**Dissertationes Forestales 370**

# Well-being and productivity of forest machine operators – ergonomic support measures

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Academic dissertation

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## ABSTRACT

Technological advances in forest operations have transformed cut-to-length (CTL) timber harvesting from a physically demanding task to a more sedentary, skill-intensive job. This shift requires operators to possess a high level of technical and environmental expertise, accompanied by strong self-management skills, to balance productivity with other work demands. Despite these advances, the sector faces a global shortage of skilled workers, exacerbated by difficulties in attracting and retaining operators.

This thesis examines the well-being and productivity of CTL machine operators, emphasising workability and the human-machine-environment interaction, alongside influencing factors. The study investigates the ergonomic aspects of the work in micro, meso and macro work systems, where machine functionality, personal resources, organisational support and regulatory frameworks collectively shape operator productivity and well-being. The study uses a mixed method approach that integrates quantitative and qualitative data.

Data from Finnish CTL machine operators indicate that, although operators generally exhibit good workability, challenges, for example, physical ergonomic aspects of the machine cabin, diminished personal resources, cognitive load from digital tasks and inadequate feedback systems can affect their long-term health and engagement. The findings highlight the importance of adaptive technologies and continuous education, both technical training and self-care guidance, to support operators in their demanding roles. Additionally, enhanced work preparation and feedback mechanisms are crucial to improving work productivity and quality, while promoting operator well-being. Future advances should prioritise ergonomic design and automation that align with operators' needs, strengthening the industry's appeal and ability to offer sustainable jobs in the bioeconomy sector.

**Keywords:** cut-to-length (CTL), forest work, workability, work system, assisting system, personal resources

**Kymäläinen, H.** (2025). Työhyvinvointia ja tuottavuutta puunkorjuuseen – ergonomiset keinot työn tukemiseen. Dissertationes Forestales 370. 42 s. https://doi.org/10.14214/df.370

# TIIVISTELMÄ

Teknologinen kehitys on muuttanut puunkorjuun työnkuvan fyysisesti raskaista tehtävistä istumapainotteiseksi ja monipuolista taitoa vaativaksi työksi. Nykyinen työ moderneilla tavaralajimetodiin perustuvilla harvestereilla edellyttää kuljettajilta asiantuntemusta niin raskaskonetekniikasta kuin metsäympäristön käsittelystä sekä vahvaa itsensä johtamisen taitoa, jotta tuottavuus voidaan tasapainottaa muiden työn vaatimusten kanssa. Kehityksestä huolimatta ala kärsii työvoimapulasta sekä kotimaassa että kansainvälisesti, minkä lisäksi uusien kuljettajien houkuttelemisessa ja pitämisessä alalla on haasteita.

Tässä työssä tarkastellaan metsäkoneenkuljettajien työhyvinvointia ja tuottavuutta painottaen työkykyä, sekä ihmisen, koneen ja ympäristön välistä vuorovaikutusta ja siihen vaikuttavia tekijöitä. Tutkimuksessa tarkastellaan työn ergonomisia ulottuvuuksia mikro-, meso- ja makrotason työjärjestelmissä, joissa koneen toiminnallisuus, henkilökohtaiset voimavarat, organisaation tuki ja sääntely yhdessä muovaavat kuljettajan tuottavuutta ja hyvinvointia. Tutkimuksessa käytetään monimenetelmällistä lähestymistapaa, jossa yhdistetään määrällistä ja laadullista aineistoa ja menetelmiä.

Tutkimusaineistot suomalaisista metsäkoneenkuljettajista osoittavat, että kuljettajien työkyky on yleisesti hyvä, mutta esimerkiksi koneiden fyysisen ergonomian haasteet, kuljettajien heikentyneet henkilökohtaiset voimavarat, digitalisaation aiheuttama kognitiivinen kuormitus sekä puutteelliset palautemekanismit työjäljestä voivat vaikuttaa kielteisesti kuljettajien pitkän aikavälin terveyteen ja työhön sitoutumiseen. Tulokset korostavat mukautuvien teknologioiden ja jatkuvan koulutuksen – sekä teknisen osaamisen että itsestä huolehtimisen ohjauksen – merkitystä kuljettajien tukemisessa. Lisäksi parannettu työn suunnittelu ja palautteenantomekanismit ovat keskeisiä tekijöitä työn tuottavuuden ja laadun kehittämisessä samalla edistäen kuljettajien hyvinvointia ja osaamista. Tulevaisuuden kehityksessä tulisi edelleen painottaa ergonomista suunnittelua ja automaatiota vastaamaan kuljettajien tarpeita, vahvistaen alan houkuttelevuutta ja kestävien työpaikkojen pitovoimaa biotaloussektorilla.

**Asiasanat:** metsäkone, metsätyö, työkyky, työjärjestelmä, avustavat järjestelmät, resurssit

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Finally, I owe my deepest thanks to my family. My parents have always encouraged me to pursue education and personal growth with an open mind. My dear sons have grounded me and brought joy beyond measure outside work. Most of all, I thank my loving husband, Timo, for his unwavering support, for encouraging my choices, for giving me space to focus when needed - and making sure the sauna was always warm when I needed to unwind.

Joensuu, 18th May 2025

Heli Kymäläinen

# LIST OF ORIGINAL ARTICLES

This thesis is based on data presented in the following articles, referred to by the Roman Numerals I-III.

**I** Kymäläinen, H, Laitila, J, Väätäinen, K, Malinen, J (2021) Workability and well-being at work among cut-to-length forest machine operators. Croatian Journal of Forest Engineering 42(3):405-417. https://doi.org/10.5552/crojfe.2021.874

**II** Kymäläinen, H, Hujala, T, Häggström, C, Malinen, J (2023) Workability and productivity among CTL machine operators – associations with sleep, fitness, and shift work. International Journal of Forest Engineering 34(3):426-438. https://doi.org/10.1080/14942119.2023.2216113

**III** Kymäläinen, H, Häggström, C, Hujala, T, Torssonen, P, Malinen, J (2024) Ergonomics in CTL harvesting – assisting systems and future visions. International Journal of Forest Engineering 36(2):133-146. https://doi.org/10.1080/14942119.2024.2438500

Heli Kymäläinen is fully responsible for the summary of this doctoral thesis. The contribution of Heli Kymäläinen to the papers included in this thesis was as follows:

**I** Heli Kymäläinen (HK) was the main author. The study was planned by Jukka Malinen (JM) and Piritta Torssonen (PT). HK carried out the study design, collected data and analysed data. HK and JM did the interpretation of the results. HK wrote the article with the help of co-authors Juha Laitila, Kari Väätäinen and JM.

**II** HK was the main author. The study was planned by JM and PT. HK did the study design, collected data and analysed data. HK and JM did the interpretation of the results. HK wrote the article with the help of co-authors Teppo Hujala (TH), Carola Häggström (CH) and JM.

**III** HK was the main author. The study was planned and designed together with JM, PT, TH and CH. HK collected data, analysed data and carried out the interpretation of the results. HK wrote the article with the help of co-authors CH, TH, PT and JM.

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## ABBREVIATIONS AND DEFINITIONS

| | |
|---|---|
| AI | Artificial intelligence |
| BTC | Boom tip control |
| CTL | Cut-to-length method |
| $E_{15}$ | Gross effective time productivity including delays shorter than 15 minutes |
| EHF | Ergonomics and/or Human Factors |
| FIOH | Finnish Institute of Occupational Health |
| HRV | Heart rate variability |
| $P_r$ | Relative productivity |
| RQ | Research question |
| SD | Standard deviation |
| SDR | Socially desirable responding |
| SV | Nightly sleep value during workdays |
| $VO_{2max}$ | Maximal oxygen uptake |
| WA | Workability |
| WAI | Workability index |
| WHO | World Health Organization |

# INTRODUCTION

## Cut-to-length harvesting and workforce challenges

Forest harvesting operations have undergone a shift from highly physical work to more sedentary and lighter tasks due to technological advances. This shift has also changed the skillset required of workers, emphasising mental capacity in forest operations. Operating a cut-to-length (CTL) harvester is demanding and independent work that requires a high level of technological and environmental expertise, particularly in the Nordic context (Ovaskainen et al. 2004; Häggström et al. 2015). Operators must continuously make decisions, conduct environmental assessments and maintain productive, yet profitable, operational performance (Palander et al. 2012).

