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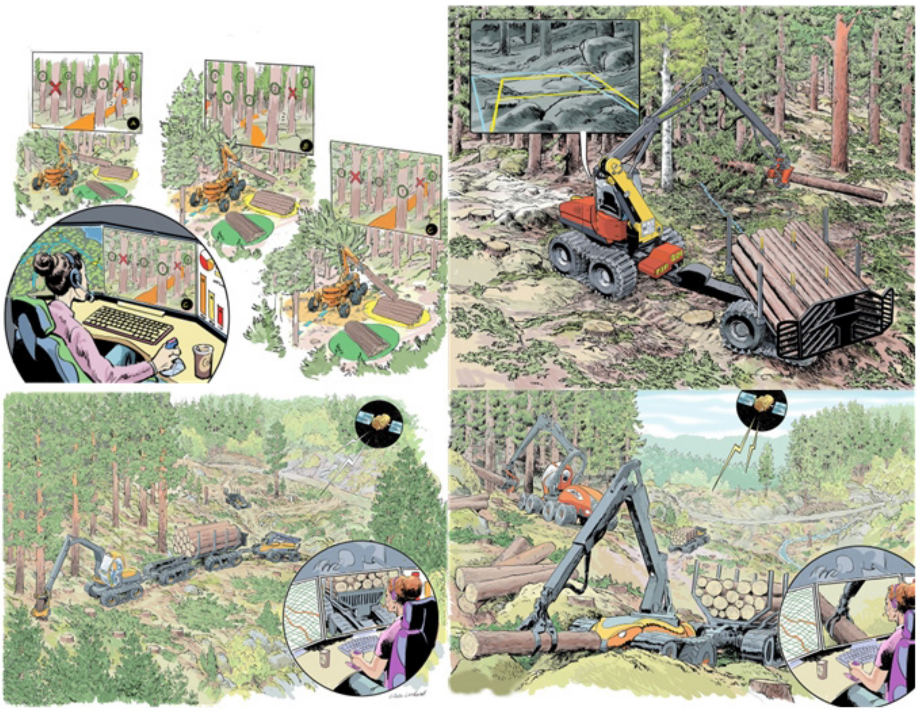
Strategic technology decision-making in Swedish large-scale forestry

Rikard Jonsson



Strategic technology decision-making in Swedish large-scale forestry

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Abstract

Technological development gives Swedish forest companies and forest owners' associations opportunities to maintain competitiveness in the highly cost-sensitive market for forest products. Development efforts are typically performed through unstructured decision processes. However, an organization's success is a product of its decisions, so the quality of these decisions is crucial. The main objectives of this thesis were therefore to describe and critically analyze strategic decision-making about forest technology. Study I investigated how and with what support forest companies and a forest owners' association make decisions about forest technology. It was concluded that these organizations value collaborations with manufacturers and researchers, that economic criteria were most important in the decision-making process, and that large risks are preferably managed in a stepwise fashion. Study II reviewed the use of Multi-Criteria Decision Analysis (MCDA) methods in forest operations and it was shown that the methods were used at various temporal scales, most commonly when making strategic decisions. Study III developed and compared two modelling approaches for machine system analysis and concluded that they produced similar results despite having different levels of detail and demanding different competences. Study IV used the previously developed modelling approaches to compare the performance of established and new machine systems in Swedish final fellings, revealing an opportunity to reduce costs by adopting the new machine system. A conceptual flowchart for strategic decision-making on forest technology development was created to improve the quality and efficiency of the decision-making process.

Keywords: decision processes; forest technology development; information needs; logging costs; machine system comparison; semi-structured interviews; cut-to-length; harwarder; optimization; multi-criteria decision analysis.

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Strategiskt beslutsfattande om teknik i storskaligt svenskt skogsbruk

Sammanfattning

Teknisk utveckling möjliggör att svenska skogsbolag och skogsägarföreningar bibehåller konkurrenskraft i den prispressade marknaden för produkter från den skogliga råvaran. Utvecklingsinsatser sker generellt genom ostrukturerade beslutsprocesser. Kvaliteten i beslutsfattandet är kritiskt för en organisation, eftersom besluten påverkar organisationens framgång. Syftet med denna avhandling var därför att beskriva och kritiskt analysera strategiskt beslutsfattande om skogsteknologi. I studie I undersöktes hur och med vilka stöd skogsföretag och en skogsägarförening fattar beslut om skogsteknologi. Det framkom att dessa organisationer värdesätter samarbeten med tillverkare och forskare, att ekonomiska kriterier var viktigast i beslutsprocesserna och att stora risker helst hanteras stegvis. I studie 2 granskades användningen av multi-kriterie analys-metoder i skoglig drift och det visades att metoderna användes till beslut på olika tidshorisonter, men var vanligast vid strategiska beslut. I studie 3 utvecklades och jämfördes två metoder för maskinsystemanalys, vilka gav liknande resultat trots att de hade olika detaljnivåer och krävde olika kompetenser. I studie 4 användes de två utvecklade metoderna för att jämföra prestandan hos ett etablerat och ett nytt maskinsystem i svenska föryngringsavverkningar, vilket visade på en möjlighet att minska kostnaderna genom att tillämpa det nya maskinsystemet. Ett konceptuellt flödesschema för strategiskt beslutsfattande om skogsteknisk utveckling skapades för att förbättra kvaliteten och effektiviteten i beslutsprocessen.

Nyckelord: beslutsprocesser; skogsteknisk utveckling; informationsbehov; drivningskostnader; maskinsystemanalys; semi-strukturerade intervjuer; kortvirkesmetoden; drivare; optimering; multi-kriterie analys.

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Strategic technology decision-making in Swedish large-scale forestry

Rikard Jonsson

Akademisk avhandling som för vinnande av skoglig doktorsexamen kommer att försvaras offentligt i Loftets hörsal, Ultuna, fredagen den 23 september 2022 klockan 13.00.

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Prepare for the worst but hope for the best
Benjamin Disraeli

Dedication

To Ludvig and Therese.

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Jonsson, R., Woxblom, L., Björheden, R., Nordström, E-M., Blagojevic, B. & Lindroos, O. Decision-making processes for strategic technology investments in Swedish large-scale forestry. Accepted for publication in *Silva Fennica*.

II. Blagojevic, B., Jonsson, R., Björheden, R., Nordström, E-M., Lindroos, O. (2019). Multi-Criteria Decision Analysis (MCDA) in Forest Operations – an Introductional Review. *Croatian Journal of Forest Engineering,* 40(1):191-205.

III. Jonsson, R., Rönnqvist, M., Flisberg, P., Jönsson, P. & Lindroos, O. (In press). Comparison of modeling approaches for evaluation of machine fleets in central Sweden forest operations. *International Journal of Forest Engineering*. 1-12.

IV. Jonsson, R., Rönnqvist, M., Flisberg, P., Jönsson, P. & Lindroos, O. Country wide case analysis of potential harwarder use in Sweden. Submitted to *Scandinavian Journal of Forest Research*.

Papers II-III are reproduced with the permission of the publishers.

The contribution of Rikard Jonsson to the papers included in this thesis was as follows:

I. Responsible for planning, study design, choice of method, data collection, analysis and article writing with support from co-authors.

II. Participated in planning, study design, choice of method, analysis and article writing with co-authors.

III. Responsible for planning, study design and data collection. Selected methods together with co-authors. Designed one modelling approach and participated in the design of the other. Responsible for analysis and article writing with support from co-authors.

IV. Responsible for planning, study design and data collection. Selected methods together with co-authors. Designed one modelling approach and participated in the design of the other. Responsible for analysis and article writing with support from co-authors.

Abbreviations

AH	Aggregated Heuristics
AHP	Analytical Hierarchy Process
DM	Decision-Maker
DO	Detailed Optimization
DSS	Decision Support System
FOA	Forest Owners' Association
HCG	Harwarder Collaboration Group
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
TMS	Two-Machine System

1. Introduction

1.1 Forest operations

Forest operations include stand establishment and tending, harvesting and transport to roadside, secondary transportation from roadside to industry, and logistics (Epstein et al. 2007; D'Amours et al. 2008; Rönnqvist et al. 2015). Forest operation problems have been discussed by authors such as Sundberg (1988) and Heinimann (2007). Heinimann (2007) asserted that forest operations consist of the "design, implementation, control, and continuous improvement of forest operations systems"; these issues are at the heart of the work presented in this thesis. Forest operations also necessarily encompass both methods and technology, and can be planned on three distinct timeframes: strategic, tactical, and operational. These definitions and timeframes provide a basis for further interpretation of strategic decision-making about forest technology.

