

Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Ecology
and Natural Resource Management

Philosophiae Doctor (PhD)
Thesis 2014:40

Human Factors and Work Studies in Norwegian Cable Yarding Operations

Ergonomi og arbeidsstudier i
taubanebasert hogst i Norge

Giovanna Ottaviani Aalmo

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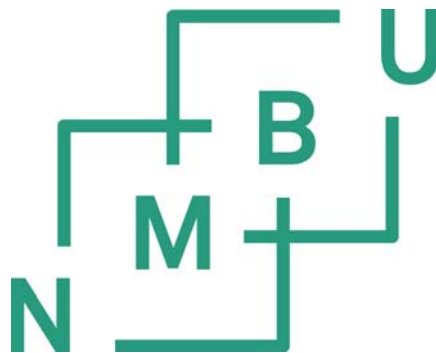
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Preface

This thesis has been submitted in partial fulfilment of the requirements for the degree of Philosophiæ Doctor (PhD) at the Norwegian University of Life Science (NMBU), Department of Ecology and Natural Resources Management (INA). The work has been carried out at the Norwegian Forest and Landscape Institute and it was funded by the Norwegian Research Council through the project “Increasing wood deliveries and environmental quality” referred as “Greenwood”, project n. 186912.

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Ås, March 2014

Giovanna Ottaviani Aalmo

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Summary

This thesis focuses on finding ways to increase the productivity of cable yarding operations through examining the relationship between workers, the harvesting system and the physical environment.

The investigation was conducted through four case studies. Each of them considers a different aspect of the research question and employs different methodologies.

In the first case study, a typical econometric statistical methodology called Stochastic Frontier Analysis was used to relate inefficiency to the macro-ergonomic aspects of steep terrain harvesting tasks. It was found that the physical work environment partially explained the inefficiency rate found from the model.

The second and third cases focussed more on the physical-ergonomic aspects of the rigging tasks with the intention of providing solutions to relieve the workload and improve guidance in selecting the right crews for these very heavy tasks. It was found that in the first case; the use of lighter equipment reduces workload. The findings also indicated that for rigging tasks young and fit workers perform better.

The last case investigated the benefits of specific training to increase both productivity and safety. Using Mixed Effects Models to predict the dependent variable, it was found that there is an evident improvement in both aspects.

The implications of reducing the workload go beyond just an ergonomic benefit. Reduced workloads also represent a positive social and economic impact. Safer harvesting techniques make the work more appealing to workers while at the same time, reduce the risks of accidents hence limiting the periods of absence from work because of injuries; or in the worse cases losses to fatalities. Reducing work strain, danger or discomfort, emphasizing and increasing the operators' capacity and skills and improving the team organization and communication in cable yarding work was demonstrated to be beneficial for the industry through improved productivity and safety in the Norwegian case and in the long run might prove to have a positive effect on recruitment and retention within the forestry sector.

Key words: Human Factors, Steep Terrain, Cable Yarding, Norway.

Sammendrag

Denne avhandlingen fokuserer på å finne måter å øke produktiviteten i taubane-operasjoner ved å undersøke forholdet mellom arbeidsstokk, hogstsystem og det fysiske miljøet.

Undersøkelsen ble utført gjennom fire case-studier. Hver studie vurderer ulike aspekter ved spørsmålet og benytter ulike metoder.

I det første tilfellet ble en typisk økonometrisk metode benyttet: Stochastic Frontier Analysis. Slik kan man kvantifisere makro - ergonomiske effekter som bratt terreng har på arbeidsoppgaver knyttet til hogst. Gjennom den statistiske modellen fant man at det fysiske arbeidsmiljøet – delvis - kan forklare arbeidslagets variasjoner i effektivitet når de utfører hogst-oppgaver.

Det andre og tredje studiet gikk dypere inn i fysiske - ergonomiske aspekter ved riggingoppgaver. Her så man på løsninger som har til hensikt å lette arbeidsmengde, så vel som arbeidsoppgaver, samt økt fokus på veiledning ved å velge riktige mannskaper til svært tunge arbeidsoppgaver. Man fant at i det første tilfellet vil lettere utstyr redusere arbeidsmengden og belastningen, samt at unge og spreke arbeidstakere bedre og lettere utfører oppgaver knyttet til rigging av tungt hogstutstyr.

Den siste studien undersøkte fordelene med spesifikk trening for å øke både produktivitet og sikkerhet. Mixed effect modeller ble benyttet for å forutsi den avhengige variabelen, og man fant at det ved å benytte spesifikk trening ser man tydelig forbedring på begge de to ovennevnte områdene.

Effekten av redusert arbeidsbelastning innebærer mer enn bare en ergonomisk fordel, men har også en positiv sosial og økonomisk betydning. Sikrere hogstarbeid med redusert belastning er mer attraktivt for arbeiderne og reduserer samtidig risikoen for ulykker hvilket igjen bidrar til reduksjon av sykefravær og reduserer antallet arbeidsulykker med tragisk/fatalt resultat. For norsk skognæring kan redusert arbeidsbelastning, redusert fare eller ubehag, økt fokus på å øke operatørens kapasitet / kompetanse, samt å forbedre teamorganisering og kommunikasjon i taubanebasert hogstarbeid, vise seg å være gunstig for bransjen som sådan. Tiltakene som beskrevet i studiene kan - for norsk skognæring - bidra til bl.a. økt rekruttering og produktivitet, samt lavere frafall og sykefravær i arbeidsstokken.

List of Papers

This thesis is based on the following articles, which will be referred to in the text by their Roman numerals:

- I. Ottaviani Aalmo, G., Baardsen, S. 2013. Environmental factors affecting technical efficiency in Norwegian steep terrain logging crews: a stochastic frontier analysis. Accepted by Journal of Forest research
- II. Ottaviani Aalmo, G., Talbot, B., Nitteberg, M., Stampfer, K. 2011 Workload benefit of using a synthetic rope strawline in cable yarder rigging in Norway. Croatian Journal of Forest Engineering 32(2):561-569
- III. Ottaviani Aalmo, G., Magagnotti, N., Spinelli, R. 2013 Forest workers and steep terrain winching: the impact of environmental and anthropometric parameters on performance. Submitted
- IV. Ottaviani Aalmo, G., Talbot, B. 2013 Operator performance improvement through training in a controlled cable yarding study. International Journal of Forest Engineering. *Published online: <http://dx.doi.org/10.1080/14942119.2014.904150>*

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To Adam, Aaron and Alex

1. Introduction

1.1 Background

Thirty six percent of the European Union surface area is covered by forests half of which are located in mountainous areas. Sixty percent of the forests in EU-27 Member States are privately owned with an average ownership size of 13 ha (Schmithüsen et al. 2010). This small ownership pattern is even more prominent in mountain forests where there is an over-representation of small fragmented ownership reaching sizes as small as 3 ha and less (Guitton et al. 2012).

In addition to the side challenge of small and fragmented holdings, the obstacles to making profitable the utilisation of the abundant available resources, are generally represented by the lack of infrastructure, a common problem in many of the mountain forest areas in the EU countries, and a lack of specific competence (Guitton et al. 2012). There is therefore a need to acquire better understanding of mountain forests utilization in order to make a sustainable and profitable use of the available resources while protecting these fragile ecosystems.

In Norway the challenges of adjusting the level of harvesting activity in the forests to the resources availability, are mainly related to the fact that the largest potential for increase is attainable in the more remote and difficult regions which are also the most complex in terms of access, forestry tradition, and preservation.

Some 150 million m³ (solid under bark) of mature or maturing timber are becoming available on slopes with an inclination steeper than 33% (steep). Of this, over 60 million m³ is on slopes exceeding 50% (very steep) (Larsson and Hylen 2007). On the other hand, the annual commercial removal is roughly 8 million m³ (95% CTL), with another c.2 million m³ harvested by owners and users (SSB 2012) indicating that the annual growth of Norwegian forests is considerably larger than the annual harvest for industrial and private consumption (figure 1).

