scand. J. Work Environ. Health. 17:337-346.

Rundgren M and Östlund M. (2002). How to make the production hall more efficient. Department of Industrial Economics and Management, Division of Construction Management and Economics, Royal Institute of Technology.

Rwamamara RA. (2005) The Healthy Construction Workplace: Best Practices in the Swedish Construction Industry to prevent work-related musculoskeletal disorders among construction workers. Licentiate Thesis 2005:39, Luleå University of Technology, 134 p.

Samuelson B and Andersson B. (2001) Värför lämnar byggnadsarbetare branschen – en enkätundersökning, BCA (2002:1). (In Swedish).

Samuelsson, B. and Lundholm, L. (2006) Arbetsskador inom byggindustrin 2005. Bygg- och anläggning. Privat sektor. BCA 2006:2. (In Swedish).

Samuelson B. and Lundholm, L. (2002) Arbetsskador inom byggindustrin 2001. Husbyggnad, väg och anläggning samt schaktarbeten. BCA (2002:2). (In Swedish).

Samuelson B and Lundholm L. Arbetsskador inom byggindustrin 2002. Husbyggnad, väg och anläggning samt schaktarbeten. BCA (2003:1). (In Swedish).

SCB. (2006). Statistik årsbok för Sverige 2006: Labour Market.

Schneider SP. (2001) Musculoskeletal Injuries in Construction: A review of the Literature. *Appl Occup Environ Hyg* 16(11):1056-1064 (2001).

Smith MJ, Sainfort PC. (1989). A balance theory of job design for stress reduction. *International Journal of Industrial Ergonomics*, 4, p. 67-79.

Swedish Social Insurance Agency (Riksförsäkringsverket) (2004) Vad kostar sjukdomarna för kvinnor och män? Sjukpenningkostnaderna fördelade efter kön och sjukskrivningsdiagnos. Redovisar 2004:5. (In Swedish).

Yin, R.K. (1994). Case Study Research: Design and Methods; 2nd Edition, Sages Publications. Thousands, Inc., Oaks.

II

*“And the temple, when it was being built, was built with stone finished at the quarry, so that no hammer or chisel or any iron tool was heard in the temple while it was being built.”* Old Testament (1 Kings 6:7)

# Risk assessment and analysis of workload in an industrialised construction process

ROMUALD A. RWAMAMARA

**Romuald Rwamamara, BSc, MSc, is a PhD candidate in Structural Engineering in the Department of Civil and Environmental and Engineering at the Luleå University of Technology. Prior to becoming a PhD student, Romuald worked as a research contractor for SHARP (Safety and Health Assessment & Research for Prevention), a research unit of the Washington State Department of Labour and Industries, in USA. His research interests focus on best practices benchmarking in construction industry, biomechanics, construction ergonomics, designing for safety and health in construction and planning safe and effective construction workplaces using virtual construction tools.**

## ABSTRACT

With the increasing industrialisation of the construction process, the intensity and the nature of production activities are changing due the application of cost-effective industrialised production methods such as off-site prefabrication and on-site assembly. However, the impact of these production methods on safety and health of the worker has not been methodically investigated and is often assumed to be positive for the construction workplace. The goal of the study was to measure the workload associated with the assembly / building of inner walls using prefabricated components or gypsum wall panels and its affects on musculoskeletal system of construction workers.

The methods used in the study are the Quick Exposure Checklist (QES) system and ErgoSAM, a method used to identify situations of high workload and risk for musculoskeletal injury.

The results of the study revealed that the installation of inner walls entails a number of work tasks that are physically demanding due to awkward work postures and lifting of heavy gypsum panels. The use of both methods to analyse the impact of an industrialised system has a lot of potential in identifying health risks and thus having a basis on which these risks can be planned out in the design of an effective and healthy construction workplace. Recommendations for consideration in the selection of ergonomically designed tools are drawn from best practices' publications.

KEYWORDS: Industrialised process, exposure assessment, health and safety, design, best practices

## INTRODUCTION

Industrialisation of the construction processes in which industrialisation changes from an on-site construction process to a more controlled factory-like construction process has been encouraged for reasons such as the attractiveness of workplaces that will strongly be enhanced by vigilant organisation, new manufacturing methods, new architectural typology based on 2D and 3D components, new components, new connections and interfaces, and new on-site assembly methods (ECT, 2005). Increased use of off-site manufacturing furthers the industrialisation of the construction process.

Building parts are manufactured in an environment suited for effective production, where advanced equipment can be used and the working conditions are good. The manufactured elements are of a high level of completion in order to minimise work at the building site. As many parts of the building as possible are manufactured in offsite production and finally assembled at the building site (Lessing et al, 2005).

By preassembling parts of buildings or constructions, or even whole constructions, the construction process becomes more standardised and less dependent on weather conditions (European Foundation for Improvement of Living and Working Conditions, 2005). This could speed up construction, improve quality, reduce waste and even the degree of waste control, and reduce the cost of constructions (Ong, 2004). The industrialisation of the construction process also reflects the use of technology to change the sector. Through advanced use of prefabricated elements and off-site construction, the sector is hoping to avoid mistakes; to lower costs and reduce completion times (Pasquire and Connolly, 2002).

Transferring as many as possible on-site activities into the factory is probably one of the most promising approaches in regard to the improvement of health and safety on the construction site (Wright et al., 2003; Gibb et al., 2004; McKay et al., 2005; Blismas et al., 2006). However, it is a fact that some construction activities requiring awkward postures and heavy lifting still remain part of the on-site construction work tasks. Therefore, when planning new industrialised construction process, measuring the interaction between the workers physical capacity and the work tasks, tool usage through ergonomic analysis is of great importance. In the manufacturing industry, production engineers are often urged to consider the ergonomic aspects of work when planning for production (Christmansson et al., 2000).

Understanding the relationships between workplace exposure parameters and the health outcomes of the musculoskeletal system is the basis for preventing and reducing work-related musculoskeletal disorders (WMSDs) (Bao et al., 2006). Awkward, repetitive postures and heavy lifting can increase the risk of musculoskeletal disorders; therefore cost-effective quantification of the magnitude for physical exposure to poor working postures is important and needed, if the potential for injury as a result of postures is to be reduced (Andrew et al., 1998). Assessing exposure to risk factors for WMSDs is an essential stage in the management and prevention of WMSDs (David, 2005). Additionally, it is desirable to use assessment tools that are able to predict the risk of future WMSDs so that the monetary costs and human suffering can be averted through remediation efforts before they are incurred (Hamrick, 2006).

The design principles which may refer to the existing best practices in industry may also be applied as way of prevention in efforts to eliminate or reduce risk factors for WMSDs (Rwamamara, 2005). In this case, the job task or equipment may be altered to facilitate the task and reengineer it such that it falls within the limitations of the worker (Amell and Kumar, 2001).

## METHODS FOR EXPOSURE ASSESSMENT

During the research study reported on in this paper, two risk assessment methods, namely ErgoSAM and QEC were used in the study to measure potential exposure to risk factors for WMSDs.

ErgoSAM is based on a sequence-based activity method (SAM), a higher-level method-time-measurement (MTM) system. The SAM system is the result of work carried out in Sweden to shorten the time needed for analyses made with MTM systems (Swedish Productivity Center, 1995). In SAM, the main activities are Get and Put. For each SAM activity, a standard time is given. In addition to the SAM information, the ErgoSAM method considers two additional pieces of information: (1) the zone relative to the worker' s body in which the activity is carried out or ends,,and (2) the weight of the objects handled or the force exerted in the activity (Christmansson et al., 2000; Laring et al., 2005). The output of ErgoSAM is the product of three types of demands namely, work posture, force and repetitivity (frequency), according to a scientific model, the Cube model (Sperling, 1993).

For every work task, the three factors in the Cube model are given a value between 1 and 3, where the values 1 and 3 are respectively the lowest and the highest. The combined value representing the load level or exposure level is obtained by multiplying the three components illustrated in figure 1.

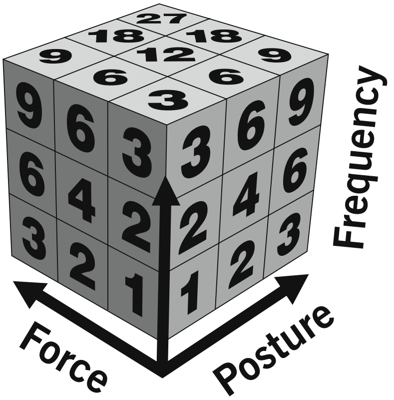



***Figure 1*** *The Cube model (Sperling, 1993).*

Combinations of these demands will largely decide whether a work situation entails risks of strain injuries or musculoskeletal disorders (Christmansson et al., 2000). ErgoSAM is implemented as a macro program in Microsoft Excel.

The Quick Exposure Check (QEC) system for work-related musculoskeletal risks has been developed by Li and Buckle (1998). The method includes the assessment of the back, shoulder / upper arm, wrist / hand and neck, with respect to their postures and repetitive movement. Information about task duration, maximum weight handled, hand force exertion, vibration, visual demand of the task and subjective responses to the work is also obtained from the worker. The magnitude of each assessment item is classified into exposure levels (Tables 1 and 2), and the combined exposures between different 'risk factors' for each anatomic region are implemented by using a score table, in which higher scores are given to the combination of two higher-level exposure of risk factors than the combination of two lower-level exposures (Li and Buckle, 1999; David et al., 2005).

***Table 1*** *Exposure scores for anatomic regions (David et al., 2005)*

| | Exposure level | | | |
|---|---|---|---|---|
| **Score** | **Low** | **Moderate** | **High** | **Very High** |
| Back (static) | 8-15 | 16-22 | 23-29 | 29-40 |
| Back (moving) | 10-20 | 21-30 | 31-40 | 41-56 |
| Shoulder / Arm | 10-20 | 21-30 | 31-40 | 41-56 |
| Wrist / Hand | 10-20 | 21-30 | 31-40 | 41-56 |
| Neck | 4-6 | 8-10 | 12-14 | 16-18 |

***Table 2*** *Exposure scores for other factors (David et al., 2005)*

| | Exposure level | | | |
|---|---|---|---|---|
| **Score** | **Low** | **Moderate** | **High** | **Very High** |
| Driving | 1 | 4 | 9 | - |
| Vibration | 1 | 4 | 9 | - |
| Work pace | 1 | 4 | 9 | - |
| Stress | 1 | 4 | 9 | - |

## GENERAL BACKGROUND OF THE RESEARCH STUDY

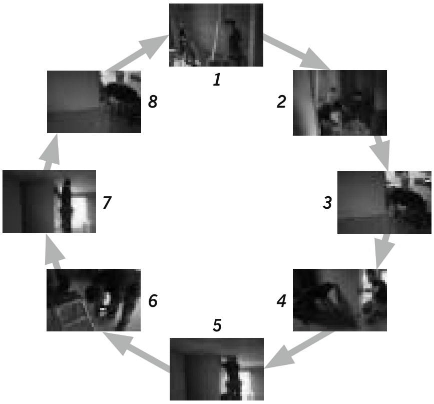
For many years now, lengthy production times in combination with high production costs have been a problem in the construction industry. A large Swedish construction company engineered a concept that is based on the principle that a large portion of building components should be prefabricated, and thus a large portion of production work is transferred to the prefab factory, a change that has a lot of advantages. Moving construction work activities from the construction site to a factory has not only shortened production time as an advantage, but it is also worth to mention that the factory is a controlled environment and more safer than the traditional construction site. Furthermore, the factory's controlled work environment is conducive to the workers health in a sense that injury risk is not as high as on construction site, and thus implying a decrease in the production mistakes and the defect frequency is reduced. Consequently, large construction companies such as company X evolved a new industrialised building concept to change the construction workplace into an 'assembly site' instead of a construction worksite. The industrialised construction approach suggests that different work tasks can be standardised which makes it possible to analyse and suggest changes with the objective of minimising musculoskeletal risks among construction workers.

## SCOPE AND OBJECTIVE OF THE STUDY

A pilot multi story residence building project was the object of the research study presented in this paper. The study was limited to the assembly of inner walls using prefabricated gypsum panels. An apparent failure to convert the whole system in order to benefit from the manufacturing input prompted this study. The primary objective was to analyse physical workloads on construction workers using different risk assessment methods.

## PROCEDURE

To perform the exposure assessment of inner wall assembly; 35 work cycles were observed and a representative work cycle was video-recorded by the researcher / author, and specific attention was paid to work methods used by workers to perform their work tasks. Interviews




**Phase 1:** Lifting and carrying of a 45 kg heavy wall panel to be installed.

**Phase 2:** Kneeling down and holding the gypsum panel against the ceiling with a crowbar.

**Phase 3:** Kneeling down and screwing two screws in a steel angle that attach firmly the panel to the floor.

**Phase 4:** Kneeling down and hammering a wedge under the panel.

**Phase 5:** Climbing on a stool and screwing two screws into a steel angle to attach firmly the panel to the ceiling.

**Phase 6:** Drilling two holes for the steel angle in concrete floor.

**Phase 7:** Drilling two holes in the concrete ceiling and then nailing in two plugs.

**Phase 8:** Kneeling down and nailing two plugs into the steel angle attaching firmly the panel to the floor.

***Figure 2*** *Eight main phases of inner walls assembly's work cycle.*

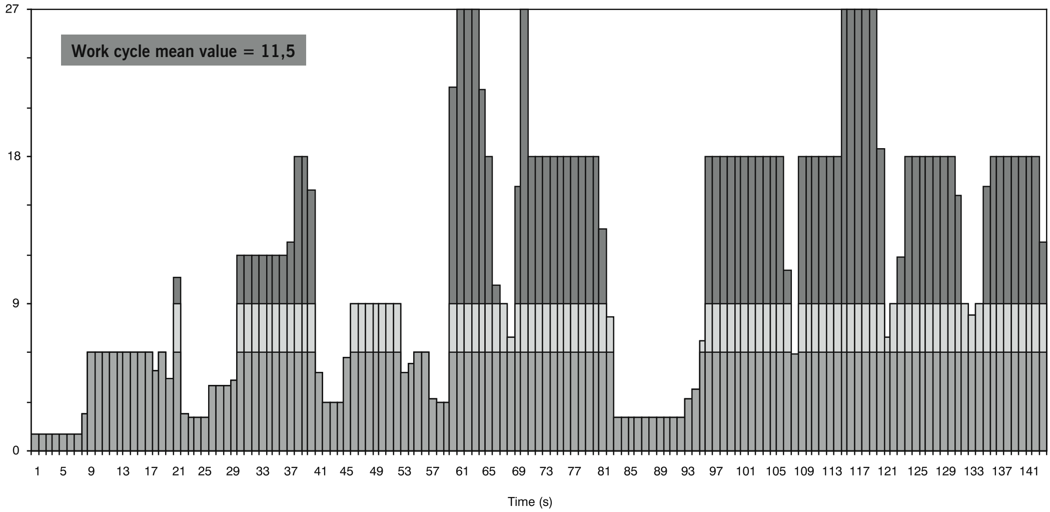



***Figure 3*** *ErgoSAM analysis of a work cycle of inner wall assembly.*

were also conducted with construction carpenters on forces, physical stress, vibration, and work tempo. Using the digital video recordings of two carpenters doing the work tasks required in the assembly of prefabricated inner walls elements, the researcher conducted ErgoSAM and QEC analyses of the inner walls assembly work cycle.