Forest harvesting work, like other industrial sectors, has been influenced by digitalisation. Since the single-grip harvesters for the CTL method were introduced in the 1970s (Kalaja 1991; Nordfjell et al. 2019), the capability of these machines to produce data has continuously increased with no end in sight. With advances in digitalisation and internet connectivity, data collection from operational tasks has become constant, increasing the amount of data operators must manage. Additionally, ongoing technological developments and changing legislation forces operators to continually update their competencies (George et al. 2022; John Deere 2024; Miinalainen 2024). Mastering all the skills needed for CTL harvesting, combined with sufficient productivity, requires a commitment to the work and typically several years of work experience (e.g. Purfürst 2010; Malinen et al. 2018).

Despite advances in forest operations that have reduced the physical workload and made CTL machinery more worker-friendly, the sector lacks skilled workers nationally in Finland as well as globally (Häggström and Lindroos 2016; Pagnussat et al. 2019; Lautanen et al. 2020; He et al. 2021). This creates a risk in the timber procurement supply chain, since there are no signs that the use of wood-based materials will decrease in society, quite the contrary (e.g. United Nations 2020; Kunttu et al. 2022). Some countries offer vocational education for CTL operators to provide the workforce, but in Finland, for example, there are challenges in filling all the available student places. Forest work is not appealing to young people, often due to the remoteness of workplaces and long commutes. Furthermore, in countries without formal education programmes, businesses are compelled to recruit and train operators themselves (Häggström and Lindroos 2016; Pagnussat et al. 2019; He et al. 2021).

In addition to difficulties in attracting a workforce to the sector, retaining skilled workers is also a challenge. Regardless of their educational background, many skilled (or potential) operators leave the field to work nearby, in population centres and more straightforward work. CTL harvesting work has been perceived as too demanding because of the high productivity expectations and other challenges, such as the harsh working conditions (Lautanen et al. 2020). The consuming and stressful nature of the work also increases the risk of health-related issues among employees, leading to potential increases in health costs (Ganster and Rosen 2013; Street and Lacey 2019). Furthermore, as a national-level challenge, experienced Finnish operators, known for their strong independent work background and ability to handle complex situations, are highly sought after abroad, and there are ongoing recruitment campaigns offering job opportunities in places like North America and Central Europe (Metsätrans Tapahtumat 2024).

## Ergonomic approach and work systems

Ergonomics and human factors (EHF) is a scientific discipline that aims to optimise human well-being and overall system performance by improving the interactions between humans and other elements of a system (IEA 2024). Much EHF research examines how individuals interact with both technical and social systems in their work environments (Hassall et al. 2015). Ergonomics can be divided into physical, cognitive and organisational domains, each representing different aspects of an individual's work (IEA 2024). While these domains manifest themselves differently in work performance, they also overlap and interact. In forest operations and advances in forest machinery, research has evolved from focusing on physical demands towards a cognitive-centred approach, highlighting the importance of mental workload, decision-making and human-machine interactions in modern forestry (Harstela 1990; Asikainen and Harstela 1993; Tynkkynen 2001a; Ovaskainen and Heikkilä 2007; Häggström et al. 2015).

However, the physical, cognitive and organisational domains are further grouped into micro and macro ergonomics (Meshkati 1989; Zink 2000; Morel et al. 2009). While micro ergonomics represents the design of human-machine interaction emphasising physical and cognitive aspects, macro ergonomics is related to larger sociotechnical systems with organisational aspects. Ideally, the design of EHF aspects between micro and macro levels would be aligned, so that the overall system would support both individual employee performance and achievements, and organisational goals (Hendrick 1987; Kleiner 2008).

Consequently, EHF design is often approached from a systems perspective (e.g. Wilson 2014; Salmon and Plant 2022). Work systems function through interactions between individual and/or collective aspects and relevant technical elements, simultaneously incorporating environmental, task and organisational characteristics (Niu and Mosier 2021; IEA 2024). A systems approach has the potential to acknowledge the holistic perspective, context and interactions between humans and their working environment, revealing the nature of the system and important emergent characteristics.

Work systems can be categorised into micro level (individual interactions and human-machine dynamics), meso level (interaction and dynamics of teams of humans and machines) and macro level (organisational or system-wide interactions) (Grote et al. 2014; Stanton 2023). In forest operations, CTL harvesting, characterised by human-machine-environment, serves as an example of a micro level system (Tynkkynen 2001b; Gellerstedt 2002; Kariniemi 2006). Additionally, harvesting work encompasses communication and interaction with other stakeholders (meso system), while organisational goals, regulations and other guidelines (macro system) create a framework for the operations.

## Work systems and their ergonomic aspects in CTL harvesting operations

While the majority of the forest machine operator's immediate work occurs in the micro level work system (Figure 1), the efficiency and smoothness of the human-machine-environment relationship are critical for successful operations. The micro system integrates aspects of physical and cognitive ergonomics, both of which influence the productivity, overall performance, well-being and attractiveness of the profession.

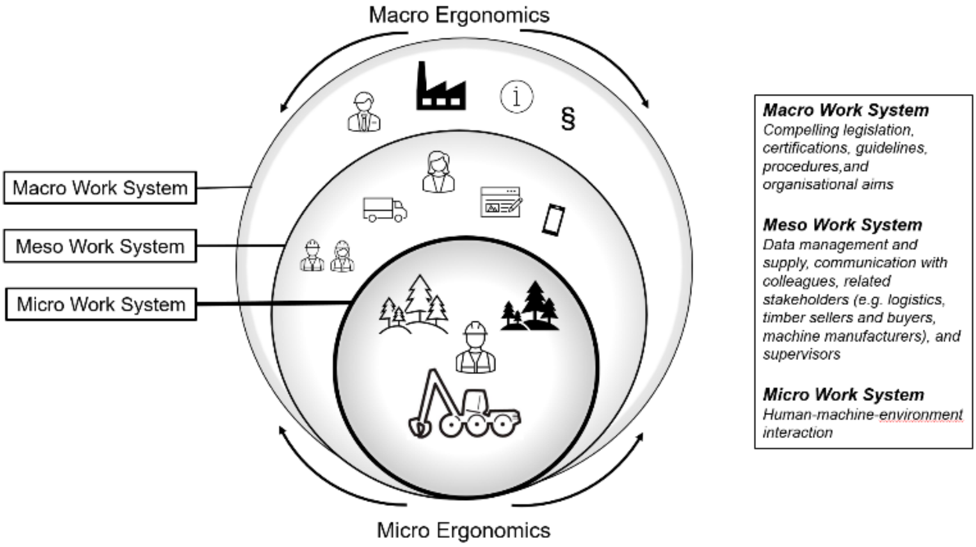


**Figure 1.** The work system levels in forest harvesting and the positioning of ergonomic systems.

Physical ergonomics in CTL machinery, focusing on human physiological, anthropometric and biomechanical characteristics, address key aspects such as the layout of the machine's cabin, the operator's posture and movements, and safety measures. There have been improvements in terms of reducing cabin noise and vibration, and decreasing the strain associated with repetitive hand movements (Manner et al. 2019; Poje et al. 2019). Additionally, rotating cabins, improved lighting and increased window surfaces have further supported the physical ergonomics of operators (Poom et al. 2007; Englund et al. 2015; Paakkunainen 2015; Ponsse 2024). Safety measures are key when working with heavy machinery, often alone and in remote locations, thus forest machines include some interlocks and safety switches. Also, many timber procurement companies have established protocols, rules and guidelines for safety measures (e.g. Stora Enso 2024). These must be followed even though, for example in Finland, independent contractors carry out the operational work.

Aspects of cognitive ergonomics, encompassing decision-making, reasoning, memory and human-computer interaction, engage operators continuously as they assess the environment and the machine's performance to ensure high-quality raw material production while maintaining sufficient productivity levels. Digitalisation has had a mixed impact on the cognitive strain (Vuori et al. 2019; Kim et al. 2023; Zacher and Rudolph 2024), both reducing and increasing the mental demands placed on operators. On the one hand, forestry operators are responsible for more tasks, such as self-monitoring and reporting of retention trees and game thickets (PEFC 2024). On the other hand, decision-support systems aim to facilitate mental work, and specialised software provided, for example, by machine manufacturers and software development companies, assists with processive work (KomatsuForest 2024; Trimble Inc. 2024). Also, CTL harvesters are equipped with self-monitoring systems that alert operators to abnormalities and maintenance services can be accessed remotely, streamlining operational support.