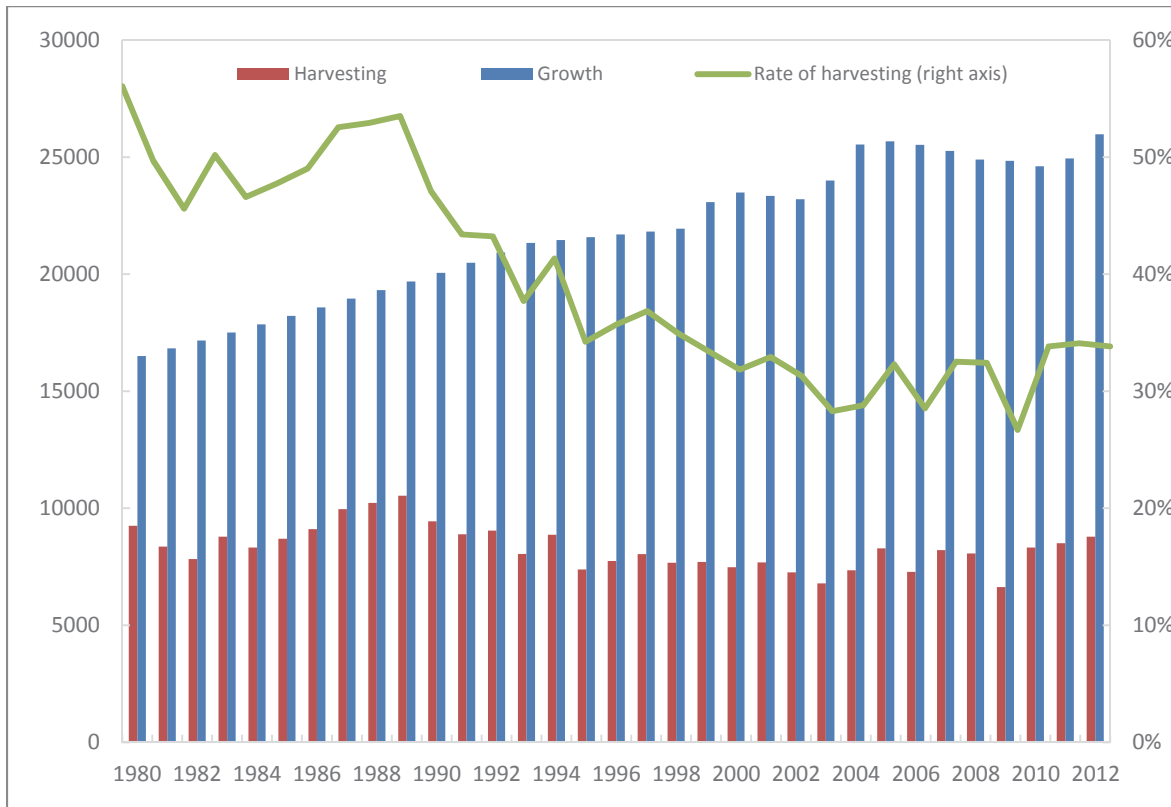


Figure 1: The difference between the annual harvesting and growth in Norway since 1980 (Bergsaker 2014).

There are a number of reasons for the under-utilisation of this sustainable resource in Norway, the primary one is the decline of global markets for forest products. In 2012/2013 pellet plants (e.g. BioWood) and paper producers (e.g. Tofte papirfabrikk, Peterson and Norske Skog Follum) shut down because of the market crisis. However, even in periods of economic growth, utilisation never exceeded 50% of the annual allowable cut (Bergsaker 2014). In Norway there is generally a strongly skewed distribution of activity to areas that are more accessible to fully mechanised harvesting systems, and closer proximity to the established and the Swedish markets. The Norwegian west coast, being characterised by steep and difficult terrain, shows a lower level of forestry activity and in most cases harvesting is taking place for the first time.

The timber revenues in Norway are quite stable due to the little alternative in timber species. Plantation forests (*Picea* spp.) were established in the 1950s through 1970s on the steep slopes of the west coast, building a substantial harvesting basin; but the terrain and poor road infrastructure implied that the selected harvesting system needs to be highly efficient in order to make the utilization worthwhile.

The net profit to the forest owners is an important factor for determining the harvesting level, as it increases the forest owners' willingness to harvest. One important means to increase profits is to reduce the costs of forest operations by improving effectiveness and efficiency.

In addition to system costs, system productivity is the main factor influencing operations efficiency (Kellogg et al. 1992). The productivity of a specific system depends on several definite factors. For steep terrain harvesting systems and, more specifically, for cable yarding systems besides the terrain steepness, these can be tree volume, yarding distance, lateral yarding distance, yarder type, working system, silvicultural treatment (Heinimann et al. 1998; Ghaffariyan et al. 2009) but also the operator and crew efficiency and machine interaction. The operator and crew efficiency is highly correlated to the well-being both in terms of workload (so health) and safety (Konz and Johnson 2000; Nicholls et al. 2004).

The challenge of increasing the proportion of the annual cut from steep slopes can partly be met by increasing cable yarding activity and productivity (Landbruksdepartementet 2004).

1.2 Steep terrain harvesting operations

Conventionally, on sites with slopes between zero and 33 percent (up to moderate), ground based systems can be used when the soil type and conditions are suitable. If the soil is too sensitive or the slope is greater than 33 percent (steep and very steep terrain) (Rowan 1977), traditional cable systems are employed, though higher costs associated with cable yarding systems and technical developments have led to a broadening of the use of ground based systems on steeper areas (LeDoux 1985).

When the terrain is severely uneven or there is no way to get a road to the site to facilitate yarding and the profitability is assured, helicopter logging could represent an option.

Ground based operations are generally least expensive followed by cable systems, with helicopter logging being the most expensive and requiring high level of organization (Stampfer et al. 2002).

1.3 Cable based systems

In Norway, topography and surface conditions are often challenging for wheel based harvesting systems applied to steep terrain even though they are widely employed. In this research only cable systems were considered (figure 2).

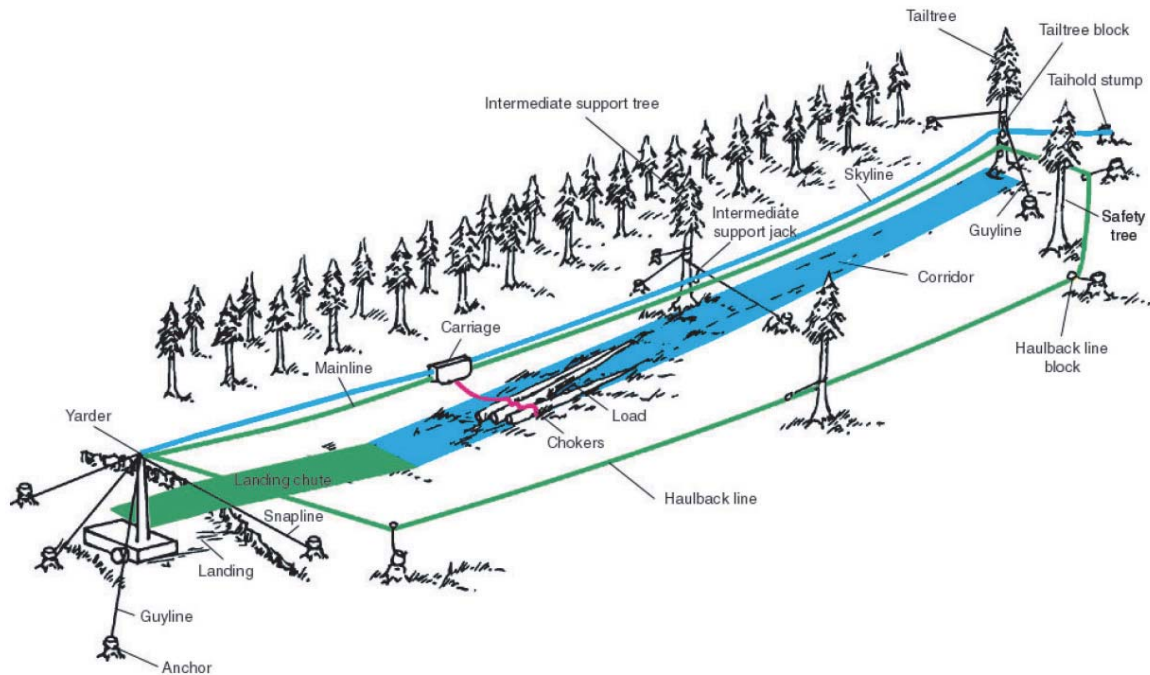


Figure 2: Overview of the general layout of a skyline system, indicating the system terminology (FESA 2001)

1.3.1 Working principles

Cable yarding systems can be set up in a number of different configurations. In Europe, two families of configurations are mostly used: standing skyline and running (or live) skyline with a strong predominance of the former. The main feature of a standing skyline layout is that the skyline cable remains fixed or anchored at both ends. A standing skyline setting can be used with a manual, mechanical or motorized slack pulling carriages. The running skyline configuration employs two lines: haul-back line and mainline, the lines can be raised and lowered by varying the tension between them. This system typically uses interlocking main and haul back line drums (FESA 2001). When operating with a mechanical slackpulling carriage, three drums are required, a mainline, haul-back line, and slackpulling line. With other carriages there are only two drums required, as mentioned above.