## RESULTS AND DISCUSSION

The work cycle (Fgure 2) of inner walls assembly is repeated 35 times per day, which equates to approximately two apartments in this project, and lifting, drilling and screwing activities occupy a larger time portion in the work cycle. During the typical 8 hour workday other wall assembly-related work tasks such as the cutting of gypsum panels and the assembly of doorframes are performed as well.

ErgoSAM analysis: An ErgoSAM analysis was performed, to assess the risk exposure for each of the two carpenters working with inner wall assembly. In general the ErgoSAM diagram, the cube value or the load level falls within three levels; where under 6 is acceptable, 6 to under 9 is conditionally acceptable and 9 and above is unacceptable. These load levels are respectively represented by green, yellow and red colours. The highest peaks in the ErgoSAM diagram (Figure 3) represent the work tasks that contribute most to the work cycle's mean value of 11.5. This mean value is above 9 and indicates that the work load during the inner wall assembly's work cycle is not acceptable, therefore the work cycle needs to be improved in order to reduce the musculoskeletal system loading to an acceptable level. By reviewing each inner wall assembly's work tasks on the video film, and method description used to generate the ErgoSAM diagram, it becomes easier to identify which work tasks are ergonomically detrimental to workers and thus these should be the first addressed in terms of improvement measures.

The ErgoSAM analysis diagram in figure 3 shows a lot of 'red peaks' indicating that the inner wall assembly work cycle entails a number of physically demanding work tasks, particularly lifting wall panels and working in awkward work postures while drilling and screwing screws into concrete. During the analysis using ErgoSAM, the frequency of work tasks performed repetitively contributed significantly to the

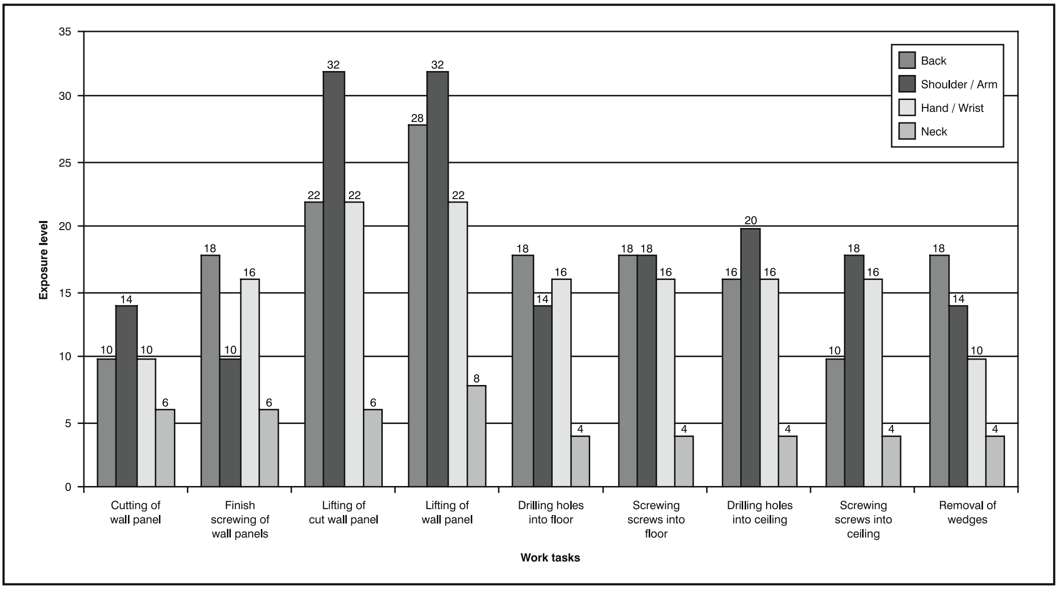



*Figure 4* *Exposure levels for various work tasks in the inner walls assembly.*

loading value or exposure level, especially in the case of drilling and screwing. The work posture adopted by the worker also influenced the loading value outcome. It was observed that a poor or good work posture was often dictated by the work method adopted in the performance of a certain work task. For example, the drilling and screwing tasks were performed either with hands closer to or further from the body, and the ErgoSAM analysis showed that these different work methods have a different impact on the worker's musculoskeletal system as far as the exposure level is concerned. The drilling and screwing work tasks performed with hands or forearms closer to the body generated acceptable cube values or loading levels.

Quick Exposure Check (QEC) analysis: In Figure 4, QEC analyses show different exposure levels for different work tasks in the assembly of inner walls cycle.

In Figure 4, according to Table 1 which shows how to determine different exposure levels, there are a number of work tasks in the assembly of inner walls that have exposure levels ranging from Moderate to High. The QEC analysis indicated that lifting the 45 kg inner walls panels has a high exposure level for the workers' shoulders and arms, whereas other body areas i.e., the back, hands, wrists and the neck) have a moderate and even low exposure levels. Furthermore, QEC analysis showed that drilling and screwing of concrete ceilings and floors have low exposure levels, but these exposure levels could have been high if for some reasons the work pace or stress was increased and thus scored high.

QEC analysis which considers the workers' own assessment of their inner wall assembly work tasks has indicated that there is no risk of whole body vibration as their work tasks do not require driving. Hand and arm vibrations due to concrete drilling were estimated as low exposure levels which do not contribute to the worker's ergonomic loading. Carpenters interviewed expressed that work pace and stress were low and therefore did not have any negative effect on their musculoskeletal system.

## USING ERGONOMIC TOOLS AS A BEST PRACTICE

After the risk assessment, work tasks with WMSDs risks were identifiable, and it was possible to develop adequate solutions to eliminate the risk exposures. The use of ergonomically-designed tools or aid devices has been shown to be one of the best practices that the Swedish construction industry uses to reduce WMSDs (Rwamamara, 2005). Therefore, in the case of inner wall installation, using specific user-centred designed aid devices for demanding work tasks should reduce risk factors. For instance, to set the inner wall at the ceiling level where the worker (Figure 5) usually works with hand-held tools above shoulder level which generates static loading on the worker's musculoskeletal system; the drill and the screw-gun should be used with a tripod / stand (Figure 6) to reduce risk factors associated with work above the shoulders. Using a human as a hand tool tripod leads often to musculoskeletal injuries. Static work restricts blood circulation to body parts and causes fatigue and time studies does indicate the influence of fatigue on efficiency at work. Therefore, it pays off to use a tripod while the body is spared from risk exposures.

*Figure 5* *Worker drilling at ceiling level.*

*Figure 6* *A drill's tripod.*

Similarly, to avoid bending work postures that strain the back during work tasks at the floor level (Figures 7a and 7b), a worker should consider using a drill with an extension structure (Figure 8a) and a screw gun cradle (Figure 8b) which fits many of the drills and screw guns found on many construction sites.

***Figure 7a*** *Horizontal drilling.*

***Figure 7b*** *Vertical screwing.*

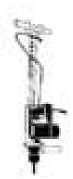


***Figure 8a*** *A horizontal extension.*

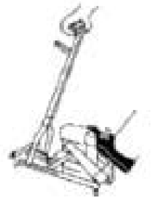


***Figure 8b*** *Cradle for vertical drill.*

As for the lifting of the heavy wall panels (Figure 9a), using a good lifting and carrying aid device (Figure 9b) should reduce the exposure related to heavy and awkward lifting and as well as static loading on the back, shoulders, hand and wrists. Heavy lifting ought to be always planned out; otherwise there is a risk of musculoskeletal injury and damaged materials when dropped down.

***Figure 9a*** *Worker lifting a heavy wall panel.*

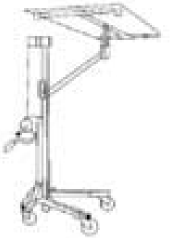


***Figure 9b*** *Lifting aid.*

The aid devices shown in Figures 6, 8a and b, and 9b are from a catalogue of good construction tools compiled by Rygginstitutet in cooperation with Bygghälsan and Arbetslivsfonden (Rygginstitutet, 1995). The catalogue was developed through practical tests of tools on construction sites with the support of the Swedish Working Life Fund (Arbetslivsfonden) and the construction industry.

The tools suggested for use in those parts of the job identified as risk factors bearers should be introduced after consulting the workers, after all, workers know the most about their jobs. Consultation at this stage will assist with the introduction new tools in the workplace.

## CONCLUSIONS

In regard WMSDs in construction industry, the assessment of exposure to risk factors is an important part of the surveillance of the industrialisation of construction processes and the preventive work. Risk assessment should be an integral part of the concept of designing for construction workers safety and health as indicated in the European Union directive (CEC, 1992; Hinze et al., 1999). The exposure assessment of risk factors is based on well-established risk factors for a number of WMSDs according to the fairly recent research findings (Hagberg et al., 1995; Moon and Sauter, 1996; Johansson et al., 2003 and Lund et al., 2006). This assessment can help in regard to planning a healthy construction workplace and introducing changes in the construction workplace in order to eliminate when possible or otherwise minimise exposure levels. If construction planners and designers have taken into account the health and safety aspects as stated in the European directives (CEC, 1992), the industrialised system investigated in the study should result in significant benefits.

Both ErgoSAM and QEC risk assessment methods showed that inner wall assembly work involves some easy work tasks but also entails of demanding work tasks specifically the lifting of gypsum panels and the drilling of the concrete slab and the screwing of screws into both the concrete and the wall panel. It is possible however to improve the way these work tasks are performed through anticipatory planning work and using user-cantered designed aid devices.

If the new industrialised construction process investigated in the study had been the old traditional process, it is certain that many construction work tasks in the inner wall building job would have been rated high in exposure levels. It could however be interesting to investigate further through a comparison of the traditional and industrialised construction methods. Moreover, because this industrialised method is not particularly advanced, the findings of this paper should not be inappropriately applied to the whole of the industrialised building sector.

In the industrialised construction process, the study of inner walls panels' installation indicated high risk values partly through heavy lifting and repetitive tasks that the workers are required to do during their workday to set up the inner wall. The industrialised construction approach brings about possibilities, in a sense that on the basis of construction work tasks analyses with instruments such as ErgoSAM and QEC, changes in the production work methods are brought about and risk factors are minimised or eliminated through a thorough planning.

A shortcoming in this study is that its conclusions are not based on broader empirical data. The study has only covered the installation of prefabricated inner wall panels and therefore cannot comment on other work tasks within the industrialised construction process.

Another shortcoming could be that neither ErgSAM nor QEC methods were developed for the industry of construction and could give a rigid assessment of the WMSDs risk exposures within the construction tasks. For example, in ErgoSAM and QEC, the weight or force exerted scales are not high enough to accommodate a fair analysis of heavier work tasks common to the construction industry. This is perhaps another sign that the strain work load on our construction workers is too high with the thought that premature retirements due to strain injuries are quite common among construction workers.

### *Further research and development*

When changes have been made in the inner wall installation work environment with the introduction of the suggested aid devices, risk exposure should be reassessed to confirm the efficiency of the intervention in reducing the risk factors for WMSDs.

## ACKNOWLEDGEMENTS

The author wish to acknowledge the essential contributions of Professors Ove Lagerqvist and Thomas Olofsson of Luleå University of Technology (LTU), and students Jonny Dömstedt and Sven Modig of Royal Institute of Technology (KTH), and a number of industrial collaborators. Funding of this research was provided by Formas-BIC IV and the Development Fund of the Swedish Construction Industry (SBUF).

## REFERENCES

**Amell, T. and Kumar, S. (2001)** Work-Related Musculoskeletal Disorders: Design as a Prevention Strategy. A review. *Journal of Occupational Rehabilitation*, Vol. 11, No. 4, pp. 255-265.

**Andrews, D.M., Norman, R.W., Wells, R.P., Neumann, P. (1998)** Comparison of self-report and observer methods for repetitive posture and load assessment. *Occupational Ergonomics* 1(3), pp. 211-222.

**Bao, S., Silverstein, B., Howard, N. and Spielholz, P. (2006)** The Washington State SHARP Approach to Exposure Assessment. In: Marras, W.S. and Karwowski, W., eds. *The Occupational Ergonomics handbook: Fundamentals and Assessment Tools for Occupational Ergonomics*. Taylor & Francis.

**Blismas, N.G., Gibb, A.G.F. & Pasquire, C.L. (2006)** Benefit evaluation for offsite production in construction, *Construction Management and Economics*,.24 (2), pp. 121-130, ISSN 0144 6193

**Rygginstitutet (1995)** Bra byggredskap. Elbranschkatalog. Rygg Institutet, Sundsvall.

**Council of the European Communities (CEC) (1992)** *Council Directive 92/57/EEC of June 24, 1992, on the Implementation of Minimum Safety and Health Requirements at Temporary or Mobile Construction Sites*. Brussels: European Commission.

**Christmansson, M., Falk, A.-C., Amprazis, J., Forsman, M., Rasmusson, L. and Kadefors, R. (2000)** Modified method time measurements for ergonomic planning of production systems in the manufacturing industry, *Int. J. Prod. Res*., 38(17), pp. 4051-4059.

**David, G.C. (2005)** Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. *Occupational Medicine*, No. 55, pp. 190-199.

**David, G., Woods, V. and Buckle, P. (2005)** *Further development of the usability and validity of the Quick Exposure Check*. HSE Books, RR211. ISBN: 0 7176 2825 6.

**ECTP (European Construction Technology Platform) (2005)** Strategic Research Agenda for the Construction Sector, Achieving sustainable and competitive construction by 2030. *http://www.ectp.org/documentation/ECTP-SRA-2005_12_23.pdf*, (accessed 4th July 2006)

**European Foundation for Improvement of Living and Working Conditions (2005)** Trends and drivers of change in the European construction sector: Four scenarios. *http://eurofound.europa.eu/emcc/publications/2005/ef0566en.pdf*, (accessed 4th July 2006)

**Gibb A.G.F, Pavitt, T.C., & McKay, L.M., (2004)** Designing or health and safety in cladding installation – implications from preassembly, *Proceedings of International Conference on Building Envelope Systems and Technologies* (ICBEST 2004), Sydney, Australia, p 1-7.

**Hagberg M, Silverstein B, Wells R, Smith MJ, Hendrick HW, Carayon P, P´erusse M** *Work related musculoskeletal disorders (WMSDs): A reference book for prevention*. London, U.K.: Taylor & Francis, 1995.