The forest sector is important for the global economy and the transition to a bioeconomy (Ollikainen 2014). In Sweden, it directly employs approximately 115 000 people and is a substantial contributor to the country's gross domestic product, accounting for around 10 percent of annual product exports (Holgert 2021; Skogsindustrierna 2022). The sector faces competition from other sectors and other countries, forcing producers such as forest companies and forest owners' associations (FOAs) to pursue constant rationalization. Good decision-making is thus vital for the sector's success and long-term viability.

Strategic technology decision-making may be influenced by factors such as ownership and organization structure. In 2021, 47 percent of Sweden's forest area belonged to private owners (with 56 percent of this area being became dominant in the 1990s. These advances have led to immense increases in productivity and reductions in costs (Ager 2017). Such technological developments can be driven by three main factors: the emergence of markets for *new products*, which require an industry to respond to new demands; the introduction of *new laws* that impose stricter requirements concerning the conduct of operations; and the creation of *new technology* that enables operational improvements (Lindroos et al. 2017). Over the last few decades, several new examples of all three factors have appeared in the forest sector. For example, tops and branches for bioenergy purposes have become important *new products*, while increasing concern about environmental issues has led to the introduction of *new laws* concerning forestry. However, *new technology* has been the most important factor for some time. Technological advances transformed forestry from an activity performed mainly with hand tools to one based on mechanized logging operations with multiple machines working within a logging system. The number of machines needed then fell gradually until the current TMS became dominant in around 1990. Technological development has of course continued since then but has mainly resulted in incremental improvements of the TMS rather than new machine types or machine systems. For instance, TMS hardware has been refined (Nordfjell et al. 2019) and innovations such as operator support and partial automation have been introduced (Hellström et al. 2009; Lindroos et al. 2017; Flisberg et al. 2021; Visser & Obi 2021).

While ideas and innovations are crucial for development, transforming an idea into a fully implemented innovation can be a long and risky process. It usually requires the investment of substantial resources, and there is always uncertainty about whether the innovation will be commercially successful once implemented. To manage these risks, manufacturers such as Komatsu Forest AB have adopted multi-step procedures for testing innovations to ensure that the machine(s) under consideration have the potential to meet the market's expectations before initiating serial production. Broadly speaking, these steps involve constructing first a concept machine, then 1-2 prototypes, and finally a null series of 5-6 machines; serial production is only implemented if satisfactory results are obtained in all three preceding steps. The full process can take around 7 years to complete. In addition, there may be an initial step in which the innovation's potential is evaluated based on 'guesstimates' (i.e., educated guesses and estimates based on uncertain inputs), followed by construction and evaluation of a virtual version of the innovation. This process presents a number of challenges, and its successful implementation requires organizations and individuals that consistently use the innovation. The factors influencing the implementation can be divided into four groups (Hambrick & Mason 1984; Kim & Chung 2017): 1) innovation characteristics, such as the innovation's perceived usefulness; 2) social factors such as subjective norms and peer usage; 3) organizational factors, including implementation policies and management support; and 4) individual factors such as personal innovativeness and demographics.

1.3 Disruptive innovation

Technological development gives forest companies and FOAs opportunities to maintain competitiveness in the highly cost-sensitive market for forest products by implementing incremental innovations and/or disruptive innovations. In this thesis, an innovation is defined as a concept or technical solution (such as a technical detail or a machine), method, or procedure that is new to a user, researcher, and/or manufacturer (Cantisani 2006). Incremental innovations are minor improvements of existing technologies and are thus readily adopted by established manufacturers and users who can draw on knowledge of the originating technology. Conversely, disruptive innovations are new technologies that require the shaping of new knowledge within the manufacturer and sometimes also within the users (Veryzer Jr 1998; Thomond & Lettice 2002; King & Baatartogtokh 2015; Si & Chen 2020). Disruptive innovations are therefore much harder to implement but can be necessary because they can motivate the introduction of new manufacturing paradigms and help companies defend their market share from competitors.

Besides demanding the shaping of new knowledge, disruptive innovations have been distinguished from incremental improvements in various ways (Thomond & Lettice 2002; King & Baatartogtokh 2015; Si & Chen 2020). In particular, they have frequently been analyzed from a process perspective and by considering their main characteristics. Seen from a process perspective, disruptive innovations often originate from products or services that are initially inferior to established alternatives in terms of qualities valued by mainstream customers. The manufacturers of the mainstream products thus fail to react to the challenge of this inferior alternative, but the innovation is gradually refined and starts taking market share until it eventually displaces the previous mainstream product. Notable characteristics of disruptive innovations may include: 1) securing customers in a new way; 2) initially reducing gross profit; 3) generally performing less well than established technologies based on metrics traditionally valued by mainstream customers; and 4) outperforming established technologies based on metrics differing from those valued most highly by current mainstream customers (Si & Chen 2020).

Several different ways to ensure successful implementation of disruptive innovations have been reported (Veryzer Jr 1998; Marra et al. 2003; Hidalgo & Albors 2008; Skarzynski & Rufat-Latre 2011; Kim & Chung 2017; Rhaiem & Amara 2021; West 2021). A particularly notable contribution was that of Skarzynski & Rufat-Latre (2011), who outlined three "core lessons" for maximizing the chance of successful disruptive innovation: 1) anticipate and act on market discontinuities; 2) link incremental and disruptive innovations with a shared objective; and 3) develop a mindset where innovation opportunities and strategy inform one-another. Success in disruptive innovation is also influenced by organizational factors including implementation policies and practices, innovation characteristics such as perceived usefulness, social factors such as peer influence, and individual factors such as personal innovativeness (Marra et al. 2003; Kim & Chung 2017).

1.4 Innovation forms in Swedish large-scale forestry

In Sweden, there is a long tradition of collaboration in technology development between users of forestry technology, machine manufacturers, and researchers. This collaboration is colloquially known as the 'development triangle' (Ager 2017) and is important because development without input from manufacturers may lead to a focus on machine concepts that the manufacturers are incapable of constructing. Likewise, development without user input may lead to a focus on concepts that are unable to fulfill specific operational objectives, and development without input from researchers may make it difficult to reliably evaluate an innovation's performance before introducing it on a large scale, slowing down progress towards fulfillment of operational objectives. The users in this development process were initially large forest companies, who had the financial resources to invest in advancing innovations from concepts to serially produced technologies. Partly because of this, forest technology developed rapidly between 1960 and 1990. However, during the 1990s, most forest companies shifted from buying the technology (i.e., forest machines) themselves to hiring contractors with their own machines. Outsourcing in this way allowed forest companies and FOAs to move their risk-taking from forest operations to other branches of their organizations (Eriksson 2016). However, it also transformed the forest companies and FOAs from direct users of forest machines to proxies for the actual users, namely the much smaller contracting firms. As a result, it weakened the formerly close collaboration between the three groups within the 'development triangle' and meant that ideas were less readily transferred to manufacturers for further testing because the contracting firms lacked the financial resources to support development efforts (Kronholm et al. 2021). This caused the pace of development to stagnate or decline when measured in terms of productivity, costs, and innovation (Björheden 2014; Eriksson 2016; Ager 2017).

Increased cost-efficiency is important in the highly competitive, cost-conscious market for forest products. Innovations in areas such as operator support and automation have the potential to significantly increase cost-efficiency and could therefore be highly beneficial and disruptive. When implementing disruptive innovations, it is often necessary to also adapt one's business model, which can be more challenging than changing technology (Christensen 2006). The introduction of autonomous machines may enable several different business models – logging operations could continue to be performed by contractors as they are today, but it would also be possible for forest companies to buy autonomous machines and insource harvesting services. Alternatively, harvesting services could be insourced by machine manufacturers, or autonomous machines could be bought and operated by new actors such as firms with IT expertise (Holgert 2021).