1.3.2 Operational details

Operating a skyline system requires the presence of a crew which in Norway typically consists of 3 people: a machine operator, a feller and a choker setter.

On a general basis, in a standing skyline configuration the machine operator dispatches the carriage which in many cases retraces its path to its origin or some pre-programmed increment from there. The choker setter can take control of the carriage, releases the drop line and choke the trees. He then moves to a safe position, lifts the drop-line and sends the carriage back to the point where control is returned to the machine operator.

In the case of running skylines the operation becomes a more intensive and complex work involving a uniform cyclic repetition of consecutive work elements. The sensorimotor and cognitive work challenges described by Gellerstedt (2002) for a single-grip harvester, could be to a certain extent approximated to the ones for using the controls of a running skyline suggesting the complexity of these tasks.

1.3.3 Advantages/disadvantages for the two settings: standing or running skylines

The standing skyline configuration employs one line in bearing heavier payloads than the running in which two lines carry the loads. Using heavier cables the set up time of the standing configuration is often longer and more demanding. It is less versatile as it places far higher demands on the anchoring requirements. In a standing skyline configuration it is easier to set up and use intermediate supports, even though it is possible also in the running configuration. The standing configuration is suitable for operations where the corridors are long and there is a need of higher load capacity. Therefore the productivity of standing skyline systems during operation is typically higher because of the higher speed of the carriage and the higher payloads. In Norway these systems often use a motorized carriage where the out-haul reaches higher speed than the carriages used in the running configurations making the standing configuration generally more productive, once set up.

In the running configuration the main and haul back drums are hydraulically interlocked in a manner that maintains relatively constant tensions by regulating drum speed. Since two lines support the load they can be smaller than the single line used in the standing configuration which has to support both the load and the carriage (Mann 1969). In addition the running skyline adjusts itself to the weight of the load, the deflection increases with heavier loads to provide lift to the suspended load without adding to the line tension (FAO 1974). In this case, the tension plays a fundamental role in the well-functioning of the harvesting system. Keeping the tension at a rate where safety requirements are fulfilled and productivity is high requires considerable skill (Visser 1998).

The running skyline is the most popular in Norwegian conditions where the slopes are mainly on the west coast; here the harvesting areas are scattered and the road network is limited and mainly located at the bottom of the slopes. The popularity of the running skyline is mainly due to the fact that the tension in the system is half what is necessary in the standing skyline, and given the small trees and shallow rooting (bedrock), tail spars are generally unstable and can seldom hold a higher tension system. The running configuration presents in fact a combination of unique assets such as: high mobility due to reducing rigging effort, and small, light lines which makes it suitable for uphill rigging; versatility due to the ability to log uphill and downhill; and lateral yarding capability for partial cut operations which is provided by the slack-pulling carriage (Mann and Mifflin 1979).

1.4 Human factors and work studies in forest operations

The interaction between human, machine, skills, and work organization constitutes the execution of forestry work. Low productivity or efficiency can be explained by the interplay or shortcomings of one or more of these factors. Understanding them and the way they interact, can give guidance on how to improve, not only productivity but also safety and worker's wellbeing.

Forestry work is considered a high risk occupation (Wettmann 2011). The workers employed in this field face many different difficulties such as tough working environment; heavy physical exertion and exposure to dangerous tools and situations. In these respects human factors studies have played an important role in forestry in the Nordic countries since the late 1940's when in the post-war period the forestry sector became of great significance for the rebuilding process even though Vik (2004) reports of studies from Germany on work physiology of forest workers from the 1920s. The first studies focussed on the work physiology especially in connection with the manual and the motor manual operations.

With modernization and the advent of more mechanized working systems, research attention shifted towards different work organization and training aspects of the operations because of the new and more complicated equipment and machinery. Mechanization brought the research to focus more on the impact of the equipment on the operators, vibrations, exposure to noise, stress, artificial lighting, working hours patterns, and muscle stress due to incorrect work postures (Abeli 1991; E. Apud et al. 1989).

The science studying these types of interactions is termed ergonomics or human factors.

“Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance. Ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people” (IEA 2000).

Ergonomics is divided into three main branches (Salvendy 1999):

- Physical ergonomics
- Cognitive ergonomics
- Macro ergonomics

Elaborating these three main research areas we can deduce that ergonomic studies may include a wide spectrum of different issues. For example: the study of the human body’s reaction to physical or physiological/mental workload, consideration of health and safety, as well as the well-being of humans within a system. In addition ergonomic studies can consider the ability to make decisions, the relations between workload and human error, the workers performances and their responses to specific training. The latter of ergonomic branch is mainly concerned with the optimization of socio-technical systems so as to design ergonomics into the job/work process and achieve a more harmonized work system. Successful ergonomic developments will likely result in, improved productivity; job satisfaction; health and safety and employee commitment.

Strategies aiming at cutting costs in relation to equipment downtime, suboptimal processing capacity, and the optimal utilization of forest resources consider ergonomics as one of the main elements to be taken into account.

Regarding work studies, from the earliest times, people have organized themselves to work together towards planned goals. The aim has always been to find the best way of performing a task. Time and productivity studies are the careful analysis of a task, its extent, the process used in its implementation, and its efficiency. As for any other anthropocentric research discipline it leads to an intrusion of the research into the workers’, crews’, and companies’ working space (Acuna et al. 2012).

Since the Industrial Revolution great attention has been given to this matter not only in terms of skills required to perform a specific task but mainly in terms of finding ways of increasing

the productivity. In this respect the work of F. W. Taylor “The principle of scientific management”(Taylor 1916) represents the milestone for the development of a whole new trend of studies about work measurement. Despite the good intentions of its founder, Scientific Management has its roots in an exploitative era characterised by rapid industrialisation and a need to quantify efficiencies and costs.

While this information is just as important in the 21st century, the integrity of the personal work space is protected by collective agreements, legislation (EU-OSHA 2012) and common respect. Through one century, the way of carrying out time studies has been elaborated under the growing influence of social sciences. The generally low remuneration capacity, the remote and exposed setting, and the demanding (and sometimes dangerous) nature of the work imply that the forestry industry is at least partially reliant on a pre-marginalised work force.

1.5 Physical workload

The identification of the critical workloads for workers is an important tool for achieving improvements in operations efficiency and safety. Workload can be measured through three main methods: physiological measurements, subjective measurements and performance based measurements. In this research only physiological methods were used.

Physiological workload measurement consists of the continuous measurements of the physical response of the body to a stimulus represented for example by the performance of a work task. According to Jung and Jung (2001) the body responds to increased physical workload with increased physical responses. Since it is generally demonstrated that there is a direct relationship between workload and heart rate (Kirk and Parker 1996b; Kirk and Sullman 2001a; Astrand 2003), these responses can be measured through heart rate monitoring. Despite some criticism, mainly pointing to heart rate sensitivity to psychological, environmental, and emotional factors (Jorna 1992) heart rate is the most common measure of workload. The use of statistical tools such Mixed Effect Models can limit the noise caused by such interactions.

1.6 Ethical concerns

Dealing with human beings, ergonomics, together with work studies, is one of the research fields most exposed to ethical criticism. It is important in this respect to make good use of a set of key concepts that have been created and made available by research institutions worldwide in order to protect the rights of the research participants.

Generally, the chosen research topic should show a social value in addition to producing useful results and increasing knowledge and understanding. The selection of subjects to be involved in research should be fair and open to all kinds of people. The constraint in this research is that steep terrain harvesting is a niche business involving a very limited number of people.

The research should show that if any risk is faced by the subjects involved in the research study, this has to be balanced by the expected benefits that the results of the research will bring to the society. The above mentioned issues must be addressed in addition to informed consent and respect for privacy (NENT 2008).

According to Bhutta (2004), general elements to be included in an informed consent should be competence, disclosure, understanding and voluntariness. With regards to competence, the subjects should be mentally able to understand the research and make a decision based on these facts; the researcher should disclose (communicate) to the subjects the aim and benefits of the research study and they should also be aware of their tasks as part of the study. It is also important that the subjects clearly understand what the researcher is telling them. This is of relevance in the present study as some of the subjects involved in this research spoke only their mother tongue (Baltic languages) and communicating via an interpreter is sometimes difficult when using technical terms. In the ergonomic trials carried out in this work, at least one of the crew was always able to translate the aim of the study, how it would be carried out, in what way the subjects were supposed to respond as well as the possible implications for them.

In our specific case there were a two levels of informed consent, one dealing with the subjects actively (physically) involved and another one at the employer (contractor).

The NENT guidelines (NENT 2008) provide the following check list drafting an informed consent agreement. The subjects involved in research are required to be:

- a. competent and understand the project's purpose and consequences of participation.