**Hamrick, C. (2006)** Overview of Ergonomic Assessment. In: Marras, W.S. and Karwowski, W., eds. *The Occupational Ergonomics handbook: Fundamentals and Assessment Tools for Occupational Ergonomics*. Taylor & Francis.

**Hinze, J.W., et al. (1999)** "Integrating Construction Worker Protection Into Project Design." *Implementation of Safety and Health on Construction Sites*. Balkema, Rotterdam.

**Johansson H., Windhorst U., Djupsjöbacka M. and Passatore M, eds.** *Chronic Work-related Myalgia: Neuromuscular Mechanisms behind Work-Related Chronic Muscle Pain Syndromes*. Gävle, Sweden: Gävle University Press, 2003.

**Laring, J., Christmansson, M., Kadefors, R. and Örtengren, R. (2005)** ErgoSAM: A preproduction Risk Identification Tool. *Human Factors and Ergonomics in Manucturing*, 15(3), pp. 309-325.

**Lessing, J., Stehn, L. and Ekholm, A. (2005)** Industrialised Housing: Definition and categorisation of the concept. *Proceedings IGLC-13*, July 2005, Sydney, Australia.

**Li, G. and Buckle, P. (1999)** Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. *Ergonomics*, Vol. 42, pp. 674-695.

**Li, G. and Buckle, P. (1998)** *The development of a practical method for the exposure assessment of risks to work-related musculoskeletal disorders*. General report to the HSE (Contract No. R3408), Robens Centre for Health Ergonomics, European Institute of Health and Medical Sciences, University of Surrey.

**Lund, T., Labriola, M., Christensen, K.B., Bultmann, U. and Villadsen, E. (2006)** Physical work environment risk factors for long term sickness absence: prospective findings among a cohort of 5357 employees in Denmark. *BMJ*, 332: 449-452.

**McKay, L., Gibb, A.G.F., Haslam, R.A. & Pendlebury, M.C. (2005)** Health and safety management of offsite construction – how close are we to production manufacturing?, *4th Triennial International Conference - cib W99, Rethinking and Revitalizing Construction Safety, Health, Environment and Quality*, Port Elizabeth, South Africa, Smallwood & Haupt (eds), pp. 432-441, ISBN 0-620-33919-5.

**Moon SD, Sauter SL, eds.** *Beyond biomechanics: Psychosocial aspects of musculoskeletal disorder disorders in office work*. London, U.K.: Taylor & Francis, 1996.

**Ong, H. C. (2004)** *Off-site manufacturing: An introduction*, Centre for Construction Innovation (CCI) Internal report on behalf of Northwest Development Agency, CCI and Constructing Excellence in the North West.

**Pasquire, C.L. and Connolly, G.E. (2002)** Leaner construction through off-site manufacturing, *Proceedings IGLC-10*, Aug. 2000, Gramado, Brazil.

**Rwamamara, R.A. (2005)** *The Healthy Construction Workplace: Best Practices in the Swedish Construction Industry to prevent work-related musculoskeletal disorders among construction workers*. Licenciate Thesis, 2005:39, Luleå University of Technology

**Sperling, L., Dalhman, S., Kilbom, Å. and Kadefors, R. (1993)** A Cube Model for the classification of work with hand tools and the formulation of functional requirements. *Applied Ergonomics*, 24, 212-220.

**Sveriges ProduktivitetsCenter AB (1995)** SAM-Sekvensbaserad aktivitets-och metodanalys (in Swedish).

**Wright, M; Pavitt, T.C.; Gibb, A.G.F. & Bendig, M. (2003)** The case for CDM: better, safer design – a pilot study, HSE Contract Research Report RR148, 2003, Greenstreet Berman, Health and Safety Executive, HSE Books, 76 pp, ISBN 0 7176 2733 0, *www.hse.gov.uk/research/rrpdf/rr148.pdf*

# III

*“Do your work; don’t let your work cling to you. The latter impedes you while the former expresses you.”* Oswald Chambers

# CONSEQUENCE OF INDUSTRIALIZED CONSTRUCTION METHODS ON THE WORKING ENVIRONMENT

**Peter Simonsson[1] and Romuald Rwamamara[2]**

## ABSTRACT

Traditionally, the working environment has been poor especially when it comes to steel reinforcement and concrete casting on construction sites. Industrialised construction methods such as self compacting concrete (SCC) casting and prefabricated steel reinforcement are creating a basis for an improved working environment. By using these methods, it is assumed that the cost for sick leaves due to ergonomic injuries and accidents are reduced as health and safety risks inherent to the traditional working methods are decreased.

Observations along with video filming and informal interviews were performed. With a sequence-based activity method ErgoSAM, an ergonomic risk analysis was conducted. The analysis showed that industrialised methods reduced ergonomic workload on concrete workers.

The industrialisation of the production process through the introduction of innovative construction methods has benefited the construction workplace environment as well as the customer value in terms of improved material handling, elimination of additional adverse affect on health of handling vibrating tools, reduced on site congestion and reduced over all material costs.

## KEY WORDS

Working environment, Steel reinforcement, Concrete casting, Industrialisation, Lean construction

## INTRODUCTION

The Swedish construction work environment is regarded as the safest in the world on the subject of physical health, working conditions, illnesses and accidents (Flanagan et al., 2001). Nevertheless, there are still work environment related health problems to be tackled. Stress and other mental strains at work present the most dramatic development in recent years in Sweden, but the most common cause of work-related disorders throughout a nine year period 1996-2005, has been the physical strain (e.g. heavy manual handling, strenuous work postures and short, repetitive operations) on the musculoskeletal system. In the construction industry more than one man in five, twice as many as for all men employed, reports musculoskeletal disorders of the musculoskeletal system. This corresponds to 50,000 men in Sweden. Musculoskeletal ergonomics studies concerned with the effects of work postures, working movements, physical loads and other conditions on the muscles and joints indicate that more than 1.5 million workers find their

[1] Ph.D. Student, Div of structural Engineering, Luleå University of Technology, 971 87 Luleå, Sweden Phone +46 920 493140, FAX +46 920 491913, Peter.Simonsson@ltu.se

[2] Ph.D. Student, Div of structural Engineering, Luleå University of Technology, 971 87 Luleå, Sweden Phone +46 920 492353, FAX +46 920 491913, Romuald.Rwamamara@ltu.se

daily work ergonomically strenuous. In the construction industry this experience is shared by over 130,000 men, and it is obvious that musculoskeletal illness is the construction industry's biggest problem (69% of all reported work-related injuries in 2005). These injuries are caused by the so-called ergonomic risk factors, and the most common risk factors are heavy lifting, strenuous work postures and prolonged one-sided work (Samuelsson and Lundholm, 2006; Lundholm and Swartz, 2006). Different occupational groups in the Swedish construction industry are affected by work-related musculoskeletal disorders (WMSDs) at different frequency levels; however the highest relative frequency of reported WMSDs belongs to the concrete workers (Lundholm and Swartz, 2006). The cost to the worker of WMSDs is pain, along with loss of income through being unable to work. This results in significant costs to organisations through sick leave or ill-health retirement, and to the tax payers in general that may have to support a person unable to work (European Agency for Safety and Health at Work OSHA, 2004).

Public debate in recent years has focused increasingly on work environment issues, not least in view of the dramatic rise in the cost of ill-health. Health and safety problems in the form of work-related illnesses and accidents cause relatively high costs influencing the projects. Safety costs will ultimately be paid for by the client either directly or indirectly. The financial, economic, environmental and social costs of deaths, injuries, disabilities and diseases to the industry, in particular, and to the society in general, is colossal (Larcher and Sohail, 1999). Work-related accidents significance for a company reputation and personnel turnover is difficult to measure for construction companies.

Many companies have little knowledge about the costs associated with work environment risks. For example, if only sick-leave costs and social contributions are included in the economic assessment, the cost picture is incomplete. Cost for overtime, decreased production, increased administration, rehabilitation and productivity loss due to reduced working ability need to be taken into account as well (Rose and Örtengren, 2000). Therefore, cutting the sector's high incidence of accidents and work-related illnesses could save for example the EU and its taxpayers up to 75 billion Euros (estimated to be about 8.5 percent of the total construction costs) a year, claims the European Agency for Safety and Health at Work (OSHA 2004).

Direct and indirect costs resulting from a poor work environment have compelled both researchers and practitioners to look for adequate strategies and plan of actions to tackle safety issues in the production planning in the construction process. Koskela (2000) states that occupational safety is notoriously worse in the construction industry than in other industries and that a number of solutions have been offered to relieve the chronic problem in construction.

The industrialisation of the construction process reflects the use of technology to change the sector's work environment for the better. Industrialised construction methods such as the use of the prefabricated steel reinforcement and the Self Compacting Concrete (SCC) have been introduced into the construction workplace for among other reasons the improvement of the work environment. These methods although often referred to as new, they are not new in principle, as they have had their applications in the industry since the early 1980's.

This paper will share some insights obtained from an investigation study on the use of these industrialized methods impact on the construction site work environment.

### WORKING ENVIRONMENT AND ECONOMY

Injury cost estimations, according to the Swedish Social Insurance Agency (2004), the single biggest cause for sick leaves is back pain which accounts for 15 % of all sick leaves among men and 12 % of sick leaves among women. The average of the total back pain illness compensation per case for men (focusing on men which constitutes 92 % of the construction industry's workforce) is about 4 600 €, this cost denotes 45 € per sick leave day. Back pain being the most common illness among men does account for 17 % of all sickness compensations. Considering only the construction industry, Samuelsson and Lundholm (2006) reported that out of all 1582 cases of sick leaves caused by occupational illnesses reported in the year 2004, 1342 cases of sick leaves were caused by ergonomic risk factors (including vibration and noise).

Furthermore, taking into account the 279 cases of WMSDs reported among concrete workers (Lundholm and Swartz, 2006), their sick leave compensations could approximately cost up to 1 280 000 € for the taxpayers. There are of course other direct and indirect costs such as productivity loss and hiring substitute workers that are not often calculated.

## RISK IDENTIFICATION METHODS

Risk assessment methods determine the risk level that employees face from exposure to hazards at work and can help establish measures that are necessary to control the risk and to protect workers health and productivity. In the study two risk identification methods were used to complement each other.

### OBSERVATION AND ERGOSAM

Observations at the bridge were done in a form of site-walkthroughs, video films of identified steel reinforcement and concrete casting activity work cycles. These observations were the basis for a further risk assessment; the ErgoSAM analysis.

ErgoSAM is based on SAM (a sequence-based activity method), and a higher-level method-time-measurement (MTM) system. The SAM system is the result of work carried out in Sweden to shorten the time needed for analyses made with MTM systems (Swedish Productivity Centre, 1995). In SAM, the main activities are Get and Put. For each SAM activity, a standard time is given. In addition to the SAM information, the ErgoSAM method considers two additional pieces of information: the zone relative to the worker' s body in which the activity is carried out or ends; and the weight of the objects handled or the force exerted in the activity (Laring et al, 2005). The output of ErgoSAM is the product of three types of demands namely, work posture, force and repetition (frequency), according to a scientific model, the Cube model (Sperling et al., 1993).

The Cube Model is used on the site observations to acquire the risk of WMSDs on combinations of the variables mentioned (posture, force and repetition). For a specific working task, and for each dimension separately, demand levels may be defined as low, medium, or high, where the demand criteria are chosen so as to discriminate between good or poor work ergonomics, and assigned weight factors 1, 2, and 3 respectively. Combinations of demands are evaluated by multiplication of the three weight factors, and this product determines the acceptability of the task (Sperling et al., 1993). ErgoSAM is implemented as a macro program in Microsoft Excel.

## FULL SCALE STUDY

A full scale study was carried out on a bridge construction with focus on the industrialised methods and their impact on the work environment. The bridge consists of a span of 10 metres with a width of 15 metres, Figure 1. One objective of the study was to examine the changes on the working environment when “new” construction methods, (use of prefabricated steel reinforcement and Self Compacting Concrete) were introduced. Other objectives presented in Simonsson and Emborg (2007), were to study the productivity at site, site logistics, economics of the changed working methods and planning process.

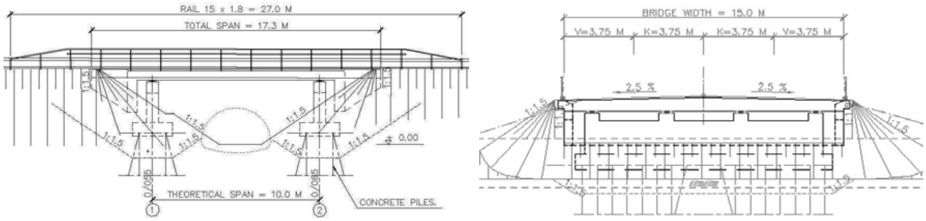



Figure 1: Full scale bridge in elevation and section (no scale).

## CONSTRUCTION METHODS

According to a study by the Danish Technological University, DTU (Nielsen, 2006) some 26 % of a workers average day consists of concrete casting and reinforcement fixing. If this is translated into time, it will be just over 2 hours per working day, or 57 full working days a year. This work is often done in awkward postures with heavy equipments such as the vibrator used to compact the conventional (traditional) concrete or with heavy material when placing the reinforcement piece by piece.

### STEEL REINFORCEMENT

Traditionally, steel reinforcement is fabricated on the construction site at its final destination involving a large labour force and a considerable amount of steel wastage. Current methods for installing steel reinforcement in concrete structures involve interpreting steel positions from plans and installation of individual bars by site workers.

If manufacturing of the steel reinforcement could be moved from its final position, i.e. in the formwork, to a more controllable position, a reinforcement workshop, the working environment could be drastically improved. Prefabricating steel reinforcement cages offers that possibility through the use of scissor lift tables, which makes it possible for the worker to work at the right height all the time instead of a bent posture as shown in Figures 2 a and b. Prefabricating steel reinforcement does not necessary equal manufacturing it in a factory, the reinforcement shop could also be located at the construction site. In this case, the benefit would be that the production flow for the worker can become even and possible waiting times can be eliminated through using this work as a buffer. During the construction of the full scale bridge, the industrial prefabrication of steel reinforcement partly replaced the manual installation on site. The prefabricated reinforcement was easily placed in the formwork, using cranes, before concrete casting commenced, see Figure 3.

a)  b) 

Figure 2: a) Traditional working position when placing reinforcement piece by piece. b) Steel reinforcement prefabricated in the factory and shipped to construction site.

a)  b) 

Figure 3: a) Placing prefabricated reinforcement for a foundation. b) Reinforcement carpet lifted into place.

Some of the benefits highlighted when using prefabricated steel reinforcement structures are improved safety and reduced on-site congestion, reduction in site fixing resulting in less exposure time, ease of identification of reinforcement with less stressful situations and improved material handling with less heavy lifting and carrying of material (http://www.bamtec.co.nz/elements/BAMTECsystem.pdf).