1.5 Decision processes

An organization's success is a product of its decisions, which may be structured, unstructured, or somewhere in between. Structured decisions are usually repetitive and may be facilitated by clear routines, whereas unstructured decisions are characterized by novelty and complexity; they are the natural beginning of something new and may be followed by structured decision procedures (Simon 1960). Because of the importance of decision-making, it has been studied extensively, and research in this area has largely focused on the human actors who make decisions. For a long time, research on decision-making viewed humans as fully rational actors based on established normative theories. However, when researchers observed decision-making, it was found that humans are not so rational after all, which led to a focus on descriptive research. Improved knowledge about what decision-makers (DMs) *should* do provided by normative decision theories and what they *actually* do provided by descriptive decision theories led to the emergence of prescriptive decision research, which aims to develop aids and guidelines to help people make the most rational decisions possible despite humanity's inherently irrational nature (Dillon 1998; Bohman 2021).

Development efforts are typically performed through unstructured decision processes, so theories of unstructured decision processes provide a good foundation for describing and understanding development. Accordingly, several authors have applied such theories in studies on the innovation process (Utterback & Abernathy 1975; Galende 2006; Narvekar & Jain 2006), other specific contexts (Lönnstedt 1997; Martin et al. 2012), as well as general models that can be used to describe decision-making processes in diverse contexts (Mintzberg et al. 1976). The model of decision-making processes described by Mintzberg et al. (1976) is colloquially known as 'the structure of "unstructured" decision processes' and is widely accepted as a foundation of modern decision process research (Vacik & Lexer 2014). This model served as a framework for the research presented in this thesis and is therefore described in more detail below.

'The structure of "unstructured" decision processes' divides the decision process into three phases: identification, development, and selection. These phases are in turn divided into a total of seven routines, as shown in Figure 1 (Simon 1960; Mintzberg et al. 1976). This gives the model a level of complexity that is sufficient for the analysis of business organizations (Martin et al. 2012).

The identification phase contains two routines. The first is recognition, which involves three steps: 1) identifying a trigger; 2) classifying it as a crisis, problem, or opportunity depending on its urgency; and 3) determining an action threshold. In a crisis, it is common for DMs to seek to avoid negative consequences that may result if actions are not taken, so one or a few stimuli/triggers can be enough to start a decision process. As such, the action threshold in a crisis is low. In a problem scenario, there may be both a risk of negative consequences and a potential for positive ones, leading to an action threshold of intermediate height. Finally, in an opportunity situation, the trigger is the potential for positive consequences, sometimes in multiple areas. However, the action threshold is usually high. The second routine in identification is diagnosis, which involves evaluating causes and effects. This should ideally be a formalized routine within a decision process.

The development phase contains two routines: search, which involves searching for suitable existing solutions, and design, which is only performed if no such solutions can be found and a new solution must be designed.

The selection phase contains three routines. The first is screening, in which non-feasible and superfluous solutions are excluded to leave a manageable number of options for further consideration. The second is evaluation-choice, which has three components - analysis, in which the consequences of the alternatives are examined, often by experts; bargaining, in which multiple DMs or important stakeholders negotiate about the options and their content; and judgment, in which an authorized DM makes the decision. The final routine is authorization, in which the decision is anchored in the lowest necessary decision instance or with crucial stakeholders (Mintzberg et al. 1976).

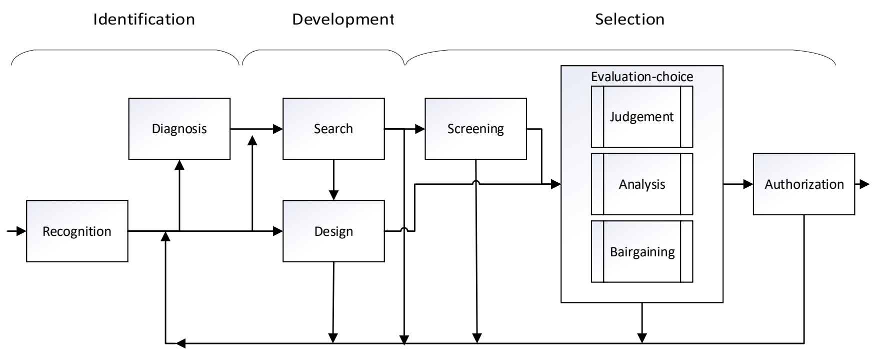

Figure 1. The structure of “unstructured” decision processes. Drawing based on Mintzberg et al. (1976).

The progress of a decision through the “unstructured” decision process varies depending on several factors. Not all routines are performed in all cases, and several iterations of the process may be needed before a final actionable decision is reached (Mintzberg et al. 1976).

When working through a decision process, alternatives (i.e., solutions to be considered) and criteria (or objectives, goals, or values) may be evaluated in different orders. If the process starts with an evaluation of alternatives that are then used to clarify the criteria, the decision process often becomes reactive. Conversely, if the criteria are defined first, it may be possible to formulate alternatives in more active and creative ways. Several researchers have therefore argued that the latter approach is preferable (Shim et al. 2002; Fülöp 2005; Keeney 2009).

1.6 Decision characteristics

The characteristics of decision situations can be categorized in different ways. For example, Mintzberg et al. (1976) classified decision situations based on the considerations that motivated their initiation – a desire to achieve positive consequences (opportunity), to avoid negative consequences (crisis), or a combination of both (problem). In this thesis, decisions are categorized in terms of certainty/uncertainty, temporal scale, the number of criteria involved (one or several), the number of DMs that are involved (one or several), and the number of alternatives under consideration, which may be discrete or continuous (Blennow & Sallnäs 2006; Segura et al. 2014; Kangas et al. 2015). Other important factors include spatial scale and the types of products and services that the decisions relate to.

1.6.1 Uncertainties

Uncertainties can be divided into three groups: knowledge, outcome, and value uncertainties (Blennow & Sallnäs 2006). Knowledge uncertainties can be reduced by learning – for example, by reading existing publications or by interviewing or observing relevant actors. Such uncertainties are common in the development of new forest machines and can be reduced by comparing a proposed innovation to established machines (Lindroos 2012). Notable knowledge uncertainties in this context include the impact of forest machine operators, stand conditions, and variation between machines. Operator uncertainties relate to variations in performance between different operators. It is common to initially study experienced operators who grasp new ideas quickly because learning to operate a machine efficiently is challenging, especially if the machine is novel and the operator has only a limited amount of time to become familiar with it (Purfürst 2010). Operator uncertainty in time studies can be alleviated by increasing the number of operators included in the study and including operators with varying levels of experience. With regard to stand conditions, two important variables that affect TMS performance are the mean stem volume and the extraction distance (Brunberg 2004; Nurminen et al. 2006; Brunberg 2007; Eriksson & Lindroos 2014). Those variables can be a source of uncertainty when making decisions about innovations, but the impact of this uncertainty can be reduced by studying new machines under the range of conditions that is expected to have the greatest impact on performance. Such research can also highlight stand conditions in which the innovation is most likely to provide significant advantages over existing alternatives. Uncertainty related to technology consistency, i.e. variation between individual machines of the same model, is unfortunately difficult to reduce other than by studying implemented machines. It can be decreased to an extent using guesstimates based on the performance of similar technology.

Outcome uncertainties are uncertainties that cannot be reduced simply by gathering additional data and can therefore only be resolved by executing decisions and observing their consequences. These uncertainties are often called 'risks' (Pasalodos-Tato et al. 2013) but are referred to as outcome uncertainties in this thesis. An example is the mechanical availability for a new machine: the machine's probable utility can be accurately estimated using statistics for machines of the same brand and model when operating in stands with similar characteristics to that under consideration, but neither users nor manufacturers can collect additional data to increase the accuracy of the estimates. These uncertainties must be accepted but DMs can let another actor take on some of the risk by purchasing insurance or similar guarantees, transforming a range of possible outcomes into a known cost.

Finally, value uncertainties arise when a DM has several criteria to consider and is not certain of their relative importance or how to balance them. For example, value uncertainty may occur when trying to account for the ecological, economic, and social consequences of harvesting operations while choosing a new harvester (Kühmaier & Stampfer 2010).