- b. capable of assessing their own situation.
- c. capable of making an independent and voluntary decision to participate, based upon the given information and the individual's own preferences and values.
- d. capable of voluntarily communicating their decision.

Besides the issues addressed above there are other considerations to take into account such as inducement, coercion and exploitation. These were not found to be of relevance in our study.

In this type of research, it is also important that the participants' privacy is guaranteed and this can be achieved in two ways, through *confidentiality* - identifying information will not be made available to anyone who is not directly involved in the study; and through *anonymity* - the participants will remain anonymous.

It is important that ergonomics research with its close links to medical research takes all the above mentioned concepts into account.

1.7 Knowledge gap and research needs

Identifying operational challenges and providing solutions so that cable yarding operations flow efficiently, is very important given the high costs of these types of operations. Ergonomic research aims at preventing injuries and improving skills, thereby resulting in reducing operational costs. In the Nordic countries, ergonomic research related to work in the forest was highly investigated until the 1980s (Vik 2004) while in the rest of the world the attention was continuous throughout the 1990s focusing on forest work implementation and organization (Axelsson 1998; Harstela 1990; Hagen et al. 1993; Kirk and Parker 1994; Kirk and Parker 1996a; Kirk et al. 1997; Stampfer 1998; Gellerstedt 1997; Trites 1992; Apud and Valdés 1995; Cristofolini et al. 1990). However, a small number of these research projects were directed on the ergonomic implications of working on steep terrain. Among the cited studies, the work of Kirk and Parker (1994) is of relevance in this research context. They investigated the effect of spiked boots on workload, safety and productivity of forest workers. Another important contribution is given by Stampfer (1998). He describes the stress and strains of forest workers in steep terrain proposing solutions aimed at reducing the workload. A quite complete picture of the ergonomic challenges of steep terrain forestry work is given in Cristofolini et al. (1990). The authors reported the results of an organizational analysis performed with the method of organizational constraints, followed by the physiological assessment of each working task performed on steep terrain operations. In the more recent

analysis of research studies on cable logging covering the years 2000-2011 (Cavalli 2011), cable system efficiency is the most common descriptor with 78 hits on 172 references. Cable logging ergonomics and safety reported only 17 hits out of which 10 dealt with the workload benefits of the use of synthetic ropes.

The gaps in the knowledge of the ergonomic challenges of steep terrain forest operations are closely related to the specificity of Norwegian conditions and the popularity of the running skyline systems. A better understanding of how the steep terrain harvesting tasks in Norwegian conditions influence worker performance and to what extent the productivity can be incremented through an ergonomic approach of work organization and implementation, could benefit the forestry sector.

1.8 Aim of the study

The overall aims of this thesis were a) to study the effects that steep terrain cable yarding operations have on the workers and b) to gain insight into the effects of some of the single tasks on the workers.

More specifically this research aimed at investigating the micro and macro-ergonomic benefits of reducing work strain, danger or discomfort, and emphasizing and improving the operators' capacity and skills. Through the four case studies making up this research project, the intention was to solve the related specific research questions as:

1. Identifying the effect of different parameters both exogenous and endogenous on crew productivity (Paper I).
2. Quantifying the effect of exogenous parameters on worker performance (Paper II).
3. Identifying and quantifying the effect of endogenous parameters on worker performance (Paper III).
4. Quantifying the effect of the combination of endogenous and exogenous parameters on performance (Paper IV).

An essential part of this research was the identification of solutions in respect to the abovementioned questions with the anticipation that this would help in achieving higher systems productivity, avoiding illness and reducing injury risk as well as increasing gratification among the workers and improving recruitment and retention within the Norwegian forestry sector.

1.9 General framework of the thesis

Steep terrain harvesting is always a demanding task seen from a financial, physical, organizational and safety point of view, when compared to other harvesting operations. This type of operation includes various work elements such as: walking in the forest, with or without tools, using hand tools and chainsaws; clearing of paths, escape routes and the base of trees from undergrowth and other obstructions; performing felling operations including taking down hung-up trees; climbing trees and occasionally delimiting and cross-cutting, choker setting and winching.

Steep terrain harvesting operations as mentioned, have been thoroughly investigated, as well as the way harvesting and stand variables affect operational efficiency of mechanized harvesting systems. The main conclusion is that the productivity is not only affected by the stem size but also to varying degrees, by the ground structure, the machine type and last but not least by the human factor (Kellogg et al. 1992).

Various literature references present how the productivity of cable yarding systems is affected by crew performance. According to Vik (1984) the productivity is affected negatively by adverse working environment conditions such as extreme steep terrain as it increases the crew's workload. Regarding crew size, Samset (1985) states that smaller steep terrain harvesting crews attain higher productivities. Other works focus on how productivity is affected by crew experience and training (Haynes and Visser 2001).

Since the 1950s great attention was given to research on work physiology, organization and ergonomics in Norway. For more than 30 years Professor Ivar Samset, led a group of researchers in a thorough investigation of ergonomics in forestry work. However, with the advent of fully mechanized forest operations in the 1980s and the general profitability decrease in the sector, the attention given to this type of research faded away. It became more important to focus on increasing productivity through other channels rather than pure work physiology based studies.

In considering the present situation of the Norwegian forestry sector and its likely development, it is clear that much of the future volumes must be sourced from steep and difficult areas. This emphasizes the importance of investigations into the implications on workers' health, safety and productivity.

The question of how to apply human factors and work studies to steep terrain harvesting operations in order to increase their productivity, can be split in two parts which are very

much interconnected; a man-technology dimension (Technologies + Human factors) and a man-environment dimension (Working Environment + Human factors) (Figure 3).

By considering each of these dimensions and how they are interconnected, the operational efficiency of cable yarding systems in Norway can be improved. Therefore this thesis applies a bi-dimensional approach in investigating how the productivity and efficiency of cable yarding systems can be improved in the implementation of different tasks.

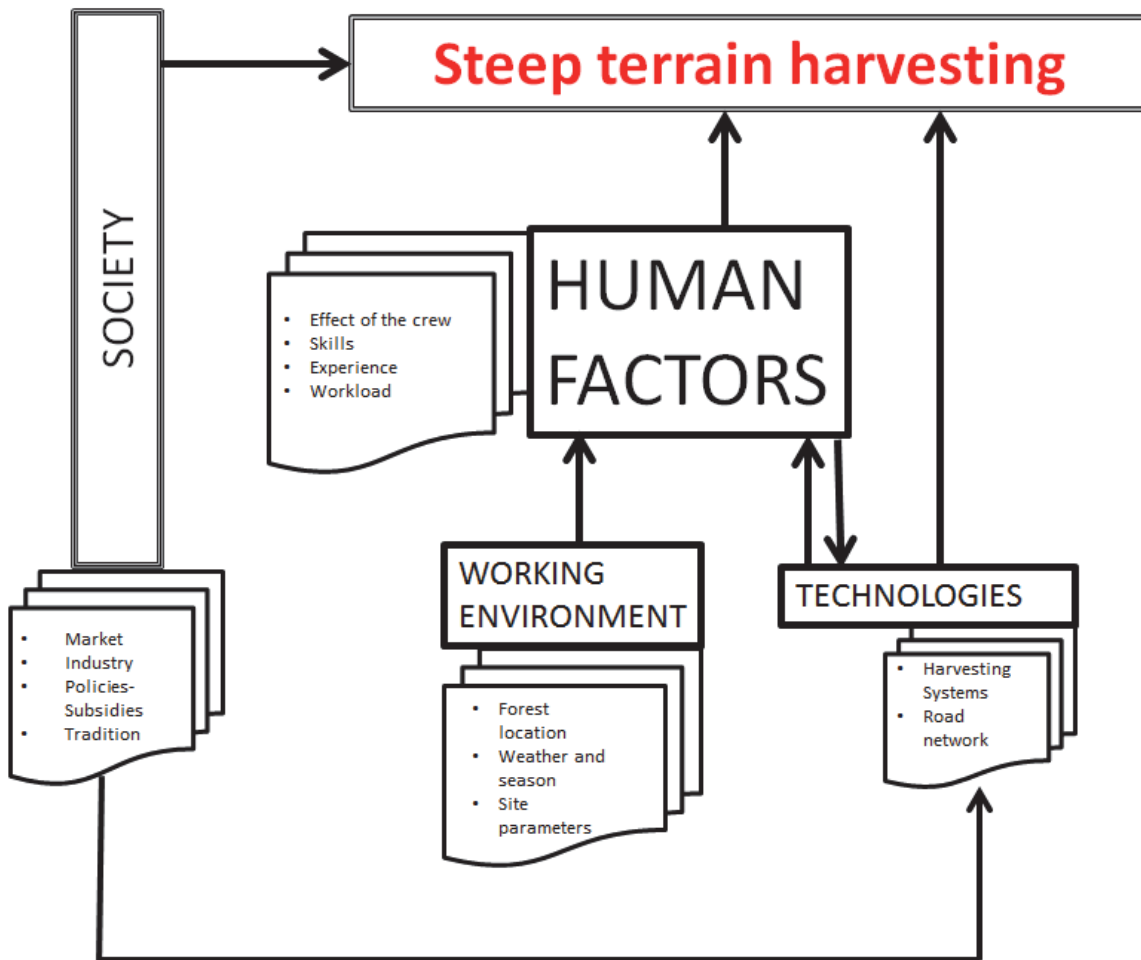


Figure 3: Illustration of the thesis concept

The **man-environment dimension** in our definition focuses on the impact of physical environmental conditions on steep terrain forest workers. Earlier research in this field was carried out during the 1970s when investigating manual felling operations in steep terrain (Vik et al. 1980; Vik 1984). Slappendel et al. (1993) also investigated the factors affecting work related injuries in forestry work without neglecting the physical environment.