## CONCRETE CASTING

Traditional concrete casting produces high noise levels and the vibrating tools used for compaction of the concrete often lead to unhealthy working postures (Figure 4a). As mentioned earlier, a typical concrete worker spends on average 10 % per day casting concrete, thus working in stressful working postures and being exposed to back pains.
Self Compacting Concrete (SCC) is a concrete to which no additional inner or outer vibration is necessary for the compaction. SCC compacts itself alone due to its self-weight and is de-aerated almost completely while flowing in the formwork. For the success of SCC, it is crucial to define the performance of the product, which can, according to the Growth project Testing-SCC (Emborg et al., 2005), be discerned into three main parameters: 1) *Filling ability* 2) *Passing ability* and 3) *Segregation proneness*. For these parameters, criteria should be established to be met by a proper mix design depending on geometry of structure to be cast, reinforcement, form type and, method and local tradition on how to pour the concrete (Figure 4).

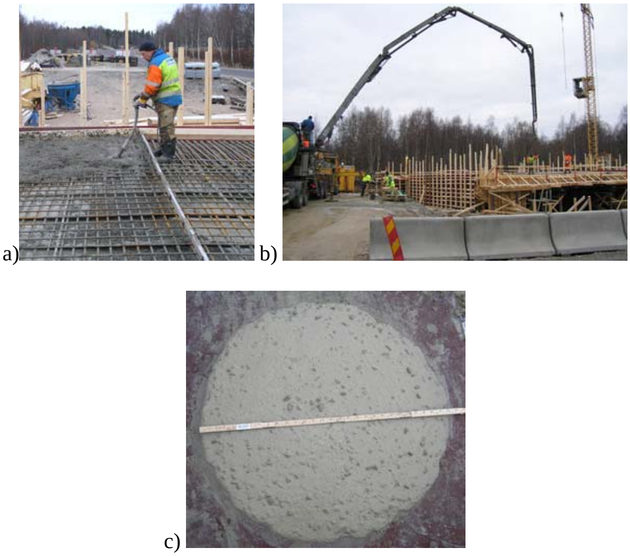



Figure 4: a) Worker using a vibrator for compacting normal concrete. b) SCC being pumped into formwork. c) Slumpflow test on SCC measuring approximately 740mm.

In general SCC offers many advantages for cast-in-place construction as well as for the pre-cast and pre-stressed concrete industry. In regard to the working environment, there is less noise-level i.e. easier communication, eliminated vibration problems, improved quality and durability results in less rectification work and reduced concrete volumes due to higher strength.

## RESULTS AND DISCUSSION

### IMPROVEMENT OF WORK ENVIRONMENT THROUGH TECHNOLOGY INPUTS

With the increasing technology inputs into the construction workplace ergonomic intervention, not only does one enhance productivity but also adds value to the whole construction project. Velasco (1998) states how productivity is brought about by the technical inputs and the quality of the performance of the worker (physiological abilities of the worker (Abdelhamid and Everett, 2002)). Prior to the production start, the main contractor and the client agreed on the technology that will fit workers in the construction workplace. Off-site produced steel reinforcement and SCC were shipped into the construction site and lifted into the site by cranes, thus avoiding any manual material handling. The construction project presented in this paper had basic objectives of production and safety management depending on each other; therefore an integration of Lean Construction and safety management were emphasised on as in Saurin et al. (2006).

### ECONOMIC BENEFITS OF 'NEW' CONSTRUCTION METHODS

From the full scale bridge project it was observed that prefabrication of components allowed a reduction in work time for on-site steel fixing and dedicated labour and minimised the amount of storage space required on what is normally considered to be a congested site. Using prefabricated steel reinforcement elements accelerated the installation process at the construction site and made the construction more economical in terms of material waste. The off-site fabrication of steel reinforcement structures ensured continuous supply regardless of inclement weather which meant the structures was ready for immediate transportation to site to complement the construction process.

The cost related to the reinforcement can be viewed from two perspectives, the production cost of the reinforcement and the construction cost for placing the reinforcement before casting concrete. For the full scale bridge carpet reinforcement, the placing cost varied from 0,02€ to 0,04€ per kilogram (bottom and top reinforcement respectively of the superstructure), the traditional price for reinforcement fixing on the superstructure is approximately 0,65€ per kilogram. The purchase price for the carpet reinforcement rose with approximately 50% in comparison with traditional reinforcement bars, but still some 35% of the total costs were saved.

Concerning the use of SCC, not only workers were pleased to have a non-vibrating and noise-free work environment, but also costs related to the concrete compaction equipment use were eliminated and vibrators are often used inefficiently. They often run wastefully, or at a reduced efficiency, for about 70 % in total of their operating time, this being made up as follows (Hong Kong City University, 2007): out of concrete and left running 15 %, wrongly positioned in the concrete 35 % and vibrating already compacted concrete 20 %. This means that the vibrator is doing useful work only 30 % of the time.

### ERGONOMIC ANALYSIS, ERGOSAM RESULTS

After several weeks of observing concrete workers performing their jobs on the construction site, and after informal interviews with concrete workers, it became obvious what were classic work cycles for different methods of steel reinforcement and concrete casting. Based on this information, video films were taken and analyses of representative short work cycles were performed to identify any risks for WMSDs for concrete workers performing their tasks using different construction methods namely conventional and industrialised methods. Results of the analyses for representative work cycles are presented in Figures 5 and 6, where different loads on concrete workers are represented by Cube values.

The Cube value or the load level falls within three levels; where under 6 is acceptable, 6 to under 9 is conditionally acceptable and 9 and above is unacceptable. For example, the work cycle mean value of 7.4 obtained in ErgoSAM analysis in Figure 5 falls into the conditionally acceptable area. The situations which still fall short of being acceptable are attributable to those tasks that have high degree of repetition and bending, such as fixing the steel structure and cutting metal rings off the rolled out carpet reinforcement. When the worker performed tasks with the manual steel rebar work. The concrete worker is exceedingly exposed to WMSD risk factors which contribute to very high cube values with a mean value of 21. This number denotes almost three times higher risk exposure to WMSDs when working with the traditional rebar reinforcement than when working with the prefabricated steel reinforcement with 7.4 for a mean value (figure 5).

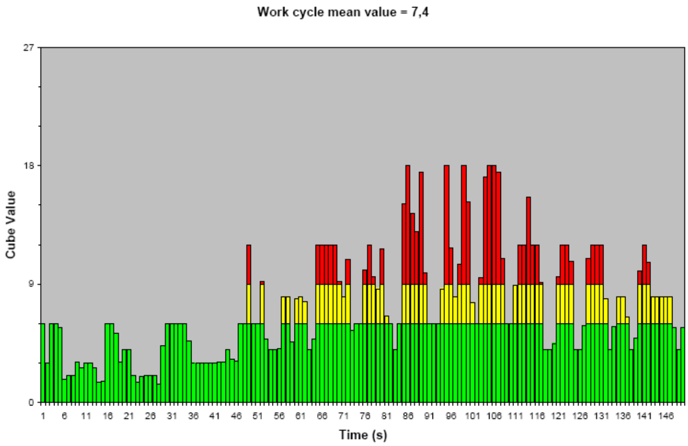



Figure 5: ErgoSAM analysis of a short work cycle of a concrete worker working with prefabricated steel reinforcement. A cube value under 6 is acceptable, 6 to under 9 is conditionally acceptable and 9 and above is unacceptable.

The work cycle mean value of 5.7 was obtained in the ErgoSAM analysis in the case of SCC casting (figure 6), thus making these work tasks acceptable as far as the workers work-related musculoskeletal health is concerned, and hence entails no risk factors for WMSDs.

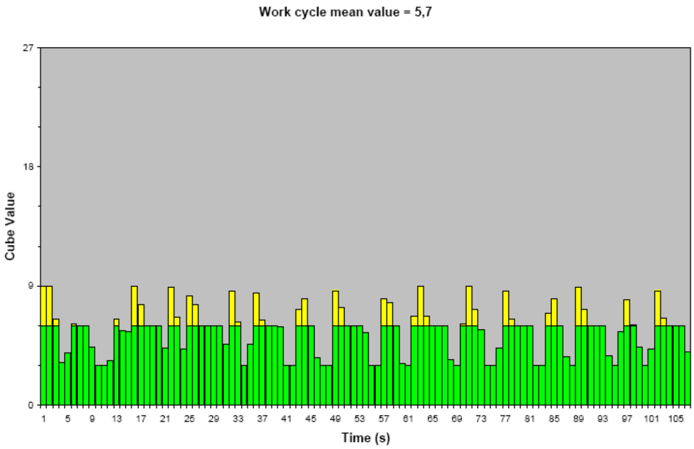



Figure 6: ErgoSAM analysis of concrete worker‘s short work cycle during SCC casting.

When the traditional concrete casting work cycle was compared to that of the SCC casting, the ErgoSAM analysis showed a mean value of 18.2, thus it became obvious that the normal concrete casting work exposed the worker to WMSD risk factors, over three times higher than working with SCC casting.

## CONCLUSIONS AND FURTHER COMMENTS

The risk analysis on steel reinforcement and concrete casting work tasks by the ErgoSAM method, has indicated that working with the prefabricated steel reinforcement and SCC reduced a great deal of physical loading on the musculoskeletal system of the worker due to the elimination of physical strain due to the common risk factors that are generally part of the traditional methods of rebar reinforcement and the use of conventional concrete.

The prefabrication of steel reinforcement structures allowed a significant reduction of on-site steel fixing and associated labour costs as well as providing a much safer working environment without risk factors such as heavy lifting and working in bent, awkward and repetitive postures. The SCC cast into a frame of reinforced steel without the need for the labour intensive mechanical vibration usually associated with concrete placing, has led to the improvement of construction work environment and the promotion of health and safety of concrete workers. In a project such as a bridge construction in areas with heavy traffic, the project completion time can be extremely important. As the new steel reinforcement was prefabricated, there was higher quality control than the traditional rebar system. The off-site fabrication of steel reinforcement accomplished difficult construction tolerances, improved handling as well as it contributed to the speed of construction and minimized wastage of material. All mentioned above contributes to the customer value, in this case to the National Road Administration in Sweden.

The use of SCC in the full scale project offered many benefits to the construction: the elimination of the compaction work resulted in reduced costs of placement, a shortening of the construction time and the number of involved workers during casting, and therefore in an improved productivity. Considering the economics of SCC, the material cost was higher than traditional concrete; however the total cost was slightly lower for SCC. The largest benefit though was the reduction in man hours used for casting the concrete, man hours that can be used for preparing upcoming work.

Finally, when working with these industrialized and innovative working methods it does give significant benefits both in terms of a healthy and safe work environment for the workers, reduced staff-related costs for the company as well as the client and the society as a whole, both in short term and long term perspectives.

## REFERENCES

Abdelhamid, T.S. and Everett, J.G. (2002). Physical Demands of Construction Work: A source of workflow unreliability. Proceedings IGCL-10, Aug. 2002, Gramado, Brazil.

Bamtech, Concrete Slab Reinforcement System: http://www.bamtec.co.nz/elements/BAMTECsystem.pdf. Last accessed 2007-05-14.

Emborg M, Jonasson J-E, Nilsson M, Utsi S, Simonsson P: Designing robust SCC for industrial construction with cast in place concrete, Proceeding of Fourth Int Rilem Symposium on SCC, Oct 30 - Nov 2, Chicago, 2005.

European Agency for Safety and Health at Work (OSHA) (2004), *Bilbao Declaration – Building in safety*, European construction safety summit, 22 November 2004, available at:http://agency.osha.eu.int/publications/other/20041122/en/index_1.htm.

Flanagan, F., Jewell, C., Larsson, B. and Sfeir, C. (2001) “Vision 2020: Building Sweden’s Future”, Department of Building Economics and Management, Chalmers University of Technology, Sweden.

Hong Kong CityU (2007). http://www.cityu.edu.hk/CIVCAL/production/traditional/concreting.html. Last accessed April 3rd 2007.

Koskela L. (2000). An exploration towards a production theory and its application to construction. A doctoral dissertation. VTT Building Technology. VTT Publications. (VTT) 2000.

Larcher, P. and Sohail, M. (1999), WELL Study; Review of Safety in Construction and Operation for the WS&S Sector: Part I. Task No:166; London School of Hygiene & Tropical Medecine and WEDC, Loughborough University, UK.

Laring, J., Christmansson, M., Kadefors, R. and Örtengren, R. (2005) ErgoSAM: A preproduction Risk Identification Tool. Human Factors and Ergonomics in Manucturing, Vol. 15 (3), pp. 309-325.

Lundholm, L. and Swartz, H. (2006). Musculoskeletal ergonomics in the construction industry. Facts & figures in brief No. 5.2006. Swedish Work Environment Authority. http://www.av.se/dokument/inenglish/statistics/Sf_2006_05_en.pdf. Last accessed 19 March 2007.

Nielsen, C 2006, New results regarding SCC and working environment, The Nordic SCC Network Workshop, SCC, Vision and Reality 19th June 2006, Copenhagen, Danish Technological University, 1981

Rose, L. and Örtengren, R. (2000). Risk management of personal injury risks in companies. Proceedings of the International Seminar on Risk Management and Human reliability in Social Context, European Safety, Reliability and Data Association, June 15-16, 2000.

Samuelsson, B. and Lundholm, L. (2006). Arbetsskador inom byggindustrin 2005. Bygg- och anläggning. Privat sector. BCA 2006:2.

Saurin, T.A., Formoso, C.T. and Cambraia, F.B. (2006). Towards a Common Language Between Lean Production and Safety Management. Proceedings IGCL-14, July 2006, Santiago, Chile.

Simonsson P and Emborg M, (2007) Industrialization in Swedish bridge engineering: a case study of Lean construction, IGLC 2007.

Sperling, L., Dahlman, S., Kilbom, Å. and Kadefors, R. (1993) A Cube Model for the classification of work with hand tools and the formulation of functional requirements. Applied Ergonomics, 24, 212-220

Sveriges Produktivitets Centre AB (1995) SAM-Sekvensbaserad aktivitets- och metodanalys (in Swedish).

Swedish Social Insurance Agency (Riksförsäkringsverket) (2004) Vad kostar sjukdomarna för kvinnor och män? Sjukpenningkostnaderna fördelade efter kön och sjukskrivningsdiagnos. Redovisar 2004:5.

Velasco, A. L. (1998) Ergonomics: An agenda for Philippine productivity in the new millennium, in P.A. Scott, R.S. Bridger, J. Charteris (eds) Global Ergonomics. First Edition 1998, Elsevier Science Ltd.

IV

*“Science is not primarily a source of authority. It is a particularly effective approach of inquiry and analysis. Skepticism is essential to science, consensus is foreign.”* Richard Lindzen, MIT professor.

Second International Conference World of Construction Project Management 2007
Prof. H.A.J. de Ridder, Prof. J.W.F. Wamelink (Eds.)