1.6.2 Temporal perspectives

Decision-making processes and problems in forestry are often categorized on a temporal scale according to which they may have a strategic, tactical, or operational perspective (Carlsson et al. 2006; Borges et al. 2014; Segura et al. 2014). However, varying definitions of these perspectives have been presented in the literature (Church 2007; Epstein et al. 2007; Gunn 2007). Moreover, temporal perspectives may differ widely within an organization: strategic planning may be performed on a 100-year horizon for some organizational units and on a 10-year horizon for others. Such differences in temporal perspective must be recognized when making comparisons. However, the core in the perspectives are the objectives, and these objectives can be considered common to most organizations and branches. This thesis therefore defines the three perspectives as described below.

Strategic planning focuses on creating policies and organizational objectives, as well as helping the organization to function and make decisions that promote its success (Mintzberg 1978; Hambrick & Fredrickson 2005). This level can and should include all parts of the organization and may include their redefinition through financial adjustment. The strategic perspective has no upper time limit but borders on the tactical planning stage at the lower end. *Tactical planning* concerns the implementation of the strategic plan during an upcoming period (e.g., the coming year) and the allocation of resources necessary for this purpose. In terms of temporal scale, the tactical planning stage lies in between strategic and operational planning; it is performed in accordance with the strategic plan and defines the conditions under which operational planning is performed. Finally, *operational planning* focuses on executing tasks defined in the tactical plan using the allocated resources.

These definitions are expected to capture (at a resolution suitable for the objective of this thesis) the nature of the planning process and its dependence on the time perspective. Precise definitions are considered crucial because the suitability of different decision support tools and their applications may vary with the time perspective.

In the context of forest technology, strategic planning would typically involve selecting one or more harvesting methods (e.g. whole-stem or cut-to-length harvesting) and suitable technologies for implementing those methods. Tactical planning would then entail investing in the technology needed to execute the subsequent operational plans and planning specific actions – for example, deciding how many machines of different sizes are needed to meet the requirements of the strategic plan. Finally, operational planning involves taking measures needed to perform specific actions, including scheduling resources for planned actions, detailed planning of actions, and on-site and real-time planning that is directly related to the plan's execution.

1.6.3 Other factors and decision-making complexity

When making decisions, it may be necessary to evaluate the available alternatives with respect to a single criterion or multiple criteria (which are often referred to as goals, values or objectives). Criteria can be quantitative (i.e., they may relate to measurable variables) or qualitative and impossible to measure objectively. They may also co-exist and demand parallel attention, such as when choosing logistical solutions to maximize profits and minimize emissions (Kanzian et al. 2013). There may be one or several DMs or stakeholders; if there are several, their preferences usually differ. The alternatives may be discrete, meaning that there is a specific known or unknown number of alternatives to consider, such as different machine systems (Ringdahl et al. 2012). However, the alternatives may also be continuous, meaning that there is a trajectory containing an unlimited number of possible solutions (Lundgren et al. 2010). The decision may also have a spatial scale – for instance, decisions may be made on the stand, region, national, or international level (Flisberg et al. 2021; Lundbäck et al. 2021; Bont et al. 2022). Finally, decision situations can relate to products (such as when choosing between different machines) or to services such as ecosystem services (Spinelli & Magagnotti 2010; Felton et al. 2016).

The complexity of decision-making has increased in recent decades because it has become increasingly important to consider a range of important factors such as climate change and operator well-being along with traditionally important factors such as costs (Vacik & Lexer 2014). Unfortunately, there is a lack of reliable knowledge about how decisions regarding forestry technology development are made and what support tools are used when making them, especially on the strategic level but also partly on the tactical level (Blagojević et al. 2019).

1.7 Decision support tools

Suitable decision support tools can greatly facilitate decision-making in cases where human judgment is important but the limits of human cognitive capacity make it hard to grasp all of the relevant information. The complexity of decision support tools varies widely; they can be as simple as a flowchart on a sheet of paper, but they can also be highly sophisticated systems. The term decision support system (DSS) has been introduced to describe complex decision support tools with multiple subsystems. Several definitions of the term DSS have been proposed (Borges et al. 2014; Vacik & Lexer 2014), but the definition used here is that a DSS is a system having: 1) a dialogue subsystem such as a user interface; 2) a knowledge subsystem such as a database; and 3) a knowledge-processing subsystem, possibly with analytical capabilities.

Decision support tools are most commonly categorized based either on their driver or the capabilities that they enable. Model-driven decision support tools emphasize access to different kinds of models, whereas data-driven tools emphasize access to and manipulation of data such as internal (and sometimes external) company data. Communication-driven tools use network and communications technologies to enable relevant collaborations and communications, document-driven tools emphasize techniques for storage and processing, and knowledge-driven tools can suggest courses of action for DMs (Power 2007; Vacik & Lexer 2014). Capability-based categorizations divide decision support tools into the groups optimization, simulations, Multi-Criteria Decision Analysis (MCDA), statistics, information systems, and economic systems (Segura et al. 2014; Ezquerro et al. 2016; Nobre et al. 2016). Because this thesis focuses on users' interactions with decision support tools, a capability-based categorization is applied.

Optimization-based tools are suitable when there is a clearly described problem with a defined objective and calculable constraints, making it possible to search for and identify an optimal solution (Lundgren et al. 2010). When using optimization models, it is common to work through a four-step optimization process in which the first step is to identify the actual problem to be solved. The second step involves formulating the problem mathematically as an optimization model with decision variables, an objective function, and constraints. The model's components must be measurable, and the actual problem may be simplified during this step; there is often a trade-off between describing the problem as accurately as possible and constructing a solvable model. The third step involves solving the optimization model with a suitable solution algorithm, and the final step involves evaluating and validating the model's output by comparison to the actual problem and making adjustments if necessary (Lundgren et al. 2010). Optimization can be used in a variety of contexts and on different geographical scales but is most commonly applied on the tactical level (Tóth & McDill 2009; Bredström et al. 2010; Segura et al. 2014; St John & Tóth 2015; Frisk et al. 2016; Dems et al. 2017; Flisberg et al. 2021; Bont et al. 2022).

According to Banks (2010, p 21), "a simulation is the imitation of the operation of a real-world process or system over time". In the context of decision support tools, simulations are used to make it easier for human actors to draw conclusions. A computer simulation can model real or imaginary events based on known conditions. Such models can be implemented on various scales but are most commonly used on smaller scales such as the stand level in the context of forestry (Eliasson 1999; Wang & Greene 1999; McDonagh 2002; Talbot et al. 2003; Väätäinen et al. 2006; Asikainen 2010; Lindroos 2012; Ringdahl et al. 2012; Talbot & Suadicani 2015). The steps involved in performing a simulation are similar to those for optimization, although Banks (2010) describes a 12-step process.

MCDA methods are suitable when there are multiple conflicting criteria to balance. Unlike other methods capable of addressing diverse goals such as optimization, MCDA methods use the DM's opinions about different criteria as an input in addition to objectively measured information. MCDA is described by Belton & Stewart (2002) "as an umbrella term to describe a collection of formal approaches, which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter". In other words, MCDA handles the process of making decisions in the presence of multiple, usually conflicting, criteria. The MCDA process can be divided into four basic phases: 1) structuring the decision problem; 2) assessing the possible impact of each alternative; 3) determining the preferences (values) of decisionmakers; and 4) evaluating and comparing the alternatives (Raiffa 1968; Keeney 1982; Belton & Stewart 2002; Nordström 2010).

In the first phase it is essential to identify the relevant DMs, define the criteria to be applied, and specify the alternatives available for consideration. This phase is essential for the quality of the decision-making process because a poorly structured decision-making problem will probably lead to poor decisions irrespective of the MCDA method employed. Most decisions, whether personal or organizational, will involve multiple stakeholders, including some who are affected by the decision and others who are tasked with implementing it (Belton & Stewart 2010). It is therefore necessary to identify the stakeholders and choose which ones will participate in the process as DMs. In group decision-making, the weights of DMs reflect their expertise and/or importance and must be defined. In the second phase, it is necessary to obtain data on the performance of each alternative under consideration with respect to all of the criteria that have been chosen. The data may be quantitative (e.g., measurements, calculations, estimates, or the outputs of model-based simulations) or qualitative (descriptive). The third phase involves defining the importance (i.e., weights) of the criteria. Finally, phase four involves evaluating and comparing the alternatives using the selected MCDA method. The details of the last two phases depend on the MCDA method that has been chosen.