From the CTL operator's perspective, the meso level work system extends both horizontally and vertically, encompassing the broader work organisation and community in which the operator functions. This includes peer colleagues (horizontal), supervisors (vertical) and various stakeholders (horizontal and vertical), such as timber truck drivers, forest owners, machine manufacturer representatives and timber buyer representatives. While this community is composed of different (independent) actors, interactions and relationships among this loose team shape the operator's working environment, impacting both productivity and overall job performance. Moreover, although some of the functions of the meso system are invisible to the operators, for example, the order and selection of worksites, it constructs the work and provides leadership and support to operators.

In macro-level ergonomics, relevant regulations, certifications, procedures, guidelines and organisations' objectives, alongside unwritten norms and rules in the sector, provide the structural framework for CTL harvesting operations. This framework is not something the operator can actively control or influence; rather, it is established externally and the operator must adapt to the system. Sectoral and societal changes eventually influence operational work, because re-arranged systems and new regulations are implemented in the field. One recent example of the influence of macro-level ergonomics was the update of the FSC (Forest Stewardship Council) and PEFC (Programme for the Endorsement of Forest Certification) certification standards, which operators had to adopt (Forest Stewardship Council 2023; PEFC 2024).

The macro level work system defines organisational goals, for example, as well as the tools and practices that influence lower work levels. Technological advances and digitalisation have significantly transformed work practices and ergonomic aspects in forest operations (Palander et al. 2024). One notable change is the reduced need for direct supervision at forest sites. For example, electrical work instructions are sent remotely to the harvesting machines and operators are responsible for reporting various metrics, such as timber volumes and calibration readings of the harvester head's measurement control system (Trimble Inc. 2024). However, while these digital advances, followed by meso and macro level system changes, have increased operator independence, they have also shifted some administrative responsibilities to the "forest end". Tasks that were traditionally handled by office or supervisory staff are now part of the operator's workload due to cost-cutting measures and increased reliance on digital reporting systems. This has created additional cognitive demands on operators, who must now manage both operational fieldwork and administrative tasks in the forest.

## Concepts of workability and well-being

The concept of workability (WA) refers to the balance between the demands of work and an individual's personal resources (Arvidson et al. 2013). Organisational factors, such as work environment, leadership and job satisfaction, and personal factors, like personal health and lifestyle choices, influence an individual's workability. Since work demands and personal resources tend to change over time, employees continually strive to maintain an optimal balance throughout their working life (Ilmarinen 2009). Workability can be evaluated using the workability index (WAI) questionnaire, developed by the Finnish Institute of Occupational Health (FIOH). This tool assesses employees' current health and well-being and their projected workability in the near future (Kettunen 2015), and offers a reliable prediction of potential work incapacity, early retirement and even mortality risks (Ilmarinen and Lehtinen 2004). Originally developed for research purposes (Ilmarinen 1991), the WAI has since been widely adopted in medical and occupational health practices across various countries (Ilmarinen 2007). It is one of the most commonly used and accepted instruments for measuring workability (De Zwart et al. 2002; Radkiewicz and Widerszal-Bazyl 2005; Ilmarinen 2007; van der Berg et al. 2008; Lundin et al. 2017).

High levels of WA are associated with better job performance, greater job satisfaction, increased career longevity and work productivity (Tuomi et al. 2001; Kuoppala et al. 2008; Vänni et al. 2015; Ahola et al. 2018), thus organisations benefit from enhancing employees' WA. On the other hand, low levels of workability are linked to a greater likelihood of early retirement, prolonged periods of unemployment, increased sick leave and long-term disability (Burdorf et al. 2005; Sell et al. 2009; Lundin et al. 2016). They are also often connected to unhealthy habits such as obesity, smoking, physical inactivity and poor diet (Tuomi et al. 2001; Arvidson et al. 2013; Oellingrath et al. 2019). In contrast, higher levels of workability are associated with positive behaviours, including regular physical activity and good sleep quality (Camerino et al. 2008; Lian et al. 2014; Kettunen 2015; Bergman et al. 2020). In terms of forest harvesting operations, high levels of WA could support, for example, long careers and productivity, both of which are beneficial for the career success of a forest machine operator.

According to studies, the WAI tends to decrease with age (Tuomi et al. 1991; Pohjonen 2001; Monteiro et al. 2006), but ageing alone does not automatically lead to a lower WAI. Instead, individual differences in workability tend to increase with age, contributing to the overall declining trend (Ilmarinen 2006). Employees who can draw on the work experience accumulated throughout their careers are more likely to maintain higher workability levels. In practice, this often involves promotions, career opportunities and changes in work tasks that allow them to apply their expertise in new ways. However, for CTL machine operators, this type of career progression is less common (Häggström 2015), as the role offers limited opportunities for advancement or diversification of tasks beyond machine operation. Moreover, younger employees are not immune to low workability levels. Factors such as being overweight, declining health (physical or mental) and the risk of long-term unemployment can negatively impact workability across all age groups, which puts a strain on well-being and career development opportunities (Bostrom et al. 2011; El Fassi et al. 2013; Lappalainen et al. 2017).

Workability is a key element of the broader phenomenon of workplace well-being. Both are crucial factors when considering professional expertise, productivity, job satisfaction and career longevity. Workplace well-being not only impacts an individual's health, but also plays a crucial role in their job satisfaction and emotional balance, encompassing both positive and negative experiences at work (Schulte and Vainio 2010; Bakker and Oerlemans 2011; Ilies et al. 2015). This type of well-being encapsulates the quality of working life and influences productivity on individual, organisational and societal levels (Schulte and Vainio 2010).

Job satisfaction emerges when individuals experience a blend of positive emotions and meaningfulness in their roles (Ryan and Deci 2001; Tov 2018; Sonnentag et al. 2023). Research suggests that achieving a state of flow, a psychological condition where a person feels fully immersed and highly engaged in their task, can significantly enhance job satisfaction. Flow is often a stronger predictor of job satisfaction than factors such as work significance or responsibility (e.g. Maeran and Cangiano 2013; Ulu and Vatan 2023). Leadership and management practices that support autonomy, competence and relatedness can foster well-being at work, enhancing both job satisfaction and performance (Sonnentag et al. 2023; Nunes et al. 2024).

To ensure sustainable and cost-effective forest operations, it is essential to maintain a skilled workforce capable of operating forest machinery and making informed operational decisions in the forests. Achieving this requires strong support for current machine operators in their demanding roles and a focus on retaining them within the industry. Additionally, the sector must attract new talent by lowering entry barriers for beginners and enhancing training opportunities. Addressing these challenges effectively requires a deeper understanding of how to improve CTL operators' ergonomics, work conditions and overall well-being throughout their careers. Currently, there is limited comprehensive data on the ergonomic challenges, workability and well-being of operators. As global demand for renewable materials and sustainable forestry grows, ensuring operator well-being becomes integral to fostering a responsible, resilient and attractive future for forest operations within the industry. This commitment should include ergonomic improvements in both timber procurement and day-to-day operations. Ongoing advances in ergonomic practices, well-being initiatives and operational support are essential not only to improve current working conditions, but also to attract the next generation of skilled professionals to the field.

# OBJECTIVES

This thesis addresses well-being and productivity of CTL machine operators. The aim is to investigate ergonomics at multiple levels from the point of view of workability and the factors that influence it. Moreover, the study explores how operators perceive the usability and functionality of the assisting systems in CTL machines, along with their opinion on the everyday work factors that hinder and enhance the work. Furthermore, operators provide their perspectives on the future potential of technological advances in these machines. Organisational characteristics that affect operators' work have also been identified through the studies. The analysis of Finnish case studies (Studies I-III, Table 1) seeks to improve the planning and organisation of forest harvesting operations while supporting operators' work well-being and long-term career success. The following research questions (RQ) will be addressed:

RQ1) What factors support forest machine operators' workability and productivity?
RQ2) How can workability and productivity be further supported?
RQ3) On what aspects should the future development of ergonomics focus, considering different work system levels?