The effect of a cold environment on forest workers was investigated by Mäkinen and Hassi (2009). Cold environment is traditionally set at or below +10 to 15° C or when the worker has

cold related symptoms (ISO 2008). Their conclusions stated that low work environment temperatures, decrease the performances of workers. In another study by Väyrynen (1984) it was found that low temperatures represent a possible cause of injuries. Besides these examples, there is little available literature on the influence of weather conditions typical of the Nordic countries on forest workers, while there are investigations on how high temperatures affect them (Staal Wästerlund 2001).

One case study was performed to investigate the effect of the environmental factors including terrain roughness, snow depth and temperature, on steep terrain crew performance. This study identifies causes of inefficiency and recommends solutions that can lead to safer and more efficient operations (Paper I).

The **man-technology dimension** is related to the interaction between the workers and the work system which includes machinery, tools and equipment in use. Generally this is the most common subject of all ergonomic research in forest operations, both because of immediate safety (e.g. hazard control and accident limitation) or long term related problems (e.g. development of back pain, white finger disease, etc.) but also because this is more closely related to the concept of productivity itself.

Researches focusing on the man-technology dimension can cover a wide range of different aspects of the interaction, from purely physiological studies on energy consumption in the implementation of different tasks to the implication of specific training in the implementation of one particular task.

In a steep terrain harvesting crew, the tasks performed by the machine operator can be categorized as light physical work. However the tasks of the feller and the choker setter can definitely be classified as heavy (Parker and Kirk 1994; Gellerstedt 1997; Stampfer 1998).

In light of this a number of researches have focussed on the fellers and the work postures assumed when performing manual felling (Harstela 1990; Brubaker et al. 1983; Wikström et al. 1994). Others have investigated the consequences of noise and vibrations on the upper limbs when using chain saws (Chetter et al. 1998; Axelsson 1998) or the effects of exposure to exhaust fumes (Stampfer 1998; Groves and Lyons 1968). Yet others have investigated the workload of the choker setter tasks (Kirk and Sullman 2001b; Leitner et al. 2009).

Besides the specific tasks belonging to each crew member, there are some common tasks which need to be performed by all as a team. These are for example all tasks related to the setting up of the cable yarding system. The set up phases involve heavy work and the case

study presented in Paper II investigates and assesses the workload difference of a rigging task performed when using synthetic rope rather than traditional steel cable. A similar task was investigated in Paper III, but in this case the study explored the possible effects of anthropomorphic characteristics on the performance of the workers.

The interaction between the whole crew and the whole system is usually investigated in productivity studies as in (Ghaffariyan et al. 2009; Aubuchon 1982). It is not often that the effect of worker experience is taken into account and the case study presented in Paper IV is used to investigate and determine the effect of specific training on productivity.

2. Material and methods

In order to investigate the two-dimensional problem (man-environment and man-technology), four case studies were carried out focusing on different elements in the harvesting system (figure 4). These system elements were chosen because of their relation to the study objectives.

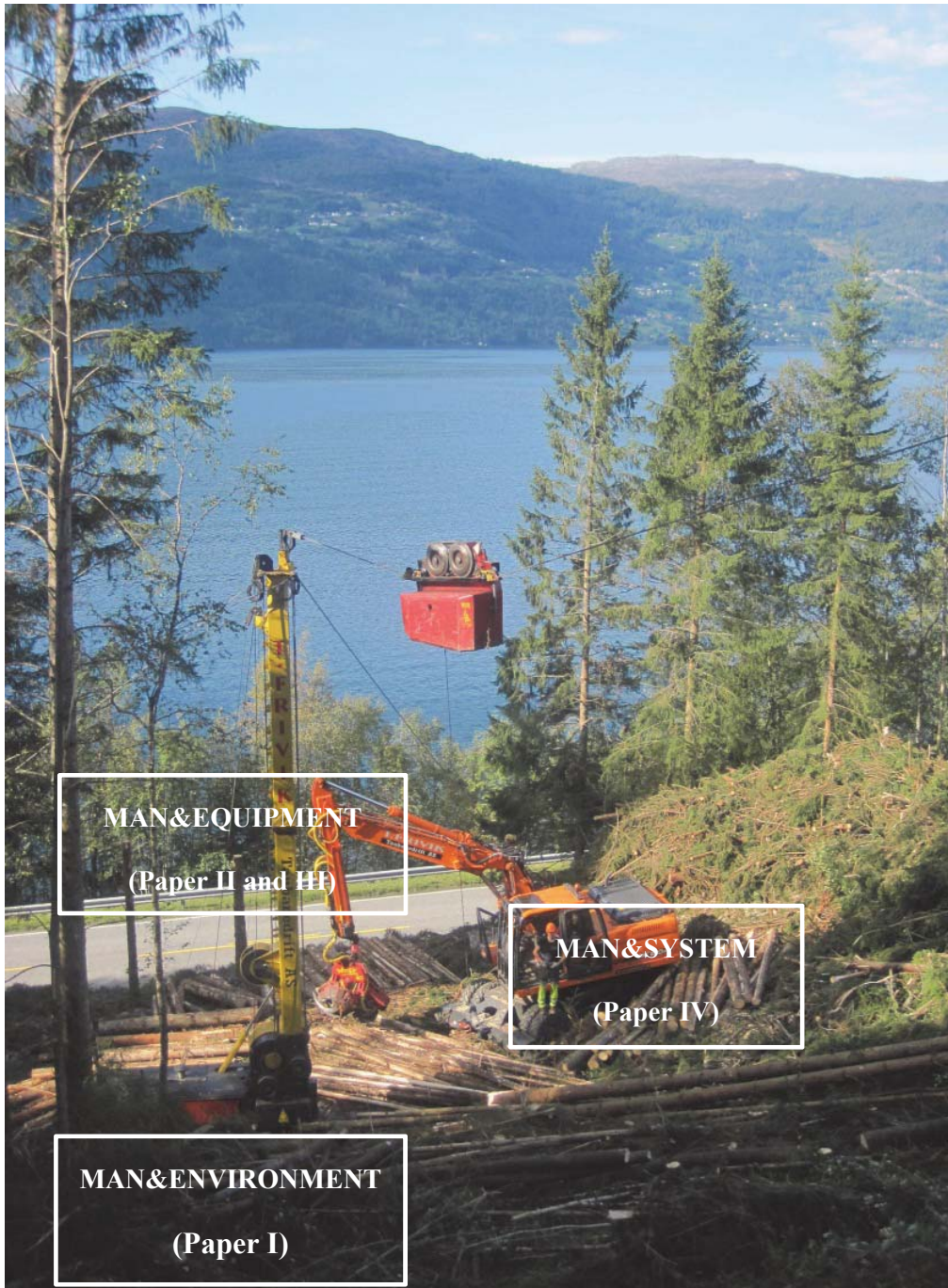


Figure 4: The focus of the different case studies in the cable yarding operation

The data used in all the case studies consist of time and productivity studies supported by physiological measurements (heart rate) of the subjects participating in the tests.

These three data collection techniques are generally used in the examination of human work and facilitate the investigation of all the factors which affect the efficiency and economy of the different operations/tasks to which they are applied. They represent a thorough analysis of tasks, investigating the extent, the process used in its implementation, its efficiency and weight in terms of workload. When the research aims at improving the benefit of an operation (increasing productivity and easing the strain), time and productivity studies in addition to physiological monitoring are the most commonly employed methodologies. The use of time and productivity studies assist in developing new technologies, improving human resources management and the human factors aspect.

2.1 The man-environment dimension

2.1.1 Effect of the physical environment on workers' productivity/efficiency (Paper I)

The data collection in this research was performed through one year of objective measures in order to investigate the interaction between selected dependent variables and independent variables by applying quantitative analysis.