Statistics, economic models, and information systems may also be important in decision-making about forest technology but are not the focus of this thesis and are therefore only discussed briefly. Statistical tools are used to analyze data from experiments (Mead 1993) using mathematical equations involving random and non-random variables. Economic models are designed and used to test hypotheses concerning economic behavior and commonly simplify the actual problem situation. Since there are no objective measures of economic outcomes, such models usually have a subjective design that enables hypothesis testing (Ouliaris 2011). Such models are rarely employed in forestry but have found similar applications in machine cost calculations (Miyata 1980; Hofsten et al 2005; Ackerman et al. 2014). Finally, information systems have capabilities for collecting, storing, processing, and communicating information (Dakhli et al. 2019). Such systems are widely used – for example, geographic information systems are used extensively to manage spatial issues in forestry (Karlsson et al. 2006).

2. The case: harwarder development

There have been several attempts to create one-machine systems for logging operations, known as harwarders. The definition of a ‘harwarder’ varies but the term is commonly understood to refer to machines that can perform the entire logging operation by themselves, either by performing harvesting and extraction separately or by performing both processes in an integrated manner. In the separate case, the machine is initially operated in a harvesting configuration before transitioning to its extraction configuration. This typically involves mounting a solid load carrier and replacing a harvester head with a forwarder grapple to enable extraction of the harvested wood (Talbot et al. 2003; Wester & Eliasson 2003; Väätäinen et al. 2006; Kärhä et al. 2008; Di Fulvio & Bergström 2013; Kärhä et al. 2018). Conversely, in the integrated case, the machine loads the logs during the harvesting process. An integrated harwarder may have a solid or a tilt- and rotatable load carrier together with either a combination head or a quick hitch that enables rapid shifts between a harvester head and a forwarder grapple. Moreover, the equipment mounted on an integrated harwarder may vary; in particular, different kinds of load carriers and heads and/or grapples may be used. The load carrier can be fixed, which was common in early harwarders, or it may be tilt- and rotatable, which is more common in recent designs (Hallonborg 1998; Jonsson 2021).

Given that advances in forest technology led to the replacement of multi-machine systems to newer systems with fewer machines, a one-machine-system was seen as the logical next step after the TMS became established in Swedish logging operations. The driving force behind attempts to develop harwarders was new technology rather than new legislation or demand for new products.

The development triangle has been emphasized as a success factor in forestry technology development (Ager 2017), and the Harwarder Collaboration Group (HCG) is a notable example of such a collaborative triangle. The HCG was established in the 1990s as a forum for users to discuss specifications, mainly for combinations but also for more general machine concepts, and to share relevant experiences and results from scientific studies. Its members include large integrated forest companies and FOAs with the capacity to actively contribute to this process. Because these firms are integrated, they control their supply chains from raw material harvesting to delivery to the receiving industries. However, they mainly outsource their harvesting operations and the logistics of transporting material from their own forests as well as material purchased from private forest owners. At the start of this study, the membership of the HCG consisted of six such users and the Forestry Research Institute of Sweden (Skogforsk), as well as some large manufacturers who participated sporadically (Jonsson et al. 2016a). The group has been a platform for evaluating several machine concepts, most of which were harwarders (Bergkvist 2010; Jonsson 2021). During 2016, its members accounted for approximately 48 percent of the total harvested volume in Swedish forestry.

By the end of the 1990s, harwarders for thinnings and small stem final fellings had been developed. These machines were equipped with combination heads and fixed or tilt- and rotatable load carriers, and the HCG initiated and supported several studies on their performance. The main criterion considered when evaluating performance was an economic criterion, namely logging costs, which were compared to those of TMSs in stands with varying characteristics. The harwarders proved able to compete in stands with short extraction distances, low total volumes and few assortments (Hallonborg & Nordén 2000; Bergkvist et al. 2003; Väätäinen et al. 2006). Most studies showed that they offered the greatest potential in stands with small stem sizes (Hallonborg 1998; Bergkvist 2007), although other studies suggested other conclusions (Lindroos 2012; Ringdahl et al. 2012). The harwarder was seen as a machine system for northern Sweden because the combination of low total volumes, few assortments, and small stem sizes is most common there. Some studies also considered criteria other than logging costs: a harwarder was compared to a forwarder with respect to the social criterion vibration exposure in one case (Granlund & Thor 2005), and other studies included the environmental and economic criterion fuel consumption, which is linked to carbon dioxide emissions (Bergkvist 2007). These development efforts showed that the harwarders did not have sufficient potential to warrant use in thinnings, although they performed better in final fellings (Andersson & Eliasson 2004; Bergkvist 2010). This however was not enough to sustain commercial interest, prompting the manufacturers to terminate serial production of harwarders.

Based on the insights from these early efforts, the harwarder concept machine Komatsu X19 was built and left the factory during 2014 after collaborations within the HCG. It was built only for final fellings and was equipped with a quick hitch and a tilt- and rotatable load carrier. Like previous harwarders, logging costs were central in its evaluation, and its ability to compete with the TMS was evaluated in stands with different characteristics. Like its predecessors, the X19 was most competitive in stands with short extraction distances and low total volume (Manner et al. 2016). However, there was little consensus concerning the impact of stem size; one study concluded that its performance was best in stands with small stem sizes (Jonsson et al. 2016a), another found no impact of stem size on performance (Manner et al. 2016), and others reported improved performance with increasing stem size (Jonsson et al. 2016b; Berggren & Öhrman 2018). The impact of the number of assortments was also complex: the harwarder appeared to perform well with both few and up to 8 assortments, but the volume distribution appeared to have a greater impact than the number of assortments per se (Manner et al. 2019b). In addition, perceptions of the harwarder gradually shifted; rather than being seen as a machine best suited for northern Sweden, it was considered better suited to southern Sweden because of the new combination of favorable stand conditions. Other conditions that may impact its relative performance, such as ground conditions and slope, have not yet been investigated. However, the potential for further development and reduction in logging costs through technological adjustments, automation, and the implementation of new methods has been explored (Manner et al. 2019a; Jonsson et al. 2020; Manner et al. 2020). In addition, the harwarder's performance has been evaluated using the economic criterion of wood value, showing no clear difference in measurement quality nor bucking splits between a harwarder and a harvester (Ågren et al. 2016).

Harwarder development efforts have also been undertaken in other countries, such as Finland and Ireland (Lilleberg 1997; Codd & Nieuwenhuis 2008; Kärhä et al. 2008) but this thesis focuses on the Swedish market.

3. Objectives

The main objectives of this thesis were to describe and critically analyze strategic forest technology decision-making in Swedish large-scale forestry. This was done in different parts of the decision process, drawing on both published research and observations made within forest companies and a FOA. The studies encompassed several decisions concerning harwarder development including some that were made during trials and concept studies but also final decisions about whether to implement a machine. The thesis includes four appended papers: Paper I presents a study with a qualitative design while the review and studies presented in papers II-IV have quantitative designs. Papers I and II focus on describing strategic decision-making, whereas papers III and IV focus on establishing a basis for strategic decision-making concerning the optimal composition of forest machine fleets for use in central and the whole of Sweden.

Paper I aimed to describe and analyze the decision processes used when making choices about investments and resource allocations in forestry technology development in general, the decision situations involved in the case of the harwarder and other technical investments, and the use of and need for decision support tools.

Paper II had two aims relating to forest operations: to introduce and explain MCDA methods to novice users, and to review existing applications of MCDA methods.

Paper III aimed to compare the outcome of two proposed modelling approaches for analyzing machine fleet composition as a basis for strategic decision-making concerning innovations.

Paper IV aimed to analyze harwarders' potential on a large scale in Swedish final fellings to provide a basis for strategic decision-making about the implementation of these machines.