# REDUCING THE HUMAN COST IN CONSTRUCTION THROUGH DESIGNING FOR HEALTH AND SAFETY – DEVELOPMENT OF A CONCEPTUAL PARTICIPATORY DESIGN MODEL

**PhD Candidate, Romuald Rwamamara[1] and Dr.-Ing. Peter Holzmann[2]**

[1]Division of Structural Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden
[2]Impasse de la Rade, F-06300 Nice, France
E-mail: rorw@ltu.se

**Abstract**
*The construction industry is still one of the highest risk industries as far as Work-related Musculoskeletal Disorders are concerned. Literature reviews written on and observation of the health and safety management of construction projects show that there are windows of opportunities for professional designers to contribute to safety and health of workers in construction and maintenance processes. A model for a participatory design is proposed to show the paramount importance of partnerships between various stakeholders in the preparation of a construction project to result in a healthy and safe construction workplace over and above an enhanced productivity and quality.*

Key words: Health and safety, design, construction, building planning, virtual design

## 1 Introduction

The construction sector remains one of the highest risk sectors in Sweden in regard to Work-related Musculoskeletal Disorders (WMSDs). These disorders are a long-term discomfort caused by work that it is the result of acute or instantaneous trauma of soft tissues or their surrounding structures (Dimov et al, 2000). In the Swedish construction industry, more than one man in five, twice as many as for all men employed, has reported work-related musculoskeletal disorders (Lundholm and Swartz, 2006) and these disorders constitute about 69% of all reported work-related injuries in 2005 (Samuelsson and Lundholm, 2006). The cost of WMSDs associated with direct worker compensations is high. The direct costs from compensation of musculoskeletal disorders are appreciated far more than the indirect costs associated with disruptions in productivity and quality, worker replacement costs, training and work absence costs. It is believed however, that the direct costs due to compensated work related musculoskeletal disorders are only a relatively low proportion (30-50%) of the total costs (Hagberg et al., 1995). The construction industry health and safety image problem and today's booming economy make it difficult for this industry to draw more educated workers. The shortage of skilled workers threatens the quality of construction, as inexperienced apprentices tend to make more mistakes requiring correction (ICAF, 2000). Thus, it is really of paramount importance to improve the construction work environment in order to keep skilled workers as well as reducing the construction time and increasing quality. Some studies have shown that a fairly large percentage of construction accidents could have been eliminated, reduced, or avoided by making better choices in the design and planning stages of a project (Hecker et al, 2005). Therefore, paying attention to health and safety issues in the design phase could have a significant impact in reducing the risk of injuries and the cost associated with health and safety related project delays.

## 2 Preventing WMSDs at the pre-build phase

Prevention through design, the concept that significant reductions in injuries can occur when safety is designed into a product, service or process, has been established within the general occupational health and safety field for many decades (Manuele, 1997). The basic philosophy of successful ergonomic design seems to be the anticipatory thinking in terms of design processes and their consequences. Thus, anticipation means that the designer is aware of the consequences of his actions (Luczak et al., 2006).

According to OSHA (2004), architects and quantity surveyors should be made aware of the potential improvements that can be introduced if manual handling methods were reviewed during the design phases of projects. Contractors, clients, and suppliers can encourage good practice standards to be fully implemented. Employers have legal duties to protect workers from WMSDs, based on European Directives. Where the risk of musculoskeletal disorders cannot be designed out at the pre-build phase, then employers should carry out a risk assessment to identify the hazards, assess the risks, and take action to prevent ill health or injury (OSHA, 2004).

## 3 Design for construction workers and end-users

Designer decisions made during the schematic and design development phases of a construction project directly impact health and safety of construction workers on the worksite. Many decisions also impact the safety of end-users, maintenance and repair workers, and construction crews during renovation or deconstruction cycles (Haas, 1999). In the design of buildings and other structures designers consider health and safety of end users in the design of the permanent structure, but similar concerns for construction workers during the building process are traditionally ignored (Rwamamara, 2005; Hecker et al., 2006). The hierarchy of controls and elimination of hazards in occupational health and safety recognizes that engineering controls and the elimination of hazards through design are preferable to administrative controls and personal protective equipment in limiting worker exposure (Manuele, 1997; Hecker et al., 2006). Health and safety concerns addressed by architects and engineers apply almost exclusively to the end-user of a building, rather than the workers who construct it. For example, in a Swedish study where a number of architects were interviewed on whether or not they take into consideration health issues into their design, to this question they responded that their design considers the health and safety of the end-user and not the construction worker (Rwamamara, 2005). Traditionally a boundary has been created between design and construction by defining expected scopes of work and standards of practice, however new safety knowledge exposes the design professional’s significant influence on worker safety (Gambatese, 1998). There are however many instances in which design improvements have been shown to affect both workers and end-users. To mention just a few examples; designing scaffolding tie-off points into exterior walls of buildings for construction and renovation purposes, and design of high parapet walls to protect workers on the roof and end-users during the life of the building. These walls will provide immediate guardrail protection and eliminate the need to construct a guardrail during construction or future roof maintenance (Behm, 2006). Further examples on impact of addressing worker’s health and safety in design are reported in Weinstein et al. (2005), whereby providing more space and height for a variety of trade workers, design changes reduced ergonomic risks, and likely alleviated problems related to congestion, access, and material handling.

## 4 Where design can make a difference

Design has the potential to reduce health and safety risk through materials and equipment design. A UK research project that studied about 100 accidents, using an ergonomics systems approach, to

identify where safety is compromised and why; an analysis of design factors in the 100 accidents suggests that approximately half of these incidents could have been prevented by design alteration (Gibb et al., 2004).
The following were the type of designers considered in the UK study and their potential in risk reduction:

- Permanent works designers (architects, civil and structural engineers, mechanical and electrical engineers, etc.) could have reduced the risk in almost half of the accidents.
- Materials designers (design of materials themselves and their packaging, delivery method, etc.) could have reduced the risk in more than a third of the accidents.
- Equipment designers (tools, plant, and equipment) could have reduced the risk in 60 of the 100 accidents through improved design of the equipment being used.
- Temporary works designers (scaffolding, formwork, etc.) could have reduced the risk of more than a third of the accidents.

In regard to WMSDs reduction, studies on ergonomic risk factors (Schneider et al., 1995) and ergonomic interventions in construction (Schneider, 1999) point us in the direction where to focus our design improvements efforts; thus it makes sense that professional designers could make a difference in the following areas identified from a study review on best practices conducive to the reduction of WMSDs (Rwamamara, 2005): the access for material and equipment; worker's anthropometry and access; the size and the weight of materials; prefabricated buildings; temporary works

These suggested areas are in line with what Toole and Gambatese (2006) have identified as the trajectories that designing for construction safety is likely to follow.

**Design for material and equipment access**

With the growing industrialization of construction and the gradual shift to offsite prefabrication of structural and finishing elements that are then assembled on site, production equipment and support structures are increasingly making room for transportation equipment (Shapira, 2007). Thus, material handling and lifting equipment dominates construction sites. Consequently, designing for material and equipment should take account that equipment and material need to be delivered and removed during and after construction work; this could be done through designing vertical wall hatches (figure 1a) on all floors which can provide access for machine stocking and mechanized lifting (figure 1b) which could greatly reduce the risk of injury.

**Fig. 1a. Hatch access provided through large windows** **Fig. 1b. Mechanized lift through wall hatches**

When designing for material and equipment, it is extremely important to produce realistic methods statements. These method statements should indicate type of materials, type of machinery, the type of tools and the actual process of working to be undertaken. By devising a comprehensive method statement for all elements of construction work, it is possible both to enhance safety and to improve productivity. When these method statements are dealt with during the design process, then one has an opportunity to value-manage the construction project (Lingard and Rowlinson, 2005).

**Design for Worker's anthropometry and access**

To have a safe work environment, designers should account for the variations in the anthropometrics of the workforce (Gnaneswaran and Bishu, 2006). People come in a great variety of sizes and the proportions of their body parts are not the same. In reality, hardly a person exists who is average in most or all respects, consequently products or processes "designed for the average" fit nobody well (Kroemer et al., 2001). Thus, devising tools, gear, and workstations (figures 2a and 2b) to fit their bodies require careful consideration; design for the statistical "average" will not work. Instead, for each body segment to be fitted, the designer must determine what dimensions are critical: this may be a minimal or a maximal value, or a range.

**Fig. 2a. A plumber in a confined space**

**Fig. 2b. Worker in awkward posture due to difficult access**

Often, a series of such decisions is necessary to accommodate body segments or whole body by workspace and equipment. To achieve ease, efficiency, and safety, it is mandatory to consider the ranges of, the variations in, and the combinations of physiologic and psychological traits to accommodate anthropometric variability (Kroemer, 2006). General criteria for workspace layout relate to human strength, speed, effort, accuracy, importance, frequency, function, and sequence of use. Achieving the task while assuring safety for humans, avoiding overuse and unnecessary effort, and assuring ease and efficiency, are the primary design goals (Kroemer, 2006). Architects can draw an assembly or arrange space to promote a safer access during work and after completion, for example by minimizing the number of confined spaces and thus minimizing awkward postures for workers. In addition to designing for worker's anthropometry and his workplace for easy access; it is important to design for access and placement by crane or other lifting equipment such as worker-lifts (figures 3a and 3b).


**Fig.3a. Indoors work tasks done on scissor lift** **Fig.3b. Heavy prefab materials in indoors workspace require mechanical lifting device**

### Size and weight of materials

Size and weight of building materials directly impact construction workers, therefore material choice and dimension can be used to protect workers and reduce the cost (Rwamamara, 2007). Design that considers the size and weight of the building materials to be used will reduce the risk of WMSDS by diminishing the likelihood of heavy manual material handling. In addition to this benefit, the cost of material waste (due to resizing) and extra work repetitive work tasks related to resizing of materials (figures 4a and 4b) on the construction site will be eliminated.

**Fig.4a. Gypsum boards being resized** **Fig.4b. Heavy gypsum board is lifted manually to be installed.**

#### Design for prefabrication

Prefabrication involves the assembly of pieces in a factory, followed by the transportation of the assembled component to its permanent location and the final fit up. According to Toole and Gambatese (2006), prefabrication does reduce the hazard level of a task in two ways: First, it allows the work location to be shifted to a lower hazard environment where risks associated with working at height or in confined spaces are reduced; secondly, prefabrication allows the work to be shifted from the construction site to a factory, which allows the use of safer, automated equipment which reduces the incidence of WMSDs. The use of prefabricated components (figures 5a and 5b) eliminates or reduces many traditional construction work tasks that are associated with WMSDs risk factors

(Simonsson and Rwamamara, 2007). Furthermore, Gibb et al. (2004) suggest that permanent works designers could reduce the risk by reducing the amount of work done on the construction site, mainly through increased use of some form of pre-assembly. Among the most important benefits attributed to the use of prefabrication or off-site production are; minimization of on-site operations, reduction of site congestion, reduction of on-site duration and improved health and safety (Gibb and Isack, 2003). These benefits which are all directly or indirectly lead to health and safety of the construction worker should be considered in their designs.

**Fig.5a and Fig.5b. show the installation of prefabricated components with the crane's help.**

**Design for temporary works**

As argued by Lingard and Rowlinson (2005) the contractor is expected to design temporary works, however in case of particularly complex elements, it is essential that the designer consider temporary works in the design process. Temporary works are often needed either because there is a risk that a structure might otherwise collapse or because it is necessary to remove some vital supporting member for renovation or alteration. All temporary works should be designed before the start of the construction phase and the level of design and drawings of temporary works such as scaffolding (figure 6a), cranes (figure 6b) and telescopic props must commensurate with the scale of the works. For example the design of scaffolding should not, unless it is very straightforward, be left to the scaffold erector; it is important that prior thought be given to the location of scaffold foundations, where standards can and cannot go and where boarded out decks are required to enable the work to proceed with as little difficulty and risk as possible.

**Fig.6a and fig.6b. show a ready assembled scaffolding system to provide a safe working platform and an effective placement of the crane which should be designed in site layout to minimize risks on workers.**

## 5 Design means and methods

Design is a problem solving process, and in this paper, this process is concerned with the designer's ability to adopt the construction work environment to suit workers health and safety needs. The design process could emulate the Construction Design and Management (CDM) regulations in UK and EU which clearly define the designer's duties in respect of reducing health and safety risks during construction to avoid hazards, combat risks and provide information. According to the CDM regulations in the UK, the best form of protection against a hazard is to eliminate the hazard at source. Where elimination and /or reduction of the impact of the hazard are not possible, the information about the hazard should be provided so that it can be dealt with as safely as possible (Wright et al., 2003). To evaluate WMSDs risk implications in construction design, the design process needs a multidisciplinary team, involving all stakeholders involved in the design, construction and use of the facility. Participants might include design professionals, the client, the principal contractor, sub-contractors, the suppliers and service consultants or maintenance contractors. A Participatory health and safety Design (figure7) which takes into account of inputs from all stakeholders in design and construction processes at the conceptual design level is proposed and presented as a conceptual model to improve the construction workplace in regard to health and safety risks in general and WMSDs risks in particular. Within the proposed model, collaboration and consultation between various project stakeholders and the project design professionals should allow a careful consideration of materials and equipment to be used, as well as permanent works design, layout and work tasks designs are optimized in regard to their interaction with construction workers in order to diminish the likelihood of WMSDs. The participatory health and safety design resulting from the consultation and collaboration between key stakeholders brings about optimal designs of materials, equipment, permanent works and work tasks. By optimal design, authors of this paper do not mean a flawless design where no future corrections or adjustments may be made; instead what is meant is the best possible or the most advantageous designs in terms of their impact on the construction workers musculoskeletal health during construction work.