**Table 1.** The research objectives in the three individual studies of the thesis.

| Study no. | Research objectives |
|---|---|
| Study I | To assess the current state of Finnish CTL operators' workability.<br>1. Determine WAI among operators.<br>2. Gather beneficial practices from operators for sustaining well-being at work and WA.<br>3. Compare operators' WAI to other occupational groups. |
| Study II | Evaluate how personal lifestyle influences WAI and productivity.<br>1. Estimate links between productivity, WAI, sleep, and shift work. |
| Study III | Investigate CTL operators' current use of assisting systems and their future desires.<br>1. Gauge the opinions of operators regarding the current functionality of assisting systems.<br>2. Assess the shortcomings and hindrances in relation to ergonomics that operators face in their daily work.<br>3. Examine operators' desires and prospects concerning future assisting systems. |

# MATERIALS AND METHODS

## Methodological approach and overview of data and methods

Ergonomic complexity in mechanised harvesting spans multiple layers, including human-machine interactions, the forest environment, technology, communication, leadership, management and the dynamic interplay between micro- and macro-ergonomics. This multi-level nature of ergonomics is connected to forest machine operators' productivity and well-being, appearing as different ergonomic aspects at work system levels. To understand the phenomena, various types of research questions are needed. This would require both quantitative and qualitative data and an analysis that uses the mixed methods approach and acknowledges the foundational characteristics of those data and methods. This thesis draws on theories from the disciplines of ergonomics and forest technology, while combining workability and work well-being knowledge to capture the interconnected dimensions of the productivity and workability of forest machine operators.

The methods and data in this study (Table 2) are not only used to answer straightforward research questions, but also to understand cultural meanings and validate and complement the insights that arise from the datasets, ensuring a comprehensive understanding of the subject matter. Quantitative data, often relying on large datasets (Creswell 2014; Borgstede and Scholz 2021; Taherdoost 2022) with condensed, discrete and distinct representations of non-overlapping categories with values, enable the use of meaningful numerical calculation methods (Schoonenboom 2023), in this case around e.g. productivity and workability. Qualitative methods and data excel at exploring phenomena and revealing underlying patterns, providing a deeper understanding of social or human issues (Creswell 2014; Borgstede and Scholz 2021; Taherdoost 2022). Qualitative data is characterised by complex structures, richness and varied meanings, which can be analysed using qualitative methods (Schoonenboom 2023). In this thesis, interviews and open-ended questions in the surveys represent the qualitative contribution of the research. The specific methods used are described

**Table 2.** The nature of research data and methods in the three individual studies of the thesis.

| Study no. | Observations | Data | Method |
|---|---|---|---|
| I | 438 responses to the survey questionnaire | Quantitative<br>Qualitative | Kruskall-Wallis test,<br>Mann-Whitney U test,<br>Basic statistic values,<br>Themed content analysis |
| II | 9 operators<br>- Workability indexes, maximum oxygen uptakes, sleep values<br>- 152,745.5 $m^3$ harvested timber | Quantitative | Kruskall-Wallis test,<br>Mann-Whitney U test,<br>Non-linear models for productivity |
| III | 20 interviews<br>20 scoring of future visions | Qualitative<br>Quantitative | Themed content analysis<br>Basic statistic values |

more precisely later in this chapter. All the analysed data were original and were collected in Finland, and the thesis author carried out each of the collection campaigns.

### Workability index

This thesis employed the workability index (WAI) tool in Studies I and II to evaluate workability, a multidimensional concept arising from various aspects of a complex system. The WAI, developed by the FIOH, assesses employees' current health status and predicts near-future workability (Kettunen 2015). Additionally, the WAI has been shown to reliably forecast work incapacity, retirement and even mortality risks (Ilmarinen and Lehtinen 2004).

The WAI questionnaire (Rautio and Michelsen 2013) is divided into seven sections containing the individual's 1) workability compared to their lifetime best, 2) workability in relation to work demands, 3) current diagnosed medical conditions, 4) disadvantages of the medical conditions related to work, 5) number of sick days during the past 12 months, 6) employee's prognosis of future workability, and 7) psychological resources (Rautio and Michelsen 2013). Each section accumulates points, and the total index score can vary between 7-49 points. The result is classified into four categories: poor (7-27 points), moderate (28-36 points), good (37-43 points), and excellent (44-49 points).

Notably, by applying the WAI in timber harvesting operational research, this thesis contributed to validating the tool in this setting. A modified version of the WAI was used here, editing section 3, which specifically details diagnosed medical conditions, and instead inquired about only the total number of conditions. This adjustment did not alter the total WAI score, since the original questionnaire scores only the total number of diagnosed medical conditions, not the quality of the condition. Using the WAI, the thesis aimed to evaluate the workability levels of CTL operators across different age groups in Finland (Study I) and to explore possible relationships between the WAI, productivity and lifestyle factors in CTL work (Study II).

**Study I**

To estimate the WAI among forest machine operators, this study was carried out by means of an electronic survey (Webropol) that contained four subject areas: A) background information, B) work environment and work organisation, C) well-being at work and free time, and D) workability index (WAI). The questions were both multiple-choice and open-ended. Section A contained questions concerning age, work experience and the respondent's location. Sections B and C investigated organisational and physical ergonomics, but also personal lifestyle choices and the balance between work and free time. Section D contained a workability index questionnaire with the modification of section 3.

The aim was for the survey to be delivered directly to forest machine operators to avoid any intermediaries such as employers or timber procurement companies. Thus, it was published through the social media group "Metsäkoneenkuljettajat" (Forest machine operators) and followed by 9,000 people on Facebook during the campaign in September 2019. The questionnaire was available for two weeks and collected 461 responses by convenience sampling, but a total of 438 responses were analysed due to imprecision in some answers. Of the respondents, 65.3% were at most 35 years old (Table 3). The data was cross-tabulated and analysed using standard statistical values for basic characteristics and to clarify the data content. The WAI was estimated through different background variables: the non-parametric Kruskal-Wallis test and the Mann-Whitney *U* test were used to evaluate the WAI and statistically significant differences between the WAI groups. The statistical significance level of $p < 0.05$ was employed for all analyses.

**Table 3.** Age and work experience (years) of the Study I respondents (operators A-I).

| Age | % | Work experience | % |
|---|---|---|---|
| ≤ 25 | 33.3 | 0-5 | 33.8 |
| 26-35 | 32.0 | 6-10 | 20.9 |
| 36-45 | 22.2 | 11-15 | 18.9 |
| 46-55 | 9.4 | 16-20 | 11.8 |
| ≥ 56 | 3.1 | >20 | 13.7 |

**Study II**

To investigate the influence of operators' personal lifestyle choices and work demands on WA, this longitudinal study evaluated a group of 14 volunteer Finnish forest machine operators with continuous data collection on productivity, activity level and sleep over a year. Furthermore, every three months the operators completed workability index questionnaires and fitness tests. The data was collected from CTL harvester machines (John Deere, Komatsu and Ponsse brands), smartwatches (Polar) and electronic questionnaires (Webropol) remotely. Wearing smartwatches was completely voluntary: participants could wear and remove them any time they wanted, or even drop out of the study completely. During the data campaign, some participants changed work tasks or even career path, and there were also some sick leaves and failures in data delivery. Eventually, the study gathered comprehensive data on productivity, smartwatches and WAI from nine participants.

Smartwatches (Polar Ignite) measured and calculated daily activity (time), daily passivity (marks), daily steps (the number of steps), nightly sleep duration (time) and fitness test data. However, the trembles and vibrations of machines heavily impacted the watches, resulting in an exaggeration of daily steps and an underestimation of passivity, so they had to be excluded from the final analysis. Operators' nightly sleep values (SV) were estimated from the average sleep time on workdays, when the SV had a value of 1 if the sleeping time was the same as the average sleep time on workdays, greater than 1 if it was more, and below 1 if it was less.

Operators implemented the smartwatch fitness test every three months, simultaneously with the WAI questionnaire. Physical fitness, which also affects workability, is generally estimated using maximal oxygen uptake, a measure of cardiorespiratory fitness. Cardiorespiratory fitness refers to an individual's functional capacity and cardiovascular health, indicating their overall bodily function and well-being, and is considered an objective indicator of physical fitness (Suliga 2014). Even small improvements in an individual's $VO_{2max}$ can significantly improve the risk profile for cardiovascular disease (CVD), which is the leading cause of death globally (World Health Organization 2024). The smartwatch fitness test that was used in this study was based on measured heart rate variability (HRV), leading to the estimation of an individual's maximal oxygen uptake ($VO_{2max}$). The test was easy to perform and did not require physical strain. The watch's algorithm categorised results according to maximal oxygen uptake ($VO_{2max}$) on a scale from 1 to 7: 1) weak, 2) low, 3) satisfactory, 4) average, 5) good, 6) very good, and 7) top performance.