4. Summary of the studies

4.1 Users' strategic decision-making on forest technology development issues

The complexity of forestry development has increased in recent decades and there are now several decision support tools that can help DMs manage decision situations. However, little is known about how forest technology development decisions are made and what support is used when making them. To bridge this knowledge gap, members of the HCG employed by six Swedish forest technology users (major forest companies and a FOA) were interviewed using a three-step approach in order to describe and analyse: 1) the decision processes used when making choices about investments and resource allocations in forestry technology development in general; 2) the decision situations involved in the case of the harwarder and other technical investments; and 3) the use of and need for decision support tools.

The conceptual framework used to analyze the decision process was based on 'the structure of "unstructured" decision processes' put forward by Mintzberg et al. (1976), while decision situations were characterized using the framework of Kangas et al. (2015). A qualitative approach was adopted because the work focused on people's decision-making processes and knowledge (Bliss & Martin 1989). Semi-structured face-to-face interviews were used to map the seven respondents' experiences of their organization's decision-making processes and use of support tools, and transcripts of the interviews were analyzed using the two frameworks.

The respondents generally indicated that they and their development units coordinated development projects and operational trials on their own and/or with other users. Moreover, they collaborated with research organizations when conducting trials and sometimes also when analyzing trials. They considered it positive for users, manufacturers, and researchers to participate in development efforts, but they did not consider this to be essential in all projects. They also thought that it was positive to be able to draw on external expertise in project leading and analysis.

The most common uncertainty related to the contexts in which new technologies would have the greatest potential to compete with established alternatives. Additionally, economic criteria were central to decision-making, the alternatives under consideration were discrete, and some important spatial and temporal aspects were mentioned.

The respondents described a need for information from both research and other users but preferred to perform their own operational trials. In the face of large uncertainties they preferred to gather more information. However, if the potential gains were large enough, they would still proceed with stepwise development in cases where such information was too hard to obtain.

These results indicate a need for greater use of existing decision-support tools including problem-structuring methods to obtain a more precise diagnosis, simulations to better understand innovations, and optimizations to better grasp their theoretical large-scale potential.

4.2 Making MCDA methods more available

Decision-making in forestry is very complex and sometimes requires consideration of trade-offs between economic, environmental, and social criteria. Different MCDA-methods have been developed for structuring and exploring the decision-making process of such problems. Although MCDA methods are often used for forest management problems, they are rarely used for forest operation problems. This indicates that scholars and practitioners working with forest operations are either unaware of MCDA methods or see no benefit in their use. Therefore, the prime objective of this literature review was to make MCDA methods more intelligible to novice users within the field of forest operations, taking the current level of understanding among such users as a point of departure. The second objective was to review applications of MCDA methods in forest operations. Different MCDA methods used in forest operations were outlined and categorized as: goal, aspiration, or reference level methods; outranking methods; or value measurement methods. The basic principles of each method were presented along with their strengths and limitations, and it was shown that MCDA applications can be helpful in decision-making about forest operations, especially those relating to harvesting and extraction. Applications were found on all three planning levels, with 9, 15, and 6 papers describing strategic, tactical, and operational uses, respectively. Moreover, 15 of the 23 papers included in the review addressed all three sustainability criteria (economic, environmental, and social). None of the presented methods stood out as being clearly superior to the others, so it was recommended that practitioners in decision situations should focus on the selection of criteria and the definition of alternatives because these factors profoundly affect the outcomes of all MCDA methods.

4.3 Detailed Optimization versus Aggregated Heuristics for comparing machine systems

When choosing which machine system to use and how to plan its operation, many factors must be considered. This involves both finding the ideal stand conditions for a system and evaluating the system's performance in the existing stand conditions by applying performance functions to several known or fictional stands. Such analyses should be performed for applicable systems and can be performed using multiple modelling approaches (Ringdahl et al. 2012). Several studies have compared the performance of harwarders (in terms of productivity and/or cost) to that of the established TMS in different stand conditions. However, previous comparisons of modelling approaches have not addressed such a complex problem as finding a machine fleet in which the machine systems together must meet the requirement of a functional supply system. Therefore, the aim of the third paper was to compare the outcomes obtained using two different modelling approaches – the Detailed Optimization (DO) and the Aggregated Heuristics (AH) – when applied to the analysis of machine fleet compositions in final fellings.

Both approaches involve extensive analysis of a large body of input data but they rely on different competences and software tools. Because there is no objectively correct answer as to how a machine fleet should be composed, the evaluation focused on the similarity of the outputs obtained with each method when analyzing two scenarios (TMS only and TMS in competition with a harwarder) in a specific set of stand conditions. The DO was performed using dedicated optimization software, whereas the AH was performed using a static spreadsheet with standard office software. The input data were collected from a forest company in central Sweden. In both cases, the time consumption of specific forest operations was estimated using established equations with adjustments to account for the harwarder's time consumption (Eriksson & Lindroos 2014; Manner et al. 2016). The differences between the two scenarios were used to estimate the potential for reducing costs by using harwarders and to identify the optimal fleet composition. A sensitivity analysis was performed to account for data uncertainties associated with time consumption equations and machine costs for the harwarder.

Both approaches gave similar results. The AH gave slightly lower total costs and machine utilization than the DO, but the total cost difference was only 3.2 percent, which is in the range expected when using such different approaches. The estimated saving achieved by adding harwarders to the machine fleet differed by 1.5 percent between the approaches.

The AH consistently gave lower estimated total costs than the DO. The sensitivity analysis indicated that the difference between the results obtained with the two approaches was generally around 3.6 percent, which is smaller than the differences reported in previous comparisons (Asikainen 2010). None of the predictions generated by either approach could be validated or shown to be objectively correct. However, forest company representatives participated in the project and considered the results to be realistic. Given reliable time equations and cost estimates for new or proposed machine systems, both approaches can be used to compare such systems with established machine systems. While both approaches are well suited for analysis of large input data materials, it was suggested that the DO should be used when high precision is needed and suitable input data are available, while the AH should be used in other cases.

4.4 Choosing between the two-machine system and the harwarder in Swedish forest operations

In the final paper, the scenarios considered in paper III were re-evaluated, this time focusing on a comparison of the machine systems rather than modelling approaches. Specifically, the objectives were: 1) to evaluate the potential benefits of using harwarders on a large scale in Swedish final fellings; and 2) to analyze the large-scale impacts of changed costs and productivity for the harwarder. As in paper III, the DO and the AH were used. Input data representing 45 M m^3sub, from 29 thousand stands were gathered from four large forest companies and one large FOA in Sweden. To my knowledge, this is the largest collection of historical data on final fellings in Sweden that has been assembled to date. Both the DO and the AH indicated that the potential savings achievable by using harwarders in northern Sweden was on the order of one percent. Much greater cost reductions were predicted in southern Sweden: the DO indicated a potential to reduce costs by almost 5.8 percent, while the AH suggested that costs could be reduced by 4.4 percent.

5. Discussion

The objectives of this thesis were to describe and critically analyze strategic forest technology decision-making because the existing knowledge about decision-making on such issues is limited and vague. Four studies were conducted to this end. In the first, representatives of forest technology users were interviewed about their decision processes as well as the decision support tools that they used and needed. The second reviewed the need for and use of MCDA approaches. The third study compared two modelling approaches, one detailed and one aggregated. Finally, the fourth study used the optimization methods examined in paper III to evaluate the performance of a new machine system against that of an established alternative. The following sections discuss the findings of all four studies and offer suggestions for further research and the practical use of decision support tools.

5.1 General observations and comparisons

In paper I, the respondents generally indicated that they and their development units coordinated development projects and operational trials on their own and/or with other users. Moreover, they collaborated with research organizations when conducting trials, and sometimes also when analyzing trials. They considered it positive for users, manufacturers, and researchers to participate in development efforts, but they did not consider this to be essential in all projects. They all considered it positive to be able to draw on external expertise in project leading and analysis, and frequently mentioned that they both find support in scientifically produced knowledge and actively participate in scientific studies. These outcomes are consistent with a previous report identifying collaboration as a solid starting point for technological development projects (Ager 2017), and with the findings of Li & Nguyen (2017), who concluded that collaboration is almost always beneficial and argued that competitors often gain advantages through collaboration. One respondent specifically mentioned the opportunity to learn as a reason for participating in joint development projects (rather than any expectation that the innovation being developed would revolutionize their organization's operations). This can be understood as an example of a spillover effect in which value is obtained by transferring discoveries to other projects and parts of an organization. Spillover effects are particularly important because many innovations fail and risk being swept under the carpet because those involved feel embarrassed, which is unfortunate because important lessons can be learned from failures (Li & Nguyen 2017; West 2021).