Data analysis can consist of simple descriptive statistics or more sophisticated statistical inference such as regression, factor analysis etc. In this research several methodologies not always typical of this specific research field have been used on data collected from ongoing operations. The majority of statistical methods analysing system efficiency and system productivity belongs to the economic domain.

This research applied one of the most common econometric methods, Stochastic Frontier Analysis (SFA), to the field of forest operations (Paper I).

The literature presents many examples of the application of this method in agriculture (Kumbhakar and Lovell 2003) but few applied to forest engineering as for instance in Chumler et al. (2002) where the authors focus on the productivity of logging crews as a function of labour and capital or in Baardsen et al. (2009) who included logging conditions. SFA can be constructively applied to panel data sets which are commonly elaborated in the field of forest operations research when collecting data by means of time and productivity studies.

Before starting to discuss the notion of SFA it is important to clarify the concept of efficiency which is often encountered in the literature split into three different concepts. The first is technical efficiency which refers, in a forest operation setting, to the ability of the harvesting system to produce a maximum level of output (or set of outputs) from a given set of inputs; the second is the allocative efficiency which measures the ability of the system to choose the optimal set of inputs; the third is the economical or profitable efficiency which combines both allocative and technical efficiency. It is achieved when the system combines resources to generate maximum output (technical), ensuring least cost in order to obtain maximum revenue (allocative) (Farrell 1957). In this thesis only technical efficiency was considered.

A stochastic frontier production model for panel data can be written as in Battese and Coelli (1993):

$$Y_{it} = \exp(x_{it}\beta + v_{it} - u_{it})$$

Where Y_{it} is the observed scalar output of the producer i , $i=1,..N$ at the time t , $t=1, \dots, T$, x_i is a vector of inputs used by the i -th producer at the t -th period of observation; β is a vector of unknown parameters to be estimated. The production process is usually subject to two economically distinguishable random disturbances: statistical noise which can be positive or negative and is represented by v_{it} , and technical inefficiency which can only assume values between 0 and 1 and is represented by u_{it} .

The v_{it} are assumed to be independently and identically distributed random errors, having zero mean and unknown variance σ^2_v . The u_{it} are assumed to be independent of v_{it} where u_{it} is obtained by non-negative truncation at zero of the normal distribution with mean $z_{it}\delta$. z_{it} is a vector of producer-specific variables which may vary over time; and δ is a vector of unknown coefficients of the producer-specific inefficiency variables.

The sum of these two parameters represents the error term of the function. The model is usually specified in (natural) logarithms, so the inefficiency term u_{it} can be interpreted as the deviation of the observed performance, y_{it} from the system's specific frontier performance.

The advantages of using a methodology such as SFA can be summarized in the fact that it accounts for data noise such as data errors and omitted variables. It is also more flexible to modelling effects of other variables (e.g., environment, quality). Standard statistical tests can be used to test hypotheses on model specification and on the significance of the variables included in the model. The drawback of SFA lies in the fact that generally this type of econometric analyses require a large data set to ensure reliable results in addition to the fact

that strong assumptions are needed on the distribution of error among each observed unit in order to be able to distinguish between error and inefficiency (Kumbhakar and Lovell 2003).

2.2 The man-technology dimension

2.2.1 *Workers' physiological responses to the performance of a specific task (Paper II and Paper III); Workers' performance response to specific training (Paper IV)*

Descriptive statistics are used to describe the basic features of the data in a study. In certain types of studies, the whole data analysis procedure may consist exclusively of calculating and interpreting descriptive statistics.

The most common types of descriptive statistics are measures of central tendency (mode, median and mean), variability (range, quartile deviation, variance, standard deviation) relative positions (percentile, standard scores) and correlation (Spearman Rho, Pearson r). Appropriate descriptive statistics can be determined by a simple plotting of the data.

The selection of the type of statistical analysis to perform on the data collected should take the results of the descriptive statistics into consideration. In this case, the methodology chosen to investigate the impact of environmental factors on crew performance was SFA.

Analyses based on stochastic frontier modelling with panel data such as that used in this case have relied primarily on results from traditional linear fixed and random effects models.

Models including fixed and random effects are also called mixed effects models. They were developed to handle data in which the observations were grouped into classes (clusters). An example of such data is *repeated measures data* in which the same object (cluster) is observed at regular intervals. Observations from the same cluster will not be independent from each other and mixed effects models represent a suitable tool for modelling cluster dependence (Paper III and Paper IV).

This type of statistical methodology is largely applied in the medical field where the individuals represent the clusters (Brown and Prescott 2006), and to some extent also in growth and yield modelling, in forestry (Hall and Clutter 2004; Mola-Yudego and Aronsson 2008). The use of mixed-effect models has been less popular in the field of ergonomics as applied in forest operations.

According to the distribution of the response variable, mixed effects models can be linear and non-linear. The data used in this research have allowed us to use only linear mixed effect

models which are those in which both the fixed and the random effects contribute linearly to the response function. The general form of such models is:

$$y_i = X_i\beta_i + Z_iu_i + \varepsilon_i$$

where y_i is the response vector, X_i and Z_i are the design matrices corresponding to the fixed and random effects, β_i is the fixed effects vector, u_i is the random effects vector for unit i , and ε_i is the error vector.

The advantage of the use of mixed effect models in this research is closely related to the need of focusing on subjects' responses to different factors. This specific statistical method allows data modelling which explicitly describes individual changes across time. They can be applied on time studies where time is a continuous variable which is convenient when analysing studies related to repeated measures as in papers III and IV.

3. Main findings

3.2 Analysis of the man-environment dimension (Paper I)

The analysis of the effects that the physical environment has on the performance of steep terrain harvesting crews revealed that there is a correlation between the overall system efficiency and the ability to move on the steep slopes without undue difficulty.

Steep slopes, combined with a high terrain hindrance index, affects the mobility of the workers on the slopes, reducing their productivity and the efficiency of the whole system, Among the variables selected for the inefficiency component, terrain hindrance was found to be the only parameter significantly affecting the level of the efficiency of the crews. Presenting a positive coefficient, it increased the inefficiency. It was also found that 83% variation in output in this specific case was explainable with the presence of technical inefficiency.

The efficiencies shown in figure 5 indicate that there is potential for increasing the output of these specific steep terrain harvesting crews, and the average output increase was estimated at 12%.

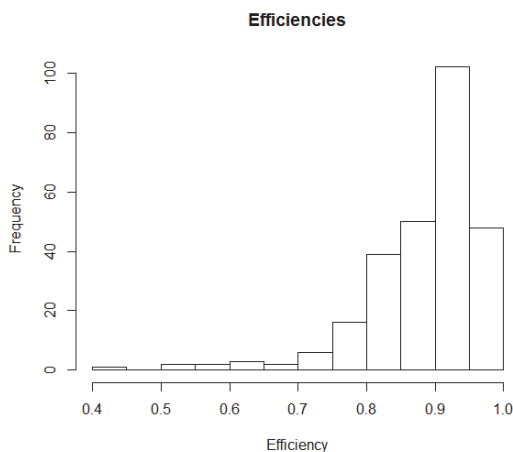


Figure 5: The efficiency distribution for the crews participating in the study

3.3 Analysis of the man-technology dimension (Paper II, III and IV)

3.2.1 *Investigations including physiological parameters (Paper II and III)*

The two case studies explained in Paper II and Paper III, focused on tasks which are related more or less closely to the strenuous activities of rigging and winching.

Paper II analysed the difference in workload when pulling out a new lightweight synthetic strawline as compared to the traditional steel wire used in rigging up a new yarding corridor.

It was found that the resistant force the subjects were exposed to was c. three times greater for the steel wire than for the synthetic rope. However, heart rate observations showed that this difference was reduced by the strain of moving up the slope, regardless of the task (figure 6).