Productivity data collected from CTL forest machines were in StanForD, StanForD2010, .pdf, and .xml formats and further converted/processed in Excel spreadsheets. Gross effective time productivity ($E_{15}$) was used in the analysis, thus productivity under 5 $m^3 h^{-1}$ and stem size smaller than 0.06 $m^3$ were removed. Also, only basic thinning and clear-cut stands were accepted in the analysis excluding, for example, power lines, road lines and plot working sites. The total volume of timber data, which was able to be combined with smartwatch data, was 152,745.5 $m^{3,}$ of which 60.3% was from clear-cuttings and 39.7% from thinnings (Table 4). Harvesting methods (thinnings and clear-cuttings) were not divided evenly between operators due to their machine type, geographical positioning or customer demands. Operators tended to work in 8-hour shifts (morning, evening), but shift structure and work tasks also fluctuated over the study period due to external causes such as market situations or weather.

Since precise productivity data in Finnish business culture is highly sensitive, the level of productivity was presented in relative volumes. A productivity model ($P_m$, equation 1) of the data by average stem size, which was given a value of 100, was created as a polynomial function.

$$P_m = a * x^2 + b * x \quad (1)$$

Where:

$P_m$ modelled productivity ratio, $m^3_{\%}/E_{15}$
a, b constant
x stem size, $m^3$

The relative productivity level of the operators ($P_r$, equation 2) was calculated by dividing the operator-specific productivity ratio ($P_0$) by the modelled productivity ratio ($P_m$). As the aim of the study was to investigate the changes in productivity, the use of scaled values did not compromise the results.

$$P_r = \frac{P_0}{P_m} \quad (2)$$

Where:

$P_r$ relative productivity
$P_0$ operator's actual productivity ratio, $m^3_{\%}/E_{15}$
$P_m$ modelled productivity ratio, $m^3_{\%}/E_{15}$

Pearson's correlation coefficient and the standard statistical parameters (mean, median, mode, standard deviation) were used to clarify data content and possible dependency relationships. Pr, WAI, $VO_{2max}$, SV and daily activity were evaluated through different background variables, and the Kruskall-Wallis test was used to assess variables. Regression analysis was used to model productivity, but no statistical differences or relevance were found in the data.

**Table 4.** The total amount of harvested timber in the study data and its distribution between harvesting methods.

| Total | Thinnings | Clear-cut |
|---|---|---|
| 152,745.5 $m^3$ | 60,670.4 $m^3$ | 92,075.1 $m^3$ |
| 100.0% | 39.7% | 60.3% |

**Study III**

In this study, 20 harvesting machine operators in Finland were interviewed by phone. The interview method modified the traditional contextual interview design, since the operators worked concurrently and actively engaged with the tasks of interest. The traditional contextual interview method can make it easier for participants to explain and demonstrate functions while working, and for a researcher to provide a deeper understanding of the user's behaviour and motivations (Beyer and Holtzblatt 1998; Page 2005; Bednar and Welch 2009).

Participants, with ages ranging from 20-60 years, and experience ranging from 1-40 years, were sought from harvester contractors across Finland (Figure 2). The study used expert sampling (Etikan 2017) to ensure interviewees' knowledge of current and latest technological harvester machine solutions. The contractors recommended technologically aware and/or experienced candidates who operated newish machinery from their staff. Participation in the study was completely voluntary.

The interview framework was semi-structured and comprised two sections: the first part focused on different aspects of the harvester machine and job characteristics, while the second addressed work difficulties/limitations, ideas and suggestions that operators had for future development, and a numeric Likert scale evaluation of 21 possible developments in CTL harvesters. These advancement possibilities, e.g. future visions, were hypothesised based on the latest steps in machine development, the short- and long-term prospects that could be seen in the sector and the features that were presumed to appeal to operators. The interview framework allowed participants to begin with familiar topics related to everyday work and existing machine features. This facilitated the establishment of an atmosphere of trust and a psychologically safe space, because as the interview progressed, it delved into more abstract and visionary matters, requiring open-mindedness and boldness to discuss complex and speculative solutions.

The average interview time was 1 h 13 min and the total interview audio data was 24 h 25 min. Data were manually transcribed verbatim and further analysed in ATLAS.ti for Windows (ATLAS.ti 2024). The data analysis was based on qualitative-themed content analysis, as some thematic areas were acknowledged or perceived before data collection. The expected themes were complemented in the coding process, and eventually the analysed codes concluded themes of *current assisting systems, work hindrances and restraints, future assisting systems, feedback, work culture* and *motivation*. Sentiment analysis was used to classify codes and quotations into negative, neutral and positive classes to evaluate, e.g. the usefulness and functionality of the assisting systems. Also, the responses were assessed through interviewees' background information and links between codes and themes were observed. The 21 future visions that operators evaluated using the Likert scale were calculated with average scores and standard deviations.

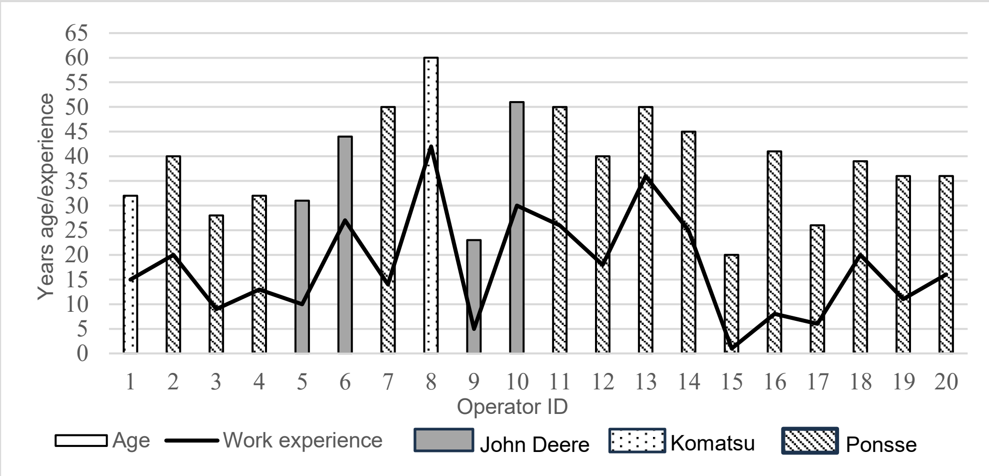


**Figure 2.** Age, work experience and machine brand of the 20 interviewed study participants.

# RESULTS

## Micro level work system and ergonomic aspects

*Human-machine-environment interaction*

According to the results from Studies I-III, the operators' productivity and ergonomic aspects were influenced by job demands, machinery, personal resources, workability index, forest environment, leadership and management. The operators' work occurs primarily in the human-machine-environment system, which involves both physical and cognitive ergonomic aspects. In this micro level system, the operators were quite satisfied with the machinery, but they emphasised the extensive adjustment options that enhanced the tuning and personalising of the machine and hoped that these options would continue to improve in the future.

Regarding physical ergonomics, operators were fairly satisfied with the machinery and were of the opinion that significant progress has been made towards achieving a more user-friendly experience. They noted, for example, that improved visibility and the introduction of boom tip control (BTC) improved physical and cognitive ergonomics, productivity and overall performance (Study III). While operators welcomed BTC, they also expressed interest in the next generation of boom automation, hoping it could further simplify boom movements and reduce repetitive hand motions. Despite these advances, operators continued to experience severe discomfort, vibration and noise. They reported pains and disabilities in their arms, neck, shoulders and back, repetitive movements and vibration (Studies I-III). Also, operators felt that technical problems with machinery took a long time to resolve and fix, leading to long periods of downtime (Study III).

On the cognitive side, operational work involves continuous decision-making and environmental assessment, which can strain operators. IT and decision-support systems, such as bucking algorithms and map layers, were seen as easing this burden (Study III). Reverse cameras, originally added to reduce physical strain, mainly helped by improving visibility behind the machine, ensuring that nothing unusual occurred.

The feature that drew the most criticism concerning machinery from operators was the use of loud alarms and notification sounds for system (mal)functions (Study III). Operators preferred a calm work environment, and often times muted the optional sounds altogether, thus the automatic system sounds were considered overly intrusive and disruptive. For future developments, operators expressed a need for more cognitive assistance, such as tools for log quality assessment and machine route planning (Study III).