During the evaluations of the Komatsu X19 harwarder concept, all companies and FOAs that expressed the desire to perform trials with the machine in their own operations were able to do so, even though the machine in question was owned by just one of the forest companies. This may be an example of the so-called dual creation of value, which is about ensuring that all collaboration partners participate actively and gain something from the collaboration (Li & Nguyen 2017). The benefits of collaboration may be enhanced by conducting trials in one's own organization before starting a full-scale implementation because doing so could make personnel feel more involved in the project and thus increase the likelihood that they will participate actively when it is time to start an implementation. However, several respondents mentioned that it can be hard to implement suggestions offered by researchers because of competing priorities and a lack of experience in consulting the scientific literature. According to Hughes et al. (2011), practitioners such as the respondents in paper I can be divided into: 1) the enthusiasts, who participate actively; 2) the uncommitted, who are open to collaboration with researchers but rarely do it in practice; and 3) the cynics, who have negative opinions of academia and its ideas. Most of the respondents seemed to belong to the first category, which is very positive from a development perspective, but some seemed to fall into the second category because they mentioned gaps in need of bridging. Gaps between research and practice can be bridged in several ways, including through publications in hybrid journals that are neither purely scientific nor popular publications but a blend of the two (Hughes et al. 2011). Other useful approaches include rotating staff between practice and research (Tkachenko et al. 2017) and increasing collaboration between researchers, practitioners, and educators (Burke & Rau 2010).

Some respondents in paper I described a stepwise technology development process whose implementation required large steps and benefitted significantly from knowledge held within the organization, which served as a source of competitive advantage. Technologies developed in this way could be seen as disruptive/revolutionary, and processes of this sort were mainly driven by large manufacturers. The clear dominance of large manufacturers in the development of potentially disruptive technologies together with the long-term dominance of a single solution (the TMS, with harvester and forwarder) in the Swedish forest sector may indicate that disruptive innovations are being held back by large manufacturers. However, this possibility is contradicted by two facts: first, there are several large competing manufacturers with no monopoly, and second, both large manufacturers and independent innovators (ATL 2009) have attempted to introduce alternative machine systems. This suggests that although disruptive innovations have not achieved commercial success, large manufacturers retain significant capacity for innovation and users are at the very least willing to test potentially disruptive innovations. In contrast, the users' development units are generally small, so their capacity to evaluate and implement disruptive innovations is limited regardless of their intentions. The size of the steps described by the respondents of paper I affects the risks associated with those steps. When proceeding from idea to implementation of an innovation, the costs associated with each step increase, which unfortunately means that the last few steps may be too large for some innovations.

According to the theory of Mintzberg et al. (1976), "unstructured" decision processes can be broken down into seven distinct routines. Based on the interviews conducted in paper I, the relative frequencies at which these routines are performed when making development decisions in the forest sector are similar to those previously reported for similar decision processes in manufacturing firms (Mintzberg et al. 1976) that have many similarities with forestry organizations. The only difference is that diagnosis was more frequent than authorization in paper I. This might indicate that the respondents' development units were more influential than those of the manufacturing firms studied by Mintzberg et al. (1976). Mintzberg et al.

(1976) also reasoned that organizations in general would benefit from formalized diagnosis routines even though few of the firms that they studied had such routines. The proportion of respondents who mentioned a formalized diagnosis routine in paper I was even lower than that observed by Mintzberg et al. (1976). This is consistent with previous findings indicating that there is a will to develop within forestry organizations but that problems are not always clarified before initiating a development process. This may cause innovations with doubtful potential to seem interesting while those with greater potential are dismissed (Lindroos 2012; Lindroos et al. 2017). A major risk of making decisions in vaguely diagnosed situations is that the chosen decision support tool and the final solution may not match the problem situation.

The respondents frequently mentioned that decisions were based on facts where possible. In cases without sufficient factual information, stepwise technical development was still performed if the possible gains were judged to exceed the estimated uncertainties. In decisions characterized by uncertainty, DMs may avoid logical reasoning and instead decide intuitively (Riabacke 2006). It was not determined whether the decisions discussed by the respondents of this study were based on intellect or intuition. However, it can be hard to distinguish between intuition and intellect in cases involving significant uncertainties because the intellect can guide both intuition and analysis, and intuition may even be trainable (Buchanan & O'Connell 2006). However, because there are far fewer ongoing development processes in the forest sector than there were during the period of rapid mechanization between 1960 and 1990, DMs have limited opportunities to develop and train their intuition.

5.2 Decision characteristics

5.2.1 Criteria

The main criteria applied in the decision processes described by the respondents in paper I seemed to be costs, particularly logging costs. Other criteria including those relating to social issues such as operator well-being and environmental issues such as rut-free logging operations and minimizing emissions were also considered but were seen as constraints. The alternatives considered in these decision processes were discrete rather than continuous because each alternative represented a specific machine or machine system. In addition, the decision processes had a spatial component arising from the need to match each alternative to appropriate districts and stands. Therefore, despite having several criteria, there was a single overall objective. The same was true for the decision situations examined in papers III and IV, in which two economic models (that lacked behavioral aspects, unlike typical economic models) were used to estimate machine costs when analyzing the total costs of logging operations. The objective in both models was to minimize total costs, including logging costs, for two different machine systems in final felling operations: the established TMS and the new harwarder. The quality of the outputs of both models depends on the input data quality, which can present a challenge when analyzing innovations for which accurate and reliable input data may be unavailable. For instance, the time consumption of the harvester and the forwarder was estimated using equations based on an analysis of a large input data set representing the time consumption of 423 harvesters and 341 forwarders during final felling (Eriksson & Lindroos 2014) and was thus considered adequately representative for a large analysis. However, the only available dataset representing harwarders derived from a time study analysis in which two operators drove a harvester, a forwarder, and a harwarder concept machine (Manner et al. 2016). Therefore, the harwarder's time consumption was estimated as the difference between the total time consumption for the TMS and the harwarder reported by Manner et al. (2016), multiplied by the TMS time consumption reported by Eriksson & Lindroos (2014).

In addition to minimizing logging costs, some respondents in paper I mentioned that factors such as operator well-being can be worth maximizing to ensure attractiveness, meaning that their decision processes involved multiple criteria. MCDA methods are well suited to such situations. However, paper II revealed that there have been few studies on the use of MCDA methods in forest operations. This suggests that most forest scholars and practitioners working with forest operations have limited knowledge of MCDA. The literature review presented in Paper II could therefore help researchers and practitioners to develop their knowledge in this area. However, it may also be that scholars and practitioners are aware of MCDA but choose not to use it for one reason or another. This was reported to be the case in the IT industry – one study found that 72 percent of IT companies were aware of MCDA methods but only 33 percent used them (Bernroider

& Schmöllerl 2013). While no comparable data exist for forest operations, a similar situation is possible. In general, the use of MCDA methods may be limited by several factors. First, practitioners may lack a clear perception of the added value such methods can offer (i.e., their perceived usefulness may be low). Second, non-experts may struggle to understand MCDA methods. Third, different MCDA methods may produce different solutions for the same problem, amplifying the confusion about which method to choose for a particular type of problem (Davis 1989; Venkatesh & Bala 2008; Giannoulis & Ishizaka 2010; Ishizaka & Nemery 2013; Ishizaka & Siraj 2018).