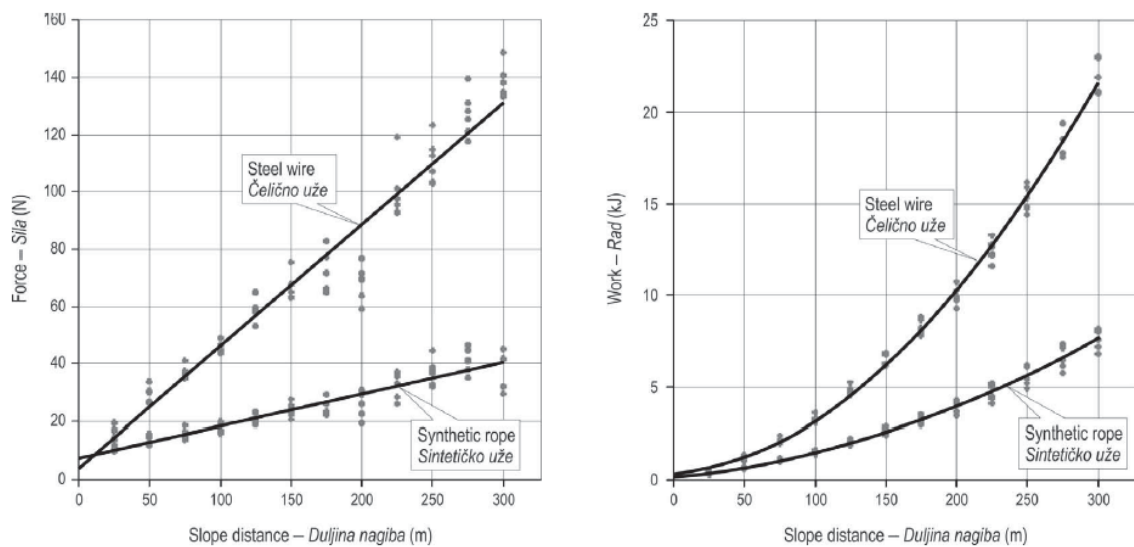


Figure 6: The tensile force exerted on the subject for the steel wire and the synthetic rope (left); the cumulative work done in pulling out the steel and the synthetic lines, net of body mass (right).

The ergonomic advantage of the use of synthetic ropes in this type of task is seen in the fact that despite the workload experienced was still being included in the “very heavy” range, the distance a worker could cover alone while pulling the line, was three times higher than when performing the same task using traditional steel wire.

In Paper III a tractor with winch was used and the task performed can easily be assimilated to the ones implemented when operating tower yarders. In this study workers with different anthropometric characteristics performed a winching task. The results showed that only the degree of fitness was possibly directly correlated to the resulting heart rate prediction for each of the time elements used in studying the task (figure 7).

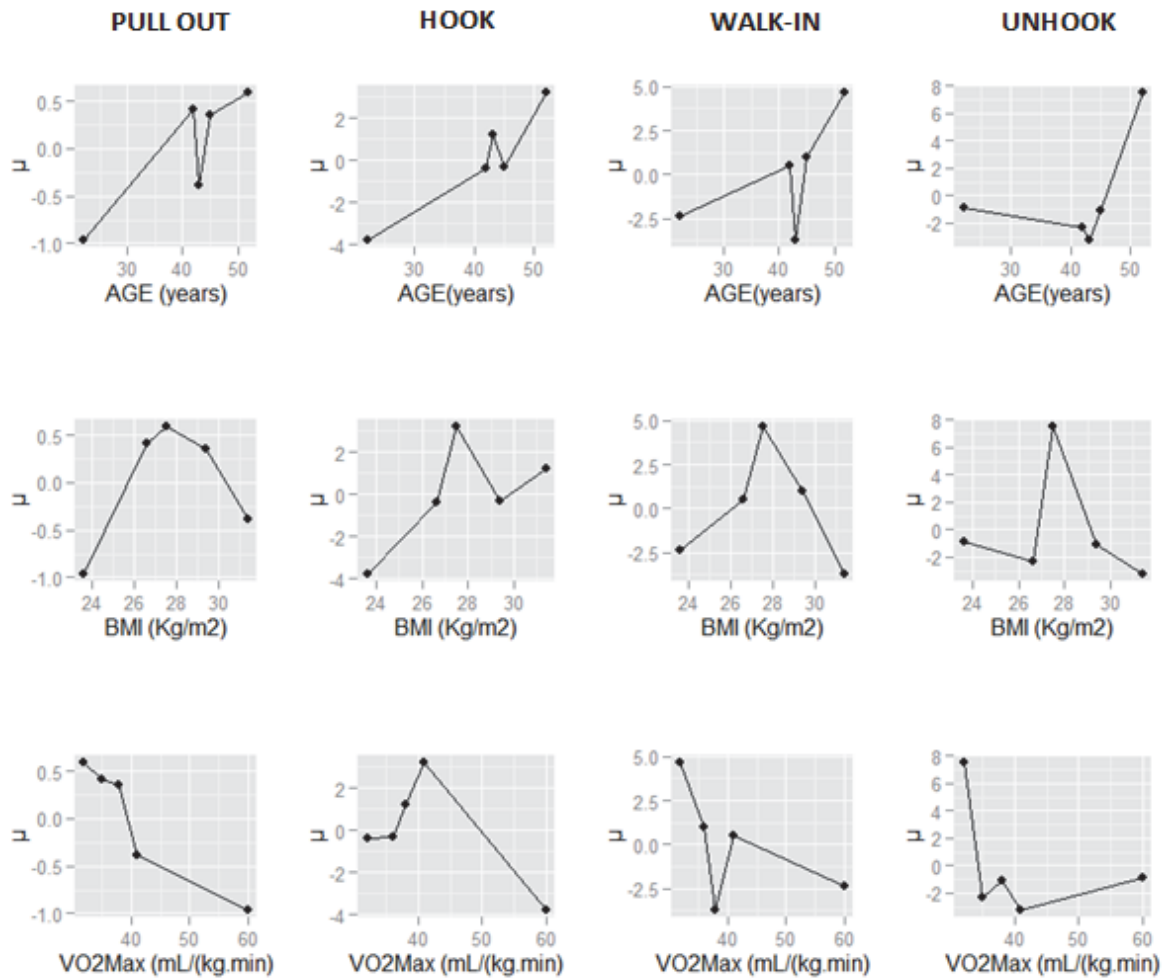


Figure 7: Plot of the intercept (μ) for each subject participating in the study and each time element (pull-out; hook; walk-in; unhook) against selected anthropometric/physiological parameters.

3.2.2 *Investigations including behavioural process (Paper IV)*

System productivity and specific training were the main features of the last case study where consecutive performances of different subjects operating a tower yarder were analysed. Results confirmed that the training improves both productivity and safety.

The subject performance showed an improvement of at least 20% in the time to complete the yarding task and this by the sixth replication of the task. The improvement is stronger for inexperienced subjects but is also significant for subjects with limited experience; while the experienced control subject showed no improvement with task repetition which is in line with the learning curve theory (figure 8).

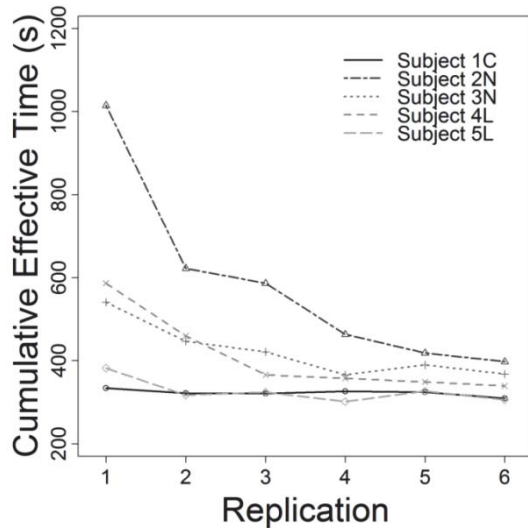


Figure 8: Values of the Cumulative Effective Time observed for each subject for six consecutive replications of the yarding task.

With respect to the performance quality and safety, the cable tension in the system represented a good indicator of how the operation was conducted. This was especially true for the running skyline setup that was being used. It was found that by the sixth replication the cable tension was within the range of the control (figure 9) meaning that the subjects participating in the study acquired enough ability to be able not only to improve the performance in terms of time requirements but also to work in a more professional way.

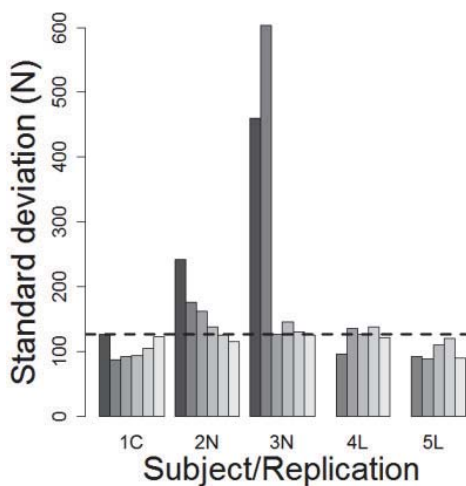


Figure 9: Standard deviation of the tension around the mean value for each replication. The dotted line represents the control's maximum standard deviation value, 126 N.

4. Discussion

In general, harvesting on steep slopes requires extra attention during the planning process but also during the operation itself. Determining harvest size and timing, selecting the appropriate harvesting system, and laying out road networks are all phases which can potentially have a strong impact on operation performance. During operation, steep terrain harvesting presents additional challenges such as the very high workloads imposed on the harvesting crews, both because of the environment they are in and the type of tasks and tools that need to be employed.