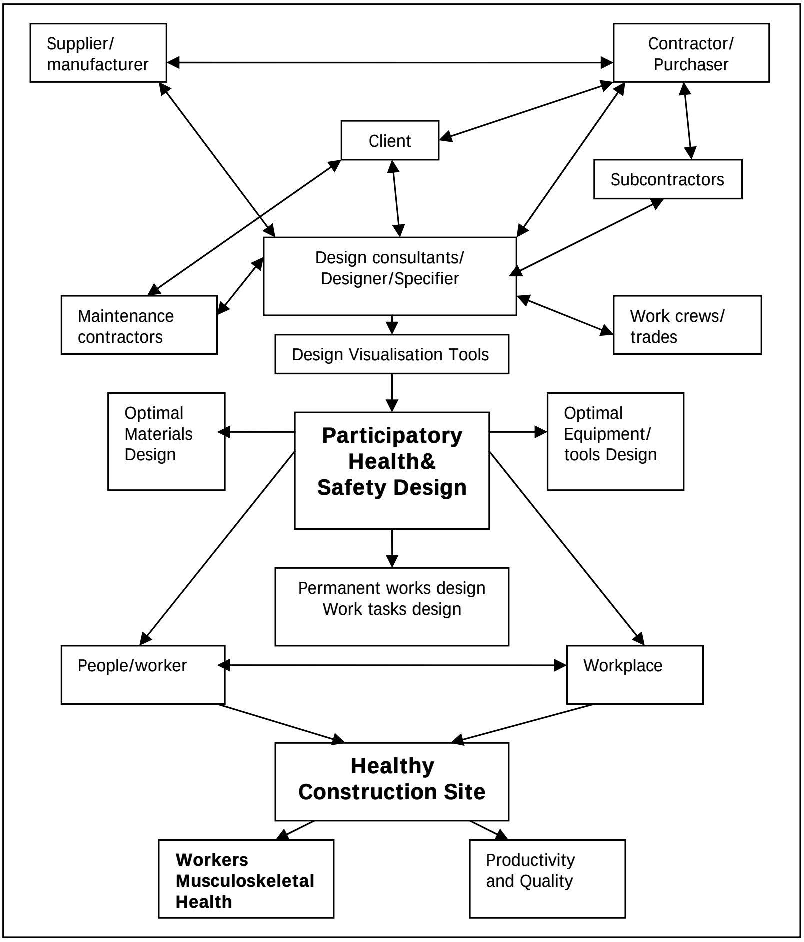



**Figure 7. Model for minimizing the WMSDs through a participatory design process**

The participatory design model in fig.7 shows those important relationships that design professionals should have in order to reach an optimal design that reduces the human and the financial cost. An optimal participatory design for health and safety is reached through the visualization design tools which makes it easier for the stockholders to visualize the construction workplace at early design stages, whereas different solutions can be simulated with 3D and 4D CAD (3D + time element) to reveal if there are any design and space conflicts issues. Visualization that incorporates the sequencing of the construction work tasks into CAD drawing is especially helpful for determining the impact of the construction process on health and safety during different stages of construction work. Designers and other project stakeholders including work crews can visualize the working conditions impacted by the design as it is being constructed (Gambatese, 2004). This visual communication can significantly improve the ability of key stakeholders in a construction project to improve their ability to comprehend designs for constructability and planning a healthy construction workplace for complex building and infrastructure projects. Designers are to get inputs from other stakeholders in a construction project in order to produce a participatory health and safety design that is not detrimental to the workers' health and safety both during the construction phase as well as during the maintenance phase for the end-users; thus the participatory design saves construction projects not only human costs by reducing or eliminating musculoskeletal injuries, as well as saving on financial costs related to productivity and quality.

## 6 Conclusion

There is an opportunity to both protect workers and reduce construction costs through paying attention to human costs during design. This paper showed specific areas where professional designers should consider in their designs in order to reduce or eliminate construction work injuries such as WMSDs. The conceptual model for a participatory design proposed in this paper, shows the vital importance of partnerships between various stakeholders at the project preparation stage. The result of such partnerships at the design stage is of course the participatory health and safety design itself which engenders the most favorable designs in relation to the musculoskeletal health for construction workers and end-users, and enhanced productivity and quality which will benefit many stakeholders especially the client in terms of reduced financial loss.

## 7 References

Behm, M. (2006) An Analysis of Construction Accidents from a Design Perspective. The Center to Protect Workers' Rights. Silver Spring, MD. January.

Dimov, M., Bhattacharya, A., Lemasters, G., Atterbury, M., Greathouse, L. and Ollola-Glenn, N. (2000) Exertion and Body discomfort perceived symptoms associated with carpentry tasks: An on-site evaluation, *American Industrial Hygiene Association Journal, 61, 685-691*.

Gambatese, J. A. (1998). "Liability in designing for construction worker safety." *Journal of Architectural Engineering*., ASCE, 4 (3): 107-112.

Gambatese, J. (2004) An overview of Design-for-safety Tools and Technologies. In S. Hecker, J. Gambatese, and M. Weinstein (eds) (2004). Designing for Safety and Health in Construction. *Proceedings from a Research and Practice Symposium.* University of Oregon Labor Education and Research Center, Eugene, OR.

Gibb, A., Haslam, R., Hide, S. and Gyi, D. (2004) The Role of Design in Accident Causality. In S. Hecker, J. Gambatese, and M. Weinstein (eds) (2004). Designing for Safety and Health in Construction. *Proceedings from a Research and Practice Symposium.* University of Oregon Labor Education and Research Center, Eugene, OR.

Gibb, A.G.F. and Isack, F. (2003) Re-engineering through pre-assembly: client expectations and drivers. *Building Research & Information*, 31(2), 146-60.

Gnaneswaran, V. and Bishu, R.R. (2006) Anthropometric differences among populations. Proceedings IEA2006 Congress, July 10-15, Maastricht, Netherlands.

Haas, C. (1999) Design for Safety. The Field Systems and Construction Automation Group at University of Texas, Austin, USA. August.

Hagberg, M., Silverstein, B.A., Wells, R.V., Smith, M.J., Hendrick, H.W., Carayon, P., Pérusse, M. (1995) Work related musculoskeletal disorders: a reference for prevention; Kuorinka I & Forcier L (eds). London: Taylor and Francis, 1995.

Hecker, S., Gambatese, J. and Weinstein, M. (2005) Designing for Worker Safety, Moving the construction safety process upstream, *Professional Safety*, September 2005, 32-44.

Hecker, S.F., Gambatese, J.A., Weinstein, M. (2006) Designing for construction safety in the U.S.: Progress, needs, and future directions. Proceedings IEA2006 Congress, July 10-15, Maastricht, Netherlands.

ICAF (Industrial College of the Armed Forces), (2000) Industrial Studies. Construction. http://www.ndu.edu/icaf/industry/2000/construction/construction.htm#_edn21.

Kroemer, K.H.E. (2006) *Engineering Anthropometry.* In W.S. Marras and W. Karwowski (eds.) (2006) "The Occupational Ergonomics Handbook" Fundamentals and Assessment Tools for Occupational Ergonomics, 2nd ed., CRC Press, Taylor & Francis Group.

Kroemer, K.H.E., Kroemer, K.B., and Kroemer-Elbert, K.E. (2001) *Ergonomics: How to design for ease and efficiency*, 2nd ed., Prentice Hall, Upper Saddle Rivert, NJ.

Lingard, H. and Rowlinson, S. (2005) *Occupational Health and Safety in Construction Project Management*. London: Spon Press.

Luczak, H., Hinrichsen, S. and Mutze-Niewöhner, S. (2006) *Human in Work System Environment.* In W.S. Marras and W. Karwowski (eds.) (2006) "The Occupational Ergonomics Handbook" Fundamentals and Assessment Tools for Occupational Ergonomics., 2nd ed., CRC Press, Taylor & Francis Group.

Lundholm, L. and Swart, H. (2006) Musculoskeletal ergonomics in the construction industry. Facts & figures in brief No. 5.2006. Swedish Work Environment Authority. http://www.av.se/dokument/inenglish/statistics/Sf_2006_05_en.pdf.

Manuele, F.A. (1997) *On the Practice of Safety*. New York: John Wiley and Sons, Inc.

OSHA (2004) Musculoskeletal disorders in construction.
http://osha.europa.eu/good_practice/sector/construction/msd_construction.pdf

Rwamamara, R.A. (2005) The Healthy Construction Workplace: Best Practices for the reduction of WMSDs among Swedish Construction workers. Licentiate Thesis, Luleå Technology University, Sweden.

Rwamamara, R.A. (2007) Risk assessment and analysis of workload in an industrialised construction process. *Construction Information Quarterly,* 9(2): 80-85.

Samuelsson, B. and Lundholm, L. (2006) Arbetsskador inom byggindustrin 2005. Bygg- och anläggning. Privat sector. BCA 2006:2.

Schneider, S., Punnet, L. and Cook, T.M. (1995) Ergonomics: Applying what we know, *Occupational Medicine*, 10, 385-394.

Schneider, S.P. (1999) Ergonomics in the Construction Industry. In W. Karwowski and W.S. Marrras (eds) (1999). "The occupational Ergonomics Handbook". CRC Press.

Shapira, A. (2007) Equipment For Concrete Building Construction. In E. Nawy (ed.) (2007) Concrete Construction Engineering Handbook. CRC Press.

Simonsson, P. and Rwamamara, R. (2007) Consequence of Industrialized Construction Methods on the Working Environment. *Proceedings of the 15th Annual Conference of the International Group for Lean Construction IGLC 15*, 18-20 July 2007, East Lansing, Michigan, USA.

Toole, T.M. and Gambatese, J. (2006) The Future of Designing for Construction Safety. http://www.designforconstructionsafety.org/Link%20Images/P75%20Future%20of%20DfCS%20toole%20and%20gambatese.doc

Weinstein, W. J. Gambatese and S. Hecker (2005). "Can Design Improve Construction Safety?: Assessing the Impact of a Collaborative Safety-in-Design Process." *Journal of Construction Engineering and Management,* ASCE, 131(10): 1125-1134.

Wright, M., Pavitt, T.C., Gibb, A.G.F., and Bendig, M. (2003) "The Case for CDM: Better, Safer Design – A Pilot Study." HSE Contract Research Report RR148, 2003, Greenstreet Berman, Health and Safety Executive, HSE Books.

V

“*That, which one cannot model, should not be built.*” a contemporary Danish artist

# USING VISUALIZATION TECHNOLOGIES FOR DESIGN AND PLANNING OF A HEALTHY CONSTRUCTION WORKPLACE

Authors

Romuald Rwamamara, Håkan Norberg, Thomas Olofsson, Ove Lagerqvist

Affiliation

[a]eBygg Center, Civil and Environmental Engineering, Luleå University of Technology

Submitted to the Journal of Construction Innovation

**Abstract**

In this age of increasingly complex construction projects, reliable planning of a healthy construction workplace becomes the focus for effective collaboration among the key stakeholders in the construction projects. Already in early stages of the construction design, communication, tools for effective communication of health and safety concerns and their solutions become necessary. The role of 3D and 4D modelling in the pre-production planning of a healthy construction workplace is investigated among project planners. Visualisation through 3D and 4D CAD models has shown a number of benefits for planning for a healthy construction site by addressing health and safety issues in the design of a project; however the 3D and 4D models as they are currently used in the design of construction projects still lack the worker reference frame and the visual interaction between the worker and the permanent as well as the temporary works.

**Key words:** Visualization, 3D CAD, 4D CAD, planning, design, health and safety

## Introduction

The construction workplace is, in terms of occupational health and safety, a high-risk workplace. Construction workers suffer a disproportionate share of occupational accidents and lost-time injuries. These injuries and accidents not only cause many human tragedies, but they also discourage construction workers, disrupt construction processes, delay progress, and adversely affect the cost, productivity, and reputation of the construction industry (Kartam, 1997).

The construction industry has unique characteristics that challenge traditional models of occupational health and risk management. Among these challenges are temporary worksites where workers employed by many different employers may be working alongside each other, frequently improvised work practices, risks caused by both one's own work, and imposed from work done by other trades (Ringen and Englund, 2006).

Many hazardous exposures result from inadequacies in access to information, measurement technology, and personal protective equipment. One of the potential solutions proposed by Ringen et al. (1995) is in the labour-management and site health and safety planning and management.

Historically, the construction workplace has suffered from health and safety problems; particularly this workplace has been plagued with work-related musculoskeletal disorders (WMSDs). Hidden health and safety issues that have not been identified and planned for during the design stage consultation process could potentially lead to injury risks during the production process. It has been difficult to create a true picture of a project before it is built, to see if a particular design approach is not just feasible, but optimal in terms of resulting into a healthy construction workplace.

Traditional design and construction planning tools, such as 2D drawings, hand sketches with site layout templates, Gantt charts and network diagrams, do not support the timely and integrated decision-making necessary to plan for health and safety for the construction workplace. The traditional approaches that represent construction planning information in an abstract textual description of construction activities, lead to the fact that planners must visually conceptualize the sequence of construction, and subcontractors must elaborate the construction plan because it lacks necessary detailing (Dawood and Mallasi, 2006).

Construction is information-intensive and the number of documents increases geometrically with the project size. Construction projects usually involve a large number of direct and indirect stakeholders, all of which must collaborate in the design and construction process. Unfortunately, these individuals often have little experience in construction and less ability to work with design tools such as architectural drawings. Even scale models may be misleading, because actual adjacencies and distances are ambiguous (McGuiness and Bauld, 2007). Current methods of information exchange and communicating building design information among them can lead to various types of problems, including incomplete understanding of the planned construction, functional inefficiencies, and impediments called information filtering and information disconnects

(Wakefield, O'Brien, and Beliveau, 2001). Therefore, a certain level of mutual understanding and know-how between different project stakeholders as well as a close coordination and communication is indispensable. The result is that there are significant barriers to communication between clients, design professionals and contractors, on the one hand, and with sub-contractors and work crews, on the other.

MacKenzie et al. (2000), state that communication is the key to designing health and safety in construction, whereby encouraging designers to think safely will only flourish in an environment where technical information is easily accessible.

Designing for construction health and safety entails consideration of the health and safety of construction workers in the design of a project. Suraji et al. (2001), reveal that a significant number of injuries and accidents originate from conditions of the upstream of the construction process during planning, scheduling and design. Furthermore, research studies (The European Foundation, 1991; Smallwood, 1996; Hecker, 2001; Gibb et al., 2004 and Behm, 2004) have identified the design aspect of projects as being a significant contributing factor to construction site health and safety. Designing to eliminate or avoid hazards prior to exposure on the jobsite is also listed as the top priority in the hierarchy of controls common to the safety and health professions (Gambatese et al, 2005).

Researchers have been investigating the ability of design visualization tools in addressing the problem of information communication in construction projects from their early design stages. Messner et al. (2003) state that visualizing a construction project using tools such as 2D drawings and Critical Path Method (CPM) schedules limit the users' ability to comprehend the impact of design and planning decisions on projects. With recent improvements in computer display technology, Gambatese (2004) in his overview of Design-for-Safety tools and technologies is able to state that CAD systems namely 3D and 4D CAD (which includes the time element) are being used increasingly in the design and construction to facilitate the visualization of the design to expose design conflicts and space issues, thus determining the impact of the construction process on health and safety during different stages of the work.

In the quest to improve the construction planning and work flow, Jongeling (2006) introduced two levels of work flow management, namely, macro- and micro-management. Scheduling of work flow on the macro-level is suggested as an alternative to the common discipline-oriented work breakdown scheduling approach. Micro-level scheduling is suggested to be initiated in the design and production planning process using 3D CAD models from which a bill of quantities can be extracted, structured according to the location-based logic. The micro-management of work flow is intended to be an instrument in the planning and control of the day-to-day construction tasks.

The purpose of this paper is to investigate how health and safety gains and improvements of the construction workplace can be made through the adoption of the current and emerging trends in the development of 3D, VR and 4D CAD visualization and simulation, which have affected or are likely to have an impact on construction project planning.