*Personal resources*

Personal resources influence all operational work, from individual decision-making, stamina and stress tolerance to the ability to cope with changing situations and job demands. CTL operational work is highly independent, which is very much appreciated by operators and an important motivational factor. At the same time, however, it requires excellent self-management skills, an ability to handle changing situations and an understanding of how decisions in harvesting operations influence the whole timber supply chain (Studies I-III).

Generally, the WAI was at a good level among operators, especially among young respondents (Studies I-II). With age, the WAI decreased and the standard deviation increased (Studies I-II), followed by statistical differences between age groups (Study I). In this thesis, personal resources, containing mean sleep duration (SV) and estimated physical fitness ($VO_{2max}$), were positively related to WAI and relative productivity ($P_r$), as operators with higher productivity had higher SV and WAI (Study II). Also, operators with better $VO_{2max}$ had higher SV and a higher WAI.

$VO_{2max}$ levels did not seem to influence productivity (Study II), but it seemed to support operators' WAI. However, the unexpected COVID-19 outbreak in February 2020 and the restrictions occurred during the Study II data collection, while operators scored lower $VO_{2max}$ levels towards the end of the data collection period. Generally, many operators supported the opinion that exercising in their free time and getting their minds off the work ensured high vitality and engagement in the machine work (Studies I-II). During work, operators reported taking exercise breaks if no other breaks arose (Study I) which gave them the opportunity to physical movement.

Independent work, forest surroundings, the ability to see actual work results, modern machinery and a like-minded and supportive work community were all factors that motivated operators in their work and retained them in the sector (Studies I III). It was also evident that operators took immense pride in their profession and were passionate and committed to their expertise (Studies I-III). Productivity was one obvious manifestation of the phenomenon, as operators accurately recognised their production metrics in various situations and also compared them to the presumed "average" level. They also repeatedly emphasised the desire to improve operational performance, but found it challenging, particularly with regards to work quality, because of limited feedback on the matter. To achieve a sufficient productivity level, operators often sought a flow state in their work, which gave a relaxed and easy rhythm to processing. This was considered important, since overexertion and working against the clock ultimately disrupt the flow and can lead to exhaustion and burnout (Studies I III). If having trouble entering the flow state, operators used, e.g. audiobooks (44.5%) or talked on the phone (26.1%) to facilitate it (Study I).

### Meso and macro level work systems and ergonomic aspects

The work at meso and macro levels relates primarily to cognitive and organisational ergonomic aspects, as operators' roles at these levels involve providing and managing data, and facilitating communication between various stakeholders connected to the worksite under operation (Study III). Operators tended to communicate with different stakeholders very closely, often more than with their supervisor, to ensure the overall success of operations, and formed a kind of loose team, although stakeholders represented different organisations with various objectives. This network of stakeholders and colleagues provided a sense of community, which served as an important counterbalance to isolated work (Studies I, III). Furthermore, colleagues not only provided peer support, but also shared information and ideas on how to use new technologies and machine features effectively. Operators also received guidance and instructions from machine manufacturers and, with the advent of internet-enabled remote control, the advice has become more accessible and comprehensive.

One of the most frequent challenges operators cited in their daily work was the inadequate preparation of harvesting sites and the inaccuracy of work instructions they received (Studies I, III). Proper worksite preparation, including sufficient instructions tailored to the site's specific characteristics, should be completed before operations begin. When these aspects were neglected by supervision or related stakeholders, it led to confusion and delays, as operators were forced to recheck, verify and finalise operational plans and secure the necessary permissions (Studies I, III). Moreover, operators were required to report on a wide range of data from completed, ongoing and upcoming tasks (Study III). They often felt that these reporting duties consumed a significant portion of their productive time and contributed to increased machinery downtime, which led to frustration and resistance.

Regardless of the extensive reporting requirements, defined at the macro work system level, operators seldom received qualitative feedback on their work, despite their interest in enhancing performance (Study III). Regarding the quality of their work, operators received occasional education and advice on mandatory regulations and recommendations from organisations to update their competence (Study III). However, operators did receive some numerical feedback, as they were provided with data on log dimensions and log-bucking success rates from sawmills (Study III). This feedback, linked to specific work site and machine identification numbers, was usually accurate and delivered on a regular basis (monthly or even weekly).

Organisations have often arranged harvesting work as a two-shift system, morning and evening, and 65.7% of operators also worked, at least occasionally, during weekends (Study I). Although operators' productivity between shifts did not differ significantly, sleep patterns between morning and evening shifts alternated. This caused sleep deprivation during morning shift weeks (Study II) and increased sleep duration in the following evening shift weeks. This phenomenon was visible throughout the data (Study II). Additionally, sleep duration increased after the peak winter season and during holiday seasons. This indicates high levels of work strain and the importance of careful shift planning by organisations.

# DISCUSSION

### Key insights into ergonomic support and challenges for machine operators

This thesis investigated the well-being and productivity of CTL machine operators from the points of view of productivity, workability and human-machine-environment system functionality. Based on studies, it also identified organisational characteristics that influenced operators' work. Summarising the findings, the operators were generally satisfied with micro level ergonomics (RQ1), the human-machine-environment interaction. However, they were still exposed to various strains, indicating that there would still be room for improvement in the micro-eergonomic design (RQ2-3). Furthermore, most of the work hindrances, shortcomings and criticisms focused on macro ergonomics and the work's organisational aspects, emphasising work site preparation, instructions and feedback (RQ2-3). Being highly independent work, the operators' resources and characteristics, which naturally vary, play a crucial role in shaping ergonomic outcomes at all ergonomic and work system levels (RQ1). However, effective, carefully implemented management and high-quality leadership can support work well-being and positively influence productivity, despite individual differences (RQ1-3).

### Micro-level ergonomics

*Human-machine-environment interaction*

Despite the efforts to improve physical ergonomics in the machinery, operators still suffer from issues such as vibration and poor work postures, leading to discomfort, pain and even disabilities in the arms, shoulders, neck and spine (Studies I-III). These results were somewhat in line with vibration and noise studies of forest machinery (Lima et al. 2019; Poje et al. 2019), even though CTL machinery seems to be the most ergonomic option in mechanised harvesting (Oliveira et al. 2021). While advances in CTL machinery have tried to address diverse anthropometric needs, the minimum requirements of which are defined in standards (e.g. ISO 14738:2002), operators continue to experience discomfort due to sedentary work and the physical constraints of the cabin layout, with limited space and adjustment options (Studies I-III), which still leaves room for improvement. CTL machines tend to operate in two shifts, meaning that at least two operators, who may vary significantly in body size and shape, use the same equipment. The range of available adjustments, such as seat settings, can substantially impact physical ergonomics. In the worst, or best, cases, these are set at "average", resulting in poor working postures for everyone. Expanding the range of tool adjustments and simplifying the toggling between settings, while maintaining usability, would greatly reduce operators' physical strain.

Assisting systems in CTL harvesters, such as bucking algorithms and BTC, are often seamlessly integrated into processive work, meaning they are widely adapted and increasingly expected as standard features (Study III). Even when used selectively, such as with map layers, these systems provide important verification in uncertain situations and help streamline the work (Study III), thus reducing cognitive burden. In this independent and often isolated work environment, operators tend to avoid uncertainty and mental workload, seeking reassurance and peace of mind by using the systems in various ways (Study III). The risk of increased workload due to automation has been a long-standing concern in the EHF field (Norman 1990; Young and Stanton 2023) and was also raised by forest machine operators. While they welcomed new assisting solutions, they strongly emphasised the importance of not increasing their workload (Study III).

In modern CTL machinery, IT systems and assistance also contribute significantly to maintenance and repairs (Study III). However, the ergonomic effectiveness of these systems was still questionable, as users encountered vague or inaccurate alarms, notifications and instructions. On the positive side, internet connectivity enables remote system control, which improves the accessibility of help and the efficiency of repairs and fine-tuning operations.

*Personal resources*

CTL machine operators' workability levels were generally good, but exhibited some decline and variation with ageing (Studies I-II). These findings were consistent with previous research on workability (e.g. Tuomi et al. 2001; Tobia et al. 2005; Costa and Sartori 2007; Ilmarinen et al. 2013; Rypicz et al. 2021). Operators perform highly independent tasks that require a versatile skill set, including technical proficiency, environmental awareness and self-management, thus factors supporting their workability include high motivation, reliable machinery and a strong sense of competence. However, several challenges to maintaining workability were identified in the thesis studies, such as exposure to machine vibrations, extended periods of sedentary work, poorly prepared worksites, inadequate organisational support, demanding environmental conditions and pressure to meet high productivity targets. Notably, no significant mental health concerns were reported by respondents (Studies I-II), despite the growing prevalence of mental health issues, increased medication use and work-related disabilities in recent years (Mcdaid et al. 2005; Blomgren and Perhoniemi 2022; Petrea 2023).