This research is a compilation of case studies focusing on some of the specific challenges the steep terrain harvesting crews face during their daily work. The study is an attempt to address different aspects of the links between human factors and productivity with the overall goal of improving the performance in terms of both productivity and safety.

Different statistical methodologies were applied to investigate the datasets. SFA was used to quantify the inefficiency of the steep terrain harvesting crews and relate it to the environmental parameters of the harvesting sites. It was found that there is a significant correlation between the level of inefficiency and the physical environmental parameters. Similar research has been conducted on system productivity, but without analysing the ergonomics of steep terrain operations in detail (Heinimann et al. 2001). The importance of relating the inefficiency to its causes lies in the possibility of finding solutions which increase work efficiency and safety.

Among the inefficiency parameters, terrain hindrance was the one which showed a significant effect and in this case study it explained most of the inefficiency. It is logical that a man moving on a steep slope will find moving harder when the terrain unevenness is high and strongly limits his mobility. This is in line with the results presented by Vik (1984) and by Magagnotti and Spinelli (2012) who stated that there was a productivity decrease due to the difficulties of moving up and down steep slopes.

These results can be of relevance not only for reducing the inefficiency but also in improving operator safety of when working on slopes (Paper I). Slips, trips and falls are common causes of injuries in steep terrain forestry work (Marshall et al. 1994). Research such as that by Kirk and Parker (1994), has been conducted to reduce the frequency of such events.

In addition to representing a source of potential hazards, steep terrain work imposes a very high strain on the forestry workers in all the tasks performed during an average working day.

This has been largely demonstrated in the tasks of choker setters (Kirk and Sullman 2001b; Leitner et al. 2009) and in those performed by the fellers (Melemez and Tunay 2010; Yovi et al. 2005; Vik et al. 1980).

The most strenuous tasks performed by the workers as a crew are the ones related to yarder set up, especially when the extraction is downhill. Rigging requires the workers to walk up and down steep slopes pulling a line and carrying heavy equipment. Reducing the workload of this specific work phase will help in maintaining human efficiency despite the limitations of the workers in terms of energy and fatigue. This could be achieved by using different tools and accessories designed to make the human component more effective and safer.

Results of our research confirm the benefit of using a synthetic rope for the rigging task (Paper II); its ergonomic advantage was quantified in: a) reducing the time during which the workers were exposed to high forces and b) increasing the pulling capacity to 900 m, for a strawline with a diameter of 3.5 mm. In the specific conditions of the study it was found that the workers exposure to high forces with the synthetic rope, was reduced by 80 seconds meaning that the overall workload was reduced. In addition, the maximum hauling distance to which one single worker was able to offset the tensile force was found to be 300 m, while using the synthetic rope the same resistance would only have developed at 1200 m. The use of synthetic rope has positive implications not only on the work load of the workers as the duration of exposure is reduced, but also on their productivity, as a single person can easily pull out the line.

The results of this research led to the research question faced in Paper III. The fact that the two subjects participating in the study reported in Paper II had quite different outcomes in relation to their physiological responses to strain, led us to investigate about the parameters which were correlated to the heart rate measured during a winching task. It was assessed that this type of analysis could be of help when selecting the crew members for specific tasks.

When investigating the relationship between workload and subject characteristics, the statistical method most commonly used is the Mixed Effects Model. We used such models in both Paper III and Paper IV. A limitation we faced was that the sample size (few subjects), which might have been larger to ensure sufficient statistical power. Larger sample sizes generally give better (i.e. unbiased) estimates of the unknown parameters (Zuur et al. 2009). However we assume that our results can be widely accepted despite the somewhat limited sample size. This is because our research does not aspire to make predictions for medical

purposes, but just gives an idea of the ergonomics facts applied to forest operations in steep terrain.

We investigated the physiological response of forest workers performing winching tasks on steep slopes. We predicted the heart rate response for each time element of a whole working cycle, in which the subjects had to: pull the cable, hook the logs, walk back to the landing area and unhook the log. This was done for the two winching directions: uphill and downhill. The results showed a higher heart rate for pulling the cable uphill and for walking uphill, as could be expected. The two time elements not requiring moving up the slope (i.e. hooking and unhooking) gave consistently higher predictions when succeeding the uphill time elements. Predicted heart rates allowed for the classification of these type of tasks to heavy and very heavy tasks (Astrand 2003). When relating the predictions to the anthropometric characteristics of each subject we could see a potential direct proportionality of heart rate predictions with age, and an inverse proportionality with the fitness status of the workers (VO₂max). Age is inversely proportional to degree of fitness, speed of reaction and acuity (Shephard 2000). This result could help in the choice of the workers for this type of heavy tasks, directing selection towards the young and fit, and leaving less demanding tasks to the older and less fit workers. This could unfortunately result in discriminatory personnel selection, though there seems to be a progressive aging of the working population in the forestry sector. This ageing workforce might represent an obstacle to not only achieving good productivity rates but also in ensuring safe operations. In fact, when the workers undergo a workload overload- which is likely to happen if older workers are performing very heavy tasks- they are more prone to commit errors and the odds of incurring injuries are increased (Slappendel et al. 1993).

In Norway an additional problem affecting the forestry sector is the lack of an experienced and skilled workforce. Labour migration towards other sectors is very common, and in Norway the forestry workers often come from abroad, and have little specific experience. Besides the implications of operating on steep slopes as seen in Paper I, they lack experience in operating the cable yarders which are the main equipment required for steep terrain harvesting. We investigated the effect of specific training on two categories of subjects: a) subjects with no experience and b) subjects with some experience in using controls similar to the ones employed in the control of the cable yarder. Their performance was compared to that of a trainer, used as a control. We used mixed effect models to observe the learning pattern of the subjects while repeating the same tasks six consecutive times. It was found that after the

sixth replication the time to perform the task approached that of the control. In addition to the productivity, we assessed the safety of the operation using the cable tension in the system as a proxy. Since the cable yarder was set up in a running skyline configuration the system's tension was a good indicator of the quality and the safety of operator performance. Also in this case it was found that within the sixth replication, the operating cable tensions for all the subjects were within the readings for the control. This corroborates that specific training improves the performance both in terms of productivity and safety of steep terrain cable harvesting. The same conclusions were arrived at by Haynes and Visser (2001), who observed an improvement of 23.7 tons per productive machine hour for the crews who had received the training.

5. Concluding remarks and further research

The economic and environmental success of cable yarding operations is influenced by the performance of the crew operating it. System productivity is determined by crew efficiency and man-machine interaction. Crew efficiency is highly correlated to comfort, both in terms of workload (so health) and safety (Konz and Johnson 2000; Nicholls et al. 2004).

The implications of reducing the workload go beyond just an ergonomic benefit, and represent a positive social and economic impact. Safer harvesting work is more appealing for the workers and at the same time reduces the risks of accidents limiting the periods of absence from work. Reducing work strain, danger or discomfort, emphasizing and increasing the operators' capacity/skills and improving the team organization/communication in cable yarding work was demonstrated to be beneficial for the industry through improved productivity and safety in the Norwegian case, and in the long run might show a positive effect on recruitment and retention within the forestry sector.

The findings of this study will hopefully raise awareness as to the heaviness of the tasks that the steep terrain harvesting crews are faced with both in terms of physical and mental workload. This research mainly focussed on the physical workload, and just a glimpse of cognitive ergonomics was given in paper IV.

Mental workload is closely related to worker vigilance, decisions-making ability, error making and ultimately, the overall worker performance. Mental workload can be analysed by means of cognitive ergonomics. Cognitive ergonomics is a branch of ergonomics that places special emphasis on the mental processes, such as perception, attention, cognitive abilities, motor control and memory storage and retrieval. Cognitive ergonomics addresses the effect of these parameters on worker interactions with co-workers and with the physical elements of the system.

Further research in this field with particular attention to the cognitive aspects of ergonomics and to the organizational aspects of work would be beneficial. The high production costs of steep terrain operations may be counterbalanced by the increase in crew efficiency when a better organized and safer work environment could be provided.

SFA could be further used in combination with tools assessing mental workload in order to provide guidance in different work organization settings aiming at increasing the efficiency.

Productivity increase may result in supporting the sector and in strengthening the institutions involved by setting the foundations for producing ad hoc policies. In Norway there is a general lack of procedures aiming at giving specific guidance on steep terrain harvesting operations, and the existing ones are not harmonized. The lack of a definite law/policy for steep terrain harvesting, on which to establish an official “best practice” manual, makes the development of this already very vulnerable sector even more difficult.

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Paper I

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Paper II

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Paper III

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Paper IV

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