## Model-based design and visualization tools

*3D CAD modelling*

The 3D design modelling focuses on the design of the building and its spatial construction. 3D visualization techniques allow spatial concepts to be conveyed in an easily understandable form. Common for all stages in the construction process is the extensive use of information. Current 3D modelling tools offer pre-defined objects that facilitate the development, routing, and connection of building systems in 3D, and provide conflict detection mechanisms that help to automatically identify physical interferences between components (Staub-French and Khanzode, 2007).

Parametric three-dimensional (3D) modelling has the potential to replace the age-old paradigm of 2D drawings as the main medium of design, communication and information storage for construction in civil engineering (Eastman et al., 2003). However, Jongeling (2006) argues that the true value of 3D modelling is to establish a common picture and understanding of a project (throughout all stages) for multiple stakeholders and the effectiveness of communication with these stakeholders.

*Virtual reality (VR) technology*

VR is a technology which enables the visualization of large amounts of complex information. Users can navigate freely in real time in a three-dimensional environment. The use of VR in design applications, (VR prototyping) requires that the 3D models from the different disciplines can be imported by the VR system in order to create the virtual environment to be explored. Applications of virtual prototyping have clearly been an area of increasing research and development activities in architecture and construction (Kähkonen, 2003). Research efforts have compiled detailed studies that assess the benefits and limitations of VR and its application at different stages of the construction process (e.g. Messner et al., 2006; Woksepp et al., 2006). Woksepp (2007) concluded in studies of large and complex construction projects that VR can substantially contribute to the quality of the end product as well as reducing costs and lead times by improving the communication and coordination between the stakeholders in the projects.

*4D Modelling*

4D CAD is a technology that has lately come into use in the construction industry. It is generally held to mean the integration of a 3D CAD model with a construction schedule creating a VR model thereby adding the element of time when the different building objects are planned to be realized. Cory (2001) states that 4D CAD focuses on integrating the technical information created in the design and construction phases. Dawood et al., (2003) agree that 4D CAD planning consists of systems where the process is visualized by building the 3D product model through time according to the critical path method. Thus there is a suggestion to work with location-based 4D models in which the flow of work through different types of locations can be planned and controlled at a macro and micro level, by integrating 3D building and 3D space models to linear scheduling methods. Macro and micro applications of 3D and 4D CAD models that are referred to in the study presented in this paper are explained by Jongeling and Olofsson (2007). Koo and Fischer (2000) explain that a 4D CAD model results from the linking of 3D graphic images to the fourth dimension of time. In the 4D model the temporal and spatial aspects of the project are inextricably linked as they are during the actual construction process.

Currently, 4D CAD is extensively used as an explanatory and communication tool in the construction phase (Heesom, 2004). The utilization of 4D visualization allows a more intuitive comprehension of the construction process than the traditional 2D drawings and schedule information (Chau et al., 2003), and provides the user with a clear and direct picture of the schedule intent and helps to quickly and clearly communicate this schedule to different stakeholders in a project, (Jongeling and Olofsson, 2007). 4D models are mainly used as a visual tool, but data can also be extracted from the 4D model providing time-based datasets to assist planners to reason quantitatively in terms of work flow scheduling (e.g. the distance between different construction trades can be analyzed and controlled over time, thereby minimizing the risk for conflicts in terms of space usage on the construction site).

**Methods**

The purpose of the interviews was to identify the advantages of the use of two virtual design tools namely 3D CAD and 4D CAD in the planning for health and safety issues in the construction work environment.

Semi-structured, in-depth interviews were conducted with project planners involved in the design process of building facilities in Sweden. The interviews were fully recorded on audio tapes and transcribed thereafter for analysis. The analysis followed a three stage process of data management; data reduction, data display, verification and conclusion drawing, as proposed by Miles and Huberman (1994). The planners came from three of the four largest construction firms in Sweden. Interviews with the project planners were planned to provide the insights that might be necessary not only for future potential users of these virtual tools, but also for potential future improvements of these design tools. The construction planners were asked to answer to the interviews open questions related to the areas:

- Interest in designing for health and safety: this area's questions sought to assess the project planners' functions in relationship to designing health and safety in construction.
- General application of 3D and 4D CAD in the design of health and safety: this area wanted to assess the project planner's familiarity with 3D and 4D tools. This section also includes questions on advantages and disadvantages of the use of 3D and 4D in a nutshell.
- Macro application of 3D and 4D CAD in health and safety issues assessment: this section gathered information on the accuracy of 3D and 4D models in comparison to the real construction work environment; what do these virtual tools have to offer to different key project stakeholders and how in general do the 3D and 4D models help reduce injuries and accidents.

- Micro application of 3D and 4D modelling of the work environment: this section assesses how the 3D and 4D modelling helps in a more detailed manner the planning for health and safety in the construction work environment.

The 3D and 4D models were also examined in three construction projects all of which have used 3D models to design the building facilities, however only one of these projects has simulated their construction project using 4D. The observations' focus was on three areas namely the logic or technical dependency among activities of a schedule, the space congestion and collisions. During these observations, relevant snapshots from a 4D model used by one of the projects investigated were used to illustrate some points made in the interviews.

**Case study objects**

*Västerport* is a construction project in the Stockholm area (construction period extending from June 2006 to June 2008). This building project consists of four building blocks of around 20 400 square meters of office space and about 9 500 square meters of garage and storage spaces divided into 7 floors of which two floors represent garages and storage rooms. Fifty-five construction workers were employed in the project production in August 2007 when the project was studied. The project design was performed using 3D CAD modelling tools.


Figure 1. A drawing showing the Västerport project with its seven-storey buildings.

*Hotellviken* is a residential construction project which started in summer 2005 and aims to finish in 2008. The construction project consists of 110 flats and town houses. In our study we only investigated a part of the project which is a building facility made of five building blocks, four of which will accommodate 30 residential apartments and the fifth building block will be a public facility. The project used 4D CAD simulation during the design and planning process (see figure 2a).

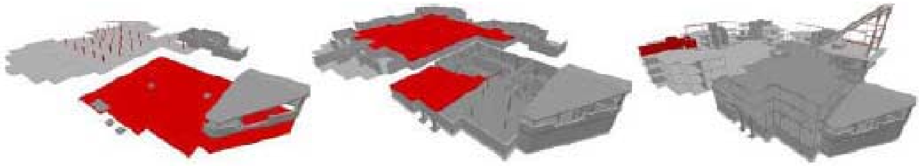


Figure 2a. Visualisation with time linking in the Hotellviken project

Figure 2b. Hotellviken, virtual picture of a part of the building

*Boden's sport arena* (figure 3a) is a construction project worth 12.5 million Euros which consists of many sports facilities including a three-storey building for dressing rooms, cafeteria and restaurant. This project started in summer 2007 and will end a year later in 2008. The multi-arena is going to have sports halls of 1 900 square meters, a soccer stadium of 12 000 square meters and the restaurant, cafeteria and dressing rooms on 2 400 square meters. Sixteen construction workers are involved in this multi-arena building construction. The project planners have designed this multi-arena using 3D CAD modelling (see figure 3b).

Figure 3a. A 3D virtual overview picture of the Boden's multi-arena

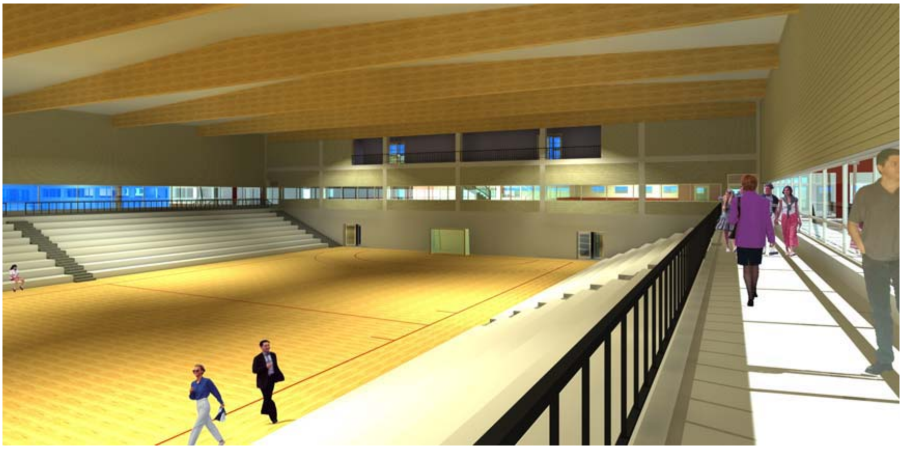


Figure 3b. A 3D snapshot of a sport hall of Boden's multi-arena, Sweden

## Results

The three projects were different in terms of their final purposes namely, office and garage buildings, residential and entertainment facilities and soccer arena with guests facilities.

The interviews with the construction planners revealed that there is a strong interest in workers' health and safety issues, however the planners expressed that it is not often that they get asked about these issues and how they deal with them in their designs.

*General application of 3D and 4D CAD in the design of health and safety*

In regard to the general application, three planners out of five revealed that they have never used 4D CAD modelling in any project designs they have been involved in in the past and that it was only in recent months that they have heard of 4D CAD simulation in building design for the first time. Although planners admitted that 3D CAD modelling has been applied only on a few construction projects designs, they still claim that there is an increasing recognition of numerous benefits it offers to their construction firms as well as to other project participants. According to the projects planners, the use of the 3D and 4D modelling by construction firms is primarily motivated by the economic benefits such as productivity through elimination of rework and reduction of uncertainties due to the lack of adequate communication.

In general, the project planners stated that planning for health and safety at early stages of the design phase was facilitated by the ease of communication offered to all projects participants. Project planners have expressed that the use of 3D and 4D modelling provides a platform for early cooperation and coordination between consultants and subcontractors. Project planners added that visualization of the construction process before it starts, becomes a communication channel through which solutions to detected health and safety issues, can be discussed between projects stakeholders especially work groups and property developers. Furthermore, planners have stated that modelling the construction facilities at the design stage allowed contractors and sub-contractors to understand easily what is going to be built and how it is conceived.

According to the planners, the 4D CAD visualization of the workflow allowed subcontractors to make early decisions to avoid congestions and work space conflicts; thus planning the workspace effectively between different construction trades. It was further mentioned by planners that 3D-4D modelling unlike 2D drawings does benefit the planning for the work tasks performed at height, thus helping the contractors to plan into the production adequate lifting aid devices of heavy materials as well as the lifting of workers themselves in order to perform their work tasks at a proper working height.

With the help of 4D CAD visualization, MEP (Mechanical, Electrical and Plumbing) installations (see figure 4) can be simulated to identify the difficulty involved in their installation or assembly of prefabricated components. Figure 4 shows an example of collision detected between installations. This kind of collision detection invites early corrections in the design in order to prevent future reworks that could induce injury risk factors at the production stage.

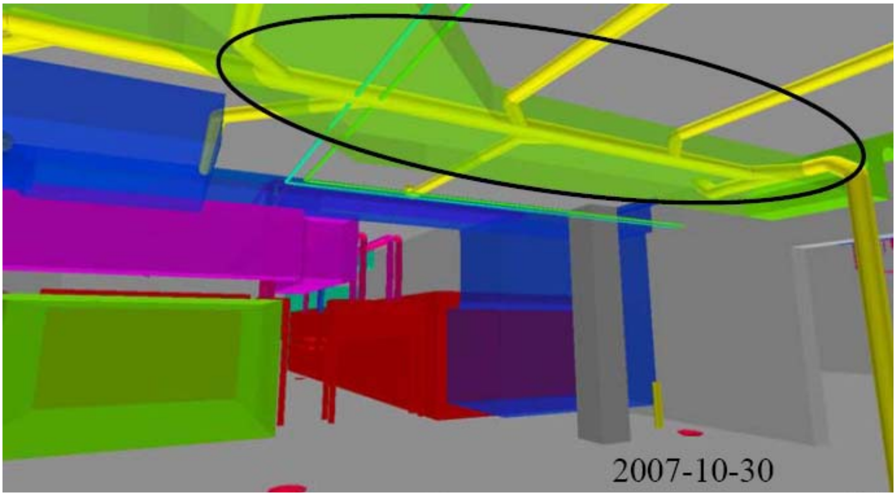



Figure 4. HVAC installations collision detected in a black circled area

Visualizing the construction work flow through a 4D CAD model makes it easier for the project participants to organize the availability and logistics of equipment and materials. This especially applies to heavy building materials that should be lifted in by a crane before covering the floor where the heavy materials will be needed. An example of this is shown in Figure 5.

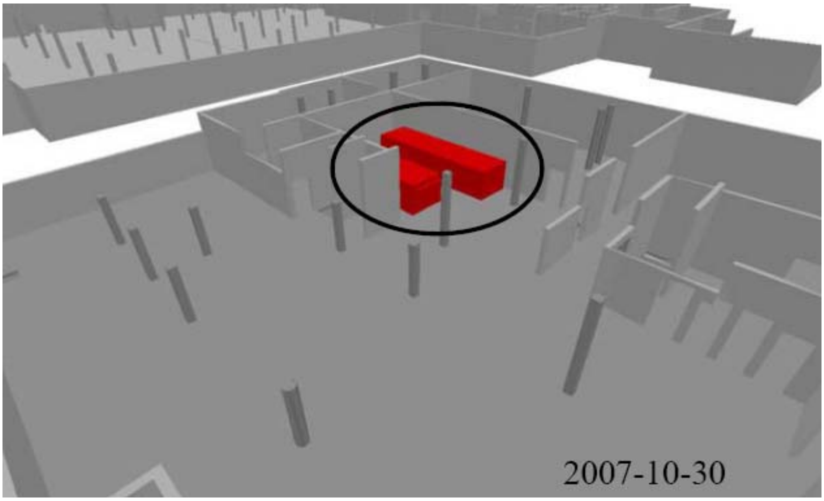



Figure 5. Two heavy building components to be lifted into the floor by a crane

Height differences in both 3D and 4D CAD models are easily noticeable compared to using 2D drawings. It is important to be able to detect different heights in order to plan for workers safety guards and materials lifting devices. An example of this is illustrated in figure 6.

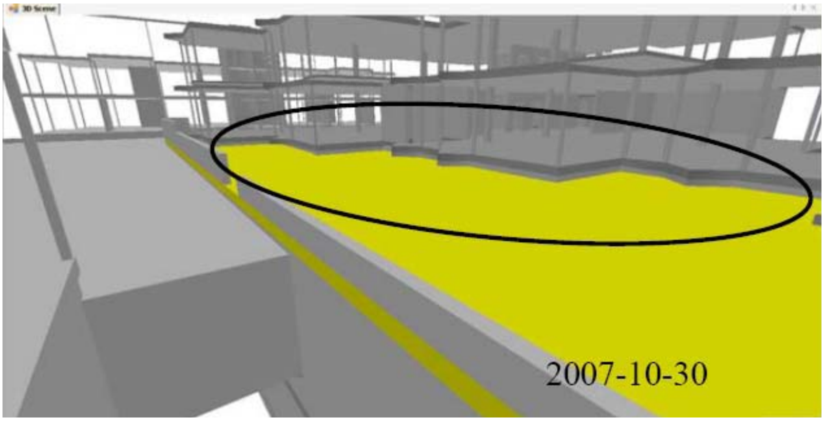



Figure 6. Noticeable height differences enhanced by colour highlights

In figure 7, there is an illustration of a mistake in the building materials specification, where the prefabricated pillar protrudes through the floor above, this specification mistake is easily visualized and can be prevented before production commences. When this type of design amendment is made, it spares construction workers a lot of unnecessary and awkward work tasks such as rework, fixing. In one of the projects investigated in this study, it was indicated that 3D and 4D visualisation helps to significantly reduce the situations of space conflicts and non-standard work in confined spaces. Furthermore, site managers in one of the projects have expressed that through the use of 3D and 4D visualisation they use only one-tenth of the time they normally use to solve space conflicts and mistakes compared to similar projects using conventional design and planning methods.