Thesis studies showed that operators with higher workability levels tend to exhibit increased productivity and higher estimations of $VO_{2max}$ levels. Previous research has indicated that workability is influenced not only by organisational factors, but also by individual mental characteristics and physical fitness (Bugajska et al. 2005; Päivärinne et al. 2019; Suorsa et al. 2022). Maintaining robust physical fitness could also mitigate physical strain in predominantly sedentary forest operational work that consists of prolonged static work postures, repetitive movements and machine vibrations. Operators reported that achieving a healthy balance between work and leisure time aids in (mental) recovery from work-related issues, with recreational activities being particularly beneficial (Studies I-II). While physical exercise is ideal in terms of offsetting the sedentary nature of their work, any activity that provides mental detachment from occupational concerns is shown to be advantageous (Sonnentag et al. 2008). However, the declining levels of physical fitness and increasingly sedentary lifestyles observed in younger generations pose a significant risk to overall well-being, which may also reduce the personal resources available for work (Leyk et al. 2012; Rabiee et al. 2015; Santtila et al. 2018).

When talking about personal characteristics and attitudes among operators, one notable trait consistently emerged across the thesis studies: a strong sense of professional pride. This was closely tied to an acute awareness of personal production metrics, how operators' productivity compared to that of colleagues and the need to meet and exceed the company's productivity demands. Given that financial transactions in the timber harvesting industry are typically based on production volumes, production naturally becomes a central focus for operators. Operators even engaged in friendly competition with colleagues, which further fostered a culture of high output (Study III).

In addition to striving for high output, operators also sought to achieve a flow state in their work, which allowed them to operate efficiently while maintaining long-term well-being. According to research, flow state is highly beneficial for job satisfaction, engagement, performance and well-being, offering benefits for both the individual and the organisation (Fullagar and Fave 2017). Operators reported that engaging in activities such as listening to audiobooks helped them enter a flow state (Study I), although they acknowledged certain risks, such as overachieving, that could disrupt it. Nevertheless, operators are not passive subjects dependent upon work circumstances with little control and research also suggests that workers can take proactive steps to enhance their likelihood of achieving flow (Bakker et al. 2019; Liu et al. 2022; Liu, Lu, et al. 2023). Interestingly, one key strategy in proactivity is incorporating playful elements into work design (Liu, Bakker, et al. 2023; Liu, Lu, et al. 2023), which operators were also already practising, e.g. through friendly competition. However, challenges in flow arose when worksite conditions, such as ambiguous instructions or excessive understory growth, impeded both productivity and flow (Study III). These obstacles often led to frustration and criticism of organisational and macro-level ergonomics, compromising work quality also.

## Macro-level ergonomics

### *Work instructions and reporting*

The biggest hindrances and shortcomings identified by operators are largely related to organisational ergonomics at the meso and macro work system levels (Studies I, III). Key criticisms include poor work preparations and instructions, inefficient reporting procedures and a lack of feedback. Operators are expected to initiate, perform and complete worksites independently, relying on preparations at the worksite, instructions provided and their professional expertise. Ambiguous instructions increase cognitive workload and are vulnerable to misinterpretation, which, according to previous research, increases the risk of errors (Radüntz et al. 2020; Claeys et al. 2019).

Providing highly detailed instructions in the Nordic countries can be challenging due to fluctuating environmental conditions. Nevertheless, operators frequently reported vague or incomplete worksite preparations and instructions, resulting in reduced productive work time, increased machine downtime and operator frustration (Studies I, III). Beyond lost productivity, poorly organised and instructed work negatively impacts motivation, work quality and engagement, a finding in research in other occupational areas also (e.g. Chan 2005; Kahya 2007; Moè 2009; Kandemir and Handley 2014; Bosch et al. 2017; Li et al. 2018; Hakanen et al. 2021). This can ultimately lead to broader challenges such as difficulty retaining staff (e.g. Trevor 2001; Kyndt et al. 2009; Sulamuthu and Yusof 2018).

As manual labour in site preparation is costly, digital tools such as forest inventory data, aerial images, trafficability maps and AI are increasingly used in planning. While cost-effective, these tools may not provide the accuracy needed for forest operations (Packalén and Maltamo 2008; Vähä-Konka et al. 2020; Vastaranta et al. 2022; Sparks et al. 2024), requiring on-site verification. However, tailoring the level of detail of instructions based on the operator's experience could be beneficial for both the planner and executor. Experienced operators, with their accumulated expertise, are better qualified to make decisions in ambiguous situations when circumstances play a crucial role, often finding satisfaction in overcoming such challenges (Study III). Previous research shows that providing challenges that align with or slightly exceed the operator's skill level supports and improves professional development (Heckhausen et al. 1985; Noe et al. 2010; van Steenbergen et al. 2015), and that tasks that have clear, well-defined objectives aligning to workers' skills facilitate the individual's flow state (Csikszentmihalyi 1997; Bakker 2008; Maeran and Cangiano 2013). Moreover, higher levels of challenges and skills predicted flow over time (Rodríguez-Sánchez et al. 2011). This emphasises the importance of providing operators with clear work instructions that match their skill levels to optimise both flow and productivity.

The macro work system level defines the type, accuracy and methods by which forest machine operators are expected to report information to the supply chain and management. Although operators are essential in providing these data, the tools designed for reporting are often inefficient and require a lot of time and manual effort, leading to prolonged machine downtime, reduced motivation and lower work quality (Study III). Reporting tasks were perceived as stressful and beyond operators' core duties, as well as secondary and outside their expertise, resulting in lower motivation to provide accurate data. Despite this, reliable data from operators are critical for planning and resourcing in areas such as timber hauling (Palander et al. 2024), so improving reporting processes and tools is essential.

*Feedback*

When conducting and completing worksites, operators received limited feedback. While numerical data on the accuracy of timber bucking is communicated effectively by sawmills and the supply chain, feedback on work quality is often lacking (Study III), even though regular and constructive feedback has significant potential to improve employees' work well-being, retain operators and improve their skills (e.g. Maeran and Cangiano 2013; Hakanen et al. 2021; Sonnentag et al. 2023). Operators expressed willingness to further develop their expertise, noting that evolving climate conditions present growing operational challenges. Also, operators often relied only on (compulsory) self-monitoring to assess their work, and they would appreciate external feedback to calibrate their assessments and understand areas for improvement (Study III). Providing constructive feedback and facilitating adaptation to changing environments could improve operators' professional expertise, enabling them to apply a broader skill set (Kluger and DeNisi 1996). Continuous learning and skill enhancement can foster greater work engagement, typically characterised by vigour, dedication and absorption in the work. Adequate feedback and social support are beneficial in this regard. Particularly for older workers, engagement fosters retention and encourages continued contribution to the industry (Tomietto et al. 2019; Wallin et al. 2021).

Since feedback is closely associated with work engagement and quality, it is a key factor in long-term success. Feedback would also foster a sense of belonging within the community, reinforcing the relevance and meaning of the operators' work and their impact on the supply chain (Bakker and Demerouti 2008; Rich et al. 2010). Additionally, the perception that one's work has a positive impact on others has been linked to more frequent experiences of flow (Maeran and Cangiano 2013), and effective feedback and social support positively influence employee well-being and engagement (Sonnentag et al. 2023). In the context of forest machine operators, this highlights the intrinsic motivational value of receiving feedback. For feedback systems to be impactful, they require clear definition and integration at the management level to enhance learning, engagement and satisfaction, yielding benefits for both employees and organisations.

*Work community and arrangements*

In terms of the work community, forest operators' networks extend beyond their immediate colleagues to include stakeholders such as timber sellers, buyers, logistics, machine manufacturers, material suppliers and infrastructure maintenance providers. This broader network and peer support provide operators with informal insights into the supply chain, local conditions and useful tips (Studies I, III). Peer support in particular was valued and it helped operators navigate challenges and adapt to new technologies and, according to research, it can positively impact the organisational and working climate, or even mitigate bad atmosphere (Colquitt et al. 2000; Parker et al. 2008; Martin 2010; Noe et al. 2010; Wingreen et al. 2021). Such support can be a major positive draw for operators, and management can further encourage this sense of community by creating opportunities for intercommunication.

The shift work structure and peak seasons in forest operations disrupt and alter operators' sleep patterns and recovery (Study II), emphasising the importance of well-implemented work arrangements and leadership, as adequate sleep and recovery are essential for individuals' well-being. In forest operations following an intense peak season, prioritising recovery becomes essential. Employers can support this by providing recreational opportunities that promote recovery and overall well-being (e.g. Donaldson-Feilder et al. 2013). Research suggests that daily recovery practices are vital for maintaining well-being and preventing exhaustion, beyond longer recovery periods such as weekends or holidays (Oerlemans and Bakker 2014). This need for daily recovery becomes particularly challenging in the context of seasonal forest work, where the peak season frequently coincides with winter, the darkest period of the year, which can exacerbate the strain on operators' well-being.

## Strengths and limitations of the thesis

This thesis investigated CTL operators' workability levels, well-being and functionality in a human-machine-environment system using a mixed method approach, integrating theoretical, methodological and conceptual tools to analyse these complex, multi-dimensional issues. Integrating multiple methodologies can yield valuable insights into the multifaced nature of these phenomena (Mingers and Brocklesby 1997); however, these approaches should be applied carefully to avoid contradictory results (Creswell and Clark 2007; Slonim-Nevo and Nevo 2009). This thesis successfully used various data and methods and, to mitigate risks, the researcher sought guidance from a diverse supervisory team, drawing expertise from fields such as forest technology and engineering, ergonomics and various research methodologies. Additionally, an external steering group, comprised of field experts, was established for Studies I and II.

All data for this thesis were original and unique. They were collected through a combination of fixed and open-ended questionnaires, incorporating both qualitative and quantitative responses, along with metrics from smart watches, CTL harvester productivity data and semi-structured interviews. While the samples were limited by either representativeness (Study I) or size (Studies II-III), presenting challenges as regards generalising the findings, they also contributed knowledge and insights in relation to the operational work and its influencing factors.

In Study I, the overall response volume was larger than in previous studies in the field and provided valuable insights into operators' workability levels, well-being and work characteristics. However, a high number of responses from younger operators was observed and, to address the uneven age distribution of respondents, the data were adjusted accordingly during the analysis.

The data collection in Study II spanned 12 months, a significantly longer duration compared to typical forestry ergonomics and well-being studies, which are often based on much shorter timeframes (e.g. Borz et al. 2019; Spinelli et al. 2020). This extended period provided unique and pioneering insights into long-term workability and well-being, accounting for the effects of shift work and seasonal variations. However, Study II involved several unforeseen challenges during the data collection phase, including an uncharacteristically mild winter season with incomplete ground frost and delayed snow cover, which restricted operations in winter stands aka peat lands, and snowless ground that made for darker working conditions. Also, in early 2020, strikes within the forest industry and the onset of COVID-19 restrictions caused temporary fluctuations in study participants' work and potentially impacted on operators' well-being, factors which were taken into account during the analysis. While the harvester machine data were objective and reliable, the smart watches showed some instabilities, which were accounted for in the analysis and excluded from the main conclusions.

In Study III, the semi-structured interview framework was carefully designed, aiming to avoid bias in questions and starting with accessible questions concerning everyday work to establish trust and create a psychologically safe environment. This approach facilitated the exploration of more complex and abstract topics related to the future of CTL machinery. The expert sampling method was employed to ensure the participants' knowledge of the latest technological solutions and systems functionality in different environments. However, some insights regarding accessibility may have been inadvertently uncovered with this approach. Interviews were audio-recorded and transcribed verbatim, allowing for precise analysis and the validation of interpretations through re-evaluation.

To enhance deeper, comprehensive and contextualised results in future research, broader and more uniformly distributed datasets, both quantitative and qualitative, are recommended. Tracking well-being factors would benefit from more accurate and reliable devices, thoroughly validated before data collection. Additionally, in long-term data collection periods, unexpected situations may occur, so backup solutions for mitigating risks and avoiding data attrition should be given sufficient attention.

## Future prospects

The findings of this thesis highlight key challenges in CTL harvesting work and could serve as a foundation for further research and specific developments. To enhance operators' work well-being, productivity and retention, future studies might explore improvements in macro ergonomics, such as work arrangements, the role of optimal guidance, support and feedback, but also in micro ergonomics, such as advances in physical and cognitive ergonomic aspects within human-machine-environment interaction. To provide meaningful, engaging work for operators, technological and ergonomic advances should be driven by operator needs, rather than using operators' work time to gather data for the broader industry. New systems should undergo a thorough ergonomic evaluation to ensure that they do not inadvertently increase operator strain.

From an organisational point of view, the seamless integration of reporting systems into operational processes would be welcomed. Generative artificial intelligence (AI) can potentially automate reporting tasks, reduce frustration and enable operators to focus on productive machine operations. AI-driven solutions could bridge the gaps where traditional technical solutions fall short, offering both operational and ergonomic benefits. Additionally, timely and effective feedback practices are crucial for retaining operators and developing their skills, particularly early in their careers. As timber harvesting is volume-driven, ICT solutions, including AI and gamification, can streamline feedback processes, making them efficient and less burdensome on supply chains. Adequate feedback not only enhances operators' skills, but also fosters a sense of relatedness, both of which are critical during the early stages of their careers.

To promote and enhance personal resources such as healthy lifestyle choices, vocational education could play a stronger role. As the prevalence of sedentary lifestyles and associated health risks continues to rise, general information on the benefits of nutrition, sleep and physical exercise may prove insufficient. Instead, personalised guidance tailored to specific needs, with support in making healthier choices and experiencing the tangible results of these decisions could be more beneficial for individuals. Personal guidance could also be adapted to work organisations, although it is recognised that individuals bear personal responsibility for their lifestyle choices.

In the human-machine-environment system, assisting technologies should adapt to the diverse conditions shaped by harvesting methods, environments, tasks, work experience and individual preferences. Enhancing system adaptability and micro-ergonomics, alongside continuous education, will better equip operators to adjust systems to evolving demands. Since operators are receptive to advice from their peers, facilitating knowledge-sharing among colleagues would further improve the effective use of machine systems. Incorporating gamification could offer further benefits and engage operators in the learning processes and the adaptation of new machine features (Krath et al. 2021).

## CONCLUSIONS

Technological advances have transformed forest operations from a physically demanding job to one which involves more sedentary, skill-intensive tasks. CTL machine operators now require a high level of technological and environmental expertise, particularly in regions such as the Nordic countries. Despite the advances, the sector faces a global shortage of skilled workers, as training programmes struggle to fill available places and operators often move to less demanding careers.

The future of timber harvesting will involve balancing technological innovation with operator well-being and environmental sustainability. Automation, AI and ICT solutions can improve efficiency, but may also increase cognitive strain. Operators prefer to focus on core tasks, such as operating heavy machinery and contributing to sustainable forest management. To avoid cognitive overload, new systems must prioritise ergonomics and ensure that technology supports, rather than hinders, operator well-being.

Workability and well-being are critical for retaining skilled operators and sustaining long and fulfilling careers. Although individuals must bear responsibility for their personal health and lifestyle choices, vocational education and employer initiatives can help promote well-being and address work-related challenges. Leadership and management practices play a significant role in enhancing operator workability levels, and tools such as the workability index, also well suited to the forestry context, can assess operator well-being.

Personalised feedback mechanisms are essential for operator development and job satisfaction, especially in an industry driven by productivity. In isolated working environments, such feedback fosters skill refinement and enhances a sense of relatedness, particularly for operators in the early stages of their careers. ICT solutions, such as AI and gamification, have great potential as regards streamlining processes and fostering continuous learning, ensuring operators remain engaged and adaptable in a rapidly changing field.

The future of timber harvesting presents both challenges and opportunities. As demand for wood-based materials and renewable resources grows, the sector will play a key role in providing raw materials and job opportunities. Simultaneously, harvesting operations face growing complexities, not only due to the isolated nature of the work, but also because of the need to adapt to changing climate conditions and biodiversity considerations. While the work itself is challenging and demanding, supportive measures for operators should be highlighted. Skilled forest machine operators will play an essential role, offering professional insights to address upcoming challenges and implementing future solutions and sustainable practices.

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