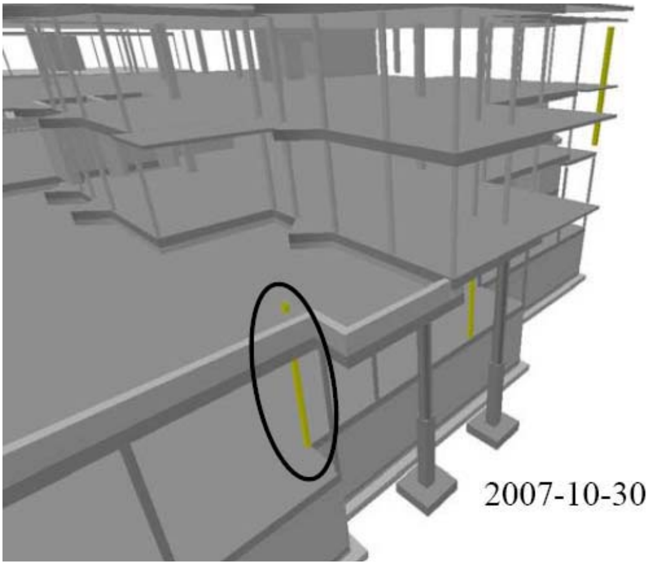



Figure 7. An example of a design specifications error

Those planners working with 3D models in the projects investigated have expressed that these models are limited in terms of how many risks they allow the planner to detect, especially because they do not show the work sequence of the production process.

***Macro application of 3D and 4D CAD in health and safety issues assessment***

As far as the interviews results are concerned, this section explored the extent to which there is an agreement between the virtual models and the reality of future work environment, the influence of 3D and 4D CAD models on decisions about the construction work environment, the contributions of different stakeholders in the design stage and the way potential work injuries are eliminated through 3D and 4D CAD modelling.

On the agreement between the virtual models and the reality of the future work environment, the planners state that their experience with 3D and 4D CAD models is that these models do agree and should agree with the real work environment right from the beginning. For those using only 3D CAD models, they reckon that these models have a very good precision which they roughly estimated to be at least 95%.

Concerning how the 3D and 4D CAD models help the planners to make early decisions, the planners said that these models have helped them in planning production work tasks sequencing, so that no work crew stands in the way of another and lifting devices equipment are made available on time for HVAC workers for specific installation scheduled times.

3D and 4D CAD models were also used as a communication tool between stakeholders who visualized the needs as far as future maintenance services required by the building facility are concerned. Two of the planners gave as an example the access into the attic which can be visualized by stakeholders such as the client and contractors to see that there is easy accessibility and that this workspace is not confined for HVAC workers and has an easy access for future maintenance workers. In all these projects where 3D CAD models were used, it was much easier for HVAC workers to see what materials were going to be used and the sizes that were going to be handled either by the work crews or by the lifting devices available. In the interviews, planners stated that 3D modelling is also seen as a partnering tool between various subcontractors, the contractor and other key actors in a construction project.

Possible reduction of work injuries through 3D and 4D CAD modelling was mainly attributed to the visualization of logical sequencing of work tasks, the avoidance of workspace congestion and elimination of collisions which could create unnecessary work and awkward work positions for work crews.

*Micro application of 3D and 4D modelling of the work environment*

This section investigated four areas namely, the 3D and 4D support to the site planning task, the degree to which these virtual design tools support the analysis of health issues in the design and planning phase, the health and safety areas which 3D and 4D models help determine or monitor and how 3D and 4D CAD models relate to certain data flows.

Sequencing of work tasks was brought up often by the planners to explain how the 3D and 4D CAD models contain construction sequences and use the logical sequencing of work tasks in order to avoid clashes between work crews or even space congestion by organizing different resources on the construction site.

Project planners stated that 3D models do support the identification and analysis of health and safety issues prior to production start. With the specifications for building techniques and installations in mind, 3D models help the subcontractors to check if a good work environment is considered in the planned production process. Construction work methods such as off-site production and on-site assembly of prefabricated building components are made easy by 3D CAD models which contain all the relevant information for safe manufacturing and assembly of the prefabricated elements. Robots in the factory prefabricate building components according to 3D CAD modelling specifications.

The planners in the investigated projects enumerated two areas of the construction workplace's health and safety where 3D and 4D CAD models do or could help determine or monitor, and these were setting up a safe workspace and early identification of what personal protective equipment would be needed for the yet to come production phase. 3D and 4D modelling allows design changes in order to create safe working spaces and heights for workers.

From their experiences, the planners have further identified which data flows 3D and 4D CAD models deal with, these being:

- Method statements where work procedures and construction methods are explained visually to those who are to execute the work tasks; workers and other actors can also see in a simple way which work crew is working with what first.
- Design problems communication: collision detection and other design problems can be communicated easily between the stakeholders.
- Resource planning can easily be visualized and adjusted through 4D CAD simulation.
- Both 3D and 4D CAD modelling give room to simulate what-if scenarios in order to identify and evaluate what impact certain designs might have on the construction work environment and work-related health.

## Discussion and conclusions

The use of visualisation technologies in the design and planning of a healthy construction workplace was discussed in interviews with the project planners that had used 3D and 4D CAD models in their construction projects. The projects planners expressed their interest in issues regarding the workers' health and safety. This attitude might be a good starting point to considering construction work environment issues in the design models they work with.

Interviewees mentioned that 3D and 4D visualisation tools were not common in construction projects design and planning; this point of view is related to those projects they have worked with in the past and those projects they are familiar with. The reason given for this uncommon use of 3D and 4D virtual tools was that they were new, however the real reason seems to be linked to the cost and the lack of training in the use of the innovative tools which might intimidate due to a sense of inadequacy that might be felt by older project planners and other users in the project..

Having mentioned these constraints, project planners said that they have noticed a growing interest in 3D and 4D modelling due to its economic benefits in regard to increased productivity associated with elimination of design conflicts, workspace conflicts that lead to rework and stressful and awkward work postures. Besides these so-called economic benefits, the working environment is improved when most of design conflicts are identified prior to construction; it results in a healthy and safe construction process for MEP subcontractors.

The interviewees expressed that 3D and 4D technologies have afforded them and other project participants an adequate communication tool through which problems were identified and addressed. Examples of identification of collisions, height differences and materials size were easily observed through 3D and 4D models, and thus rework and heavy manual material handling could be avoided through other design alternatives, lifting devices and planning a logical work tasks sequencing. Here, it is especially the 4D model that allowed all members of the work crew to visualise their tasks and the relationships that exist between the work of the different construction trades in the future or actual site.

The interviewees mentioned that 3D and 4D technologies gave all stakeholders the possibility to visualize a building design and allowing design changes in the workspace and height lead to a healthy worksite for the workers. Weinstein et al. (2005) supports this statement in their studies on construction worker safety where he found that by providing more space and height for a variety of workers, these design changes reduced ergonomic risks and likely alleviated problems related to congestion, access and material handling; and thus the worker could work standing rather than in awkward or constrained postures which contribute to the risk for WMSDs.

Furthermore, interviewees argued that 3D and 4D visualization gave them an opportunity to simulate alternative scenarios and assess the benefit and detriment of optional design approaches as far as health and safety of workers is concerned.

In conclusion, the most important benefit frequently mentioned in the study's interviews on the use of 3D and 4D models is that through these visualization tools, the healthy construction workplace design process is becoming more of a collaborative effort, involving the design and building contractors, the owner's procurement team in charge of supervising the project, their consultants, workers representatives from contractors and subcontractors and the eventual users who will have to make use of the facility.

Finally, the study in this paper has investigated construction site health and safety possibilities afforded by the use of 3D and 4D visualization. These virtual tools proved to be an adequate communication channel at the design stage for planning a healthy construction workplace and thus improving workers health and safety. Furthermore, through the exchange of knowledge, all designers and other project stakeholders were able to make known to each other through the 3D and 4D visualization, their respective considerations for improving health and safety in the course of designing.

## Future improvements to 3D and 4D CAD

Improvements to be investigated include construction tasks modelling using visualization tools that adapt tangible products and processes to human capabilities during the design process to improve the task performance, the physical comfort and the health and safety of construction workers. Therefore, to incorporate ergonomic considerations in a purely digital (CAD) phase, early in the design process, a designer will need digital representations of the future users or avatars.

## Acknowledgements

The authors gratefully acknowledge the contribution made by senior planners from three Swedish construction companies who provided project data and valuable answers in the interviews. The financial support for this research study came from The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) and The Development Fund of the Swedish Construction Industry (SBUF).

**References**

Behm, M. (2004). "Establishing the link between construction fatalities and disabling injuries and the design for construction safety concept." PhD dissertation, Oregon State Univ., Corvallis, Ore.

Chau, K.W., Anson, M., and Zhang, J.P. (2003) "Implementation of visualization as planning and scheduling tool in construction." *Building and Environment*, 38(5), 713-719.

Cory, C. A. (2001) "Utilization of 2D, 3D, or 4D CAD in construction communication documentation." *Fifth International Conference on Information Visualization,* London, UK CSR Hebel Technical Manual.

Dawood, N. and Mallasi, Z. (2006) Construction Planning: Assignment and Analysis Utilizing 4D Visualisation Technologies. *Computer-Aided Civil and Infrastructure Engineering,* 21, 498-513.

Dawood, N., Sriprasert, E., Mallasi, Z., and Hobbs, B. (2003) "Development of an integrated information resource base for 4D/VR construction process simulation." *Automation in Construction*, 12(2), 123-131.

Eastman, C. M., Lee, G., and Sacks, R. (2003) "Development of a Knowledge-Rich CAD System for the North American Precast Concrete Industry." *ACADIA 22:Connecting-Crossroads of Digital Discourse*, Indianapolis, IN, 208-215.

European Foundation for the Improvement of Living and Working Conditions, (1991) *From drawing board to building site*, HMSO Books, London.

Gambatese, J. (2004). An Overview of Design-for-Safety Tools and Technologies. In S. Hecker, J. Gambatese and M. Weinstein (eds). Designing for Safety and Health in Construction. *Proceedings from a Research and Practice Symposium*. University of Oregon Labor Education and Research Center, University of Oregon Press.

Gambatese, J., Behm, M., Hinze, J.W. (2005) Viability of Designing for Construction Worker Safety. *Journal of Construction Engineering and Management,* September 2005, 1029—1036.

Gibb, A., Haslam, R., Hide, S., and Gyi, D. (2004) "The role of design in accident causality." *Designing for safety and health in construction: Proc., Research and Practice Symp.*, S. Hecker, J. Gambatese, and M. Weinstein, eds., UO Press, Eugene, Ore.

Hecker, S., Gibbons, B., and Barsotti, A. (2001) "Making ergonomic changes in construction: Worksite training and task interventions." *Applied ergonomics*, D. Alexander and R. Rabourn, eds., Taylor & Francis, London, 162–189.

Heesom, D. and Mahdjoubi, L. (2004) Trends of 4D CAD applications for construction planning. *Construction Management and Economics*, 22, 171-182.

Jongeling, R. (2006) A process Model for Work-Flow Management in Construction. Doctoral Thesis, Luleå Technology University, pp. 65.

Jongeling, R., Olofsson, T. (2007) "A method for planning of work-flow by combined use of location-based scheduling and 4D CAD." *Automation in Construction*, 16(2), 189-198

Kartam, N.A. (1997) Integrating Safety and Health Performance into Construction CPM. *Journal of Construction Engineering and Management*, June 1997, pp-121-126

Koo, B., and Fischer, M. (2000) "Feasibility study of 4D CAD in commercial construction." *Journal of Construction, Engineering and Management*, 126(4), 251-260.

Kähkönen, K. (2003) Editorial: Virtual Reality Technology in Architecture and Construction. *Electronic Journal of Information Technology in Construction (ITcon)*, 8, 101-103.

MacKenzie, J., Gibb, A. and Bouchlaghem, N.M. (2000) Communication: The Key to designing safely. *Designing for safety and health conference*, June 2000.

McGuiness,K. and Bauld, S. (2007) "Seeing is believing: Virtual reality can save you money". *Summit*, March 2007.

Messner, J.I., Riley, D.R. and Moeck, M. (2006) Virtual facility prototyping for sustainable project delivery, *ITcon*, 11, 723-738.

Messner, J., Yerrapathruni, S.C.M., Baratta, A.J. (2003) Using Virtual Reality to Improve Construction Engineering Education. *Proceedings of the 2003 American Society of Engineering Education Annual Conference & Exposition.*

Miles, M.B. and Huberman, A.M. (1994) Qualitative Data Analysis: An Expanded Sourcebook. Sage Publications.

Ringen, K., Seegal, J. and Englund, A. (1995) Safety and Health in the Construction Industry. *Annual Review of Public Health*, 16, 165-188.

Ringen, K. and Englund, A. (2006) The Construction Industry. Annals New York Academy of Sciences, 1076(1), 388.

Smallwood, J. J. (2004) "The influence of engineering designers on health and safety during construction." *J. South African Institution Civil Engineering, SAICE,* **46**(1), 2–8.

Staub-French, S. and Khanzode, A. (2007) 3D and 4D modelling for Design and Construction Coordination: Issues and Lessons Learned. *ITcon* Vol.12, pp. 381-407.

Wakefield, R., O'Brien, and Beliveau, M. (2001) Industrializing the residential construction site: Phase II Information Mapping. Report, U.S. Department of Housing and Urban Development, Washington, DC.

Weinstein, W., Gambatese, J. and Hecker, S. (2005) Can Design Improve Construction Safety?: Assessing the Impact of a Collaborative Safety-in-Design Process. *Journal of Construction Engineering and Management*, ASCE, 131(10): 1125-1134.

Woksepp, S. and Olofsson, T. (2006) Using Virtual Reality in a large-scale industry project, *ITcon*, 11, 627-639.

Woksepp, S. (2007) Virtual Reality in Construction: Tools, Tools, and Processes. Doctoral Thesis, Luleå University of Technology, Sweden, 77 pages.