Only a few applications of MCDA in forest operations were identified, most of which involved strategic planning. This is unsurprising – MCDA is frequently applied to strategic issues, partly because strategic planning generally requires less precise data than operational planning and may involve a mixture of quantitative and qualitative criteria that the DM(s) want to maximize/minimize. As stated in paper II, the MCDA method used most frequently in forest operations was the Analytical Hierarchy Process (AHP), followed by Multicriteria Approval (MA) and Multi-Attribute Utility Theory (MAUT). This is consistent with the findings of previous studies on forest operations – for example, Diaz-Balteiro & Romero (2008) found that AHP, MAUT, and Goal Programming (GP) were the most commonly used methods in this context. These MCDA methods are also used frequently in related fields – for example, the most commonly used MCDA methods in environmental applications were reported to be AHP, MAUT, and the Preference Ranking Organization Method for Enrichment evaluation (PROMETHEE) (Huang et al. 2011). AHP thus appears to be the dominant MCDA method in both forest operations and when managing environmental problems. This can be attributed to the fact that AHP is understandable and user-friendly, easy to use in group settings, and can effectively combine qualitative and quantitative data.

5.2.2 Uncertainties

In the face of large uncertainties, the respondents of paper I preferred to gather more information. However, if such information was prohibitively difficult to obtain, they were willing to proceed with stepwise development in cases where the potential gains were large enough. In a situation like that considered in paper IV, where the innovation's potential to deliver gains was not obvious over the scale of the analysis, the next step for the DM(s) would be to reduce the uncertainty by performing further analyses of available data, gathering additional data (by conducting new studies and trials) or to terminate the innovation. Paper IV also presented a sensitivity analysis in which the performance and costs of the innovation were varied over an interval representing a range extending from a worst case scenario for the innovation to a best case scenario. This made it possible to evaluate the stability of the innovation's estimated potential. The respondents in paper I highlighted several uncertainties relating to factors such as time consumption, operator impact, costs of new machines, and mechanical availability. Uncertainty about time consumption has traditionally been addressed through research by first performing comparative studies (for example, comparing the harwarder to the established TMS) and then conducting descriptive studies (Bergstrand 1987). However, there are other important sources of uncertainty, in particular those relating to operator impact. Modern forest machines are highly complex, so their performance is very sensitive to the skill of the operator (Purfürst & Erler 2011; Häggström & Lindroos 2016). Because working with innovations places significant demands on the operator and the operator's capabilities are a major source of uncertainty even without these additional demands, the most experienced and fastest learning operators are traditionally chosen to participate in studies on innovations. The operators' ability to learn and adapt is especially important when evaluating potentially disruptive innovations. However, for such innovations to capture a significant market share, it must also be shown that they can compete when operated by other operators. Consequently, it is desirable to include a wider variety of operators in studies as the innovation advances towards implementation. After obtaining information about its performance with a wider array of operators, further uncertainties regarding operator impact can be treated as uncertainties of outcome, which DM(s) must simply accept if they choose to move forward with the innovation. Like uncertainties relating to time consumption, uncertainty about the investment costs of an innovation can be regarded as an uncertainty of knowledge that can be reduced through estimation before advancing to the next step of a decision process. However, such uncertainties can only be reduced to a certain extent; the remaining uncertainty must again be accepted as an uncertainty of outcome. Uncertainty about mechanical availability is similar to uncertainty about operator impact and can also initially be treated as an uncertainty of knowledge. However, a machine's mechanical availability is also closely related to its technical complexity and the maturity of its components within the environment. In general, a complex machine is more likely to have low availability than a simpler one because it will have more components that could break down. However, despite the increasing complexity of harvesters and forwarders, their mechanical availability has increased over time (Nordfjell et al. 2010; Brunberg 2017). This is probably because the manufacturing processes for these machines have reached maturity over the decades in which the TMS has been dominant in cut-to-length-dominated countries such as Sweden. A factor closely related to mechanical availability is machine utilization, i.e. the proportion of time in which a machine is mechanically fit and able to do productive work (Björheden & Thompson 2000). Within the TMS, one of the two machines – usually the harvester – will operate more rapidly than the other in terms of volume per hour, necessitating a careful balancing act. To account for this, the fastest machine was not allowed to exceed 100 percent machine utilization in the DO and the AH presented in papers III and IV. It is notable that the respondents interviewed in paper I discussed uncertainties of knowledge and outcome but not of values because the criteria applied in the decision process and their relative weights when evaluating innovations were both quite clearly understood and articulated.

Decisions about innovations present additional challenges, some of which arise from costs associated with supply and demand. The machine fleet must be designed in a way that allows supply and demand to be matched, which can be ensured in different ways in a model. In papers III and IV, supply and demand were matched on a seasonal basis over the analyzed year when modelling with the DO. This approach provides a good reflection of operational realities. Conversely, with the AH, matching was only performed for the case as a whole and not for individual machine systems, which is a large simplification. Both approaches can be used to estimate the number of machine system teams needed within a region and thus to support decision-making on a tactical level. However, the DO can also provide information on where the teams should be located and how they should work operationally. Another challenge relates to spatial variation, which both the AH and the DO addressed within a geographical region but in different ways. The DO model had no geographical sublevel corresponding to districts, so the machine fleet and its work were optimized for the region as a whole. This is valuable from a top-level strategic point of view but may be challenging to implement if district borders are strongly adhered to in daily operational work. Conversely, in the AH modelling, district borders were key elements for managing spatial variation because the model would only allocate resources to districts with enough work for at least one machine system team. Therefore, while the handling of spatial variation was not addressed directly in paper III or paper IV (such as including roads), one might expect that output of the DO would be extra applicable in regions where variation in stand condition does not align well with district borders. The outputs of optimization methods such as the DO and the AH cannot be verified because future outcomes cannot be known in advance. However, this uncertainty can be reduced by comparing the outputs obtained using different methods and by asking experts to validate the assumptions made in the models. In papers III and IV, the DO and the AH yielded similar results. In addition to the inherent differences between the two approaches, the two models were developed by different people. The fact that their outputs were so similar despite the differences in the modelling approaches strongly supports their validity. The authors of papers III and IV collaborated with machine users within the HCG when choosing their modelling assumptions and consulted HCG members to verify the plausibility of the models' outputs before publishing them. It should be noted that it is vital to ensure that any assumptions about unknown input data for modelling are not excessively optimistic in order to avoid a situation where implementation is initiated even though there is little or no prospect that the innovation being development will provide operational benefits. Conversely, if the assumptions are overly pessimistic, few or no innovations will advance to serial production and further implementation. I therefore recommend making the most realistic assumptions possible because brutal facts provide the best basis for decisions. However, if this is impossible, it is better to err slightly on the side of pessimism when making assumptions in order to reduce expenditure of resources on efforts to implement innovations with questionable potential while enabling those with real potential to display their merits and advance to implementation.

The respondents in paper I described their working practices during technology development efforts. However, none of them described formally structured processes. DMs are subject to several biases that may cause them to make non-optimal decisions even in cases where the available information would make a more rational decision possible. Previous studies have identified effective tools for overcoming such biases, including checklists and routines known as debiases (Montibeller & Winterfeldt 2015ab). The low use of such tools in the respondents' organizations despite the tools' familiarity to researchers may indicate that academic knowledge transfer to the forest sector has been limited.

Several respondents in paper I stated that some of the steps between the initial conception of an idea and the ordering of serially produced machines are very large. Deeper analysis could help to reduce the uncertainties associated with such large steps. However, it is important to note that changing the scale of analysis affects the quantity of resources that must be invested as well as the magnitude of the uncertainty.

5.3 Conceptual models of decision processes in forest technology development

5.3.1 A prescriptive model for decision processes

Based on both the studies included in this thesis and my personal experiences as coordinator of the HCG, I have come to believe that although strategic forest technology decision-making appears to be unstructured, it can be described in a structured manner. In particular, I suggest that it can be conceptualized using the model outlined in Figure 2. This model is designed to be prescriptive to help large-scale users such as forest companies or FOAs seeking to advance from initiation to a decision about whether to implement an innovation while minimizing resource expenditure, subject to the constraint that uncertainty must be reduced to an acceptable degree. The acceptable level of uncertainty depends on the user's risk attitude – a more risk-seeking attitude allows a higher level of uncertainty to be accepted. Additionally, greater uncertainty may be accepted if an innovation is not expected to have a major impact on operations or if the user wants to spend the required resources. Conversely, if implementing the innovation would have a major operational impact, even users with relatively substantial development resources will probably accept only a very low level of uncertainty. Limited resource availability will also naturally reduce the likelihood of initiating a decision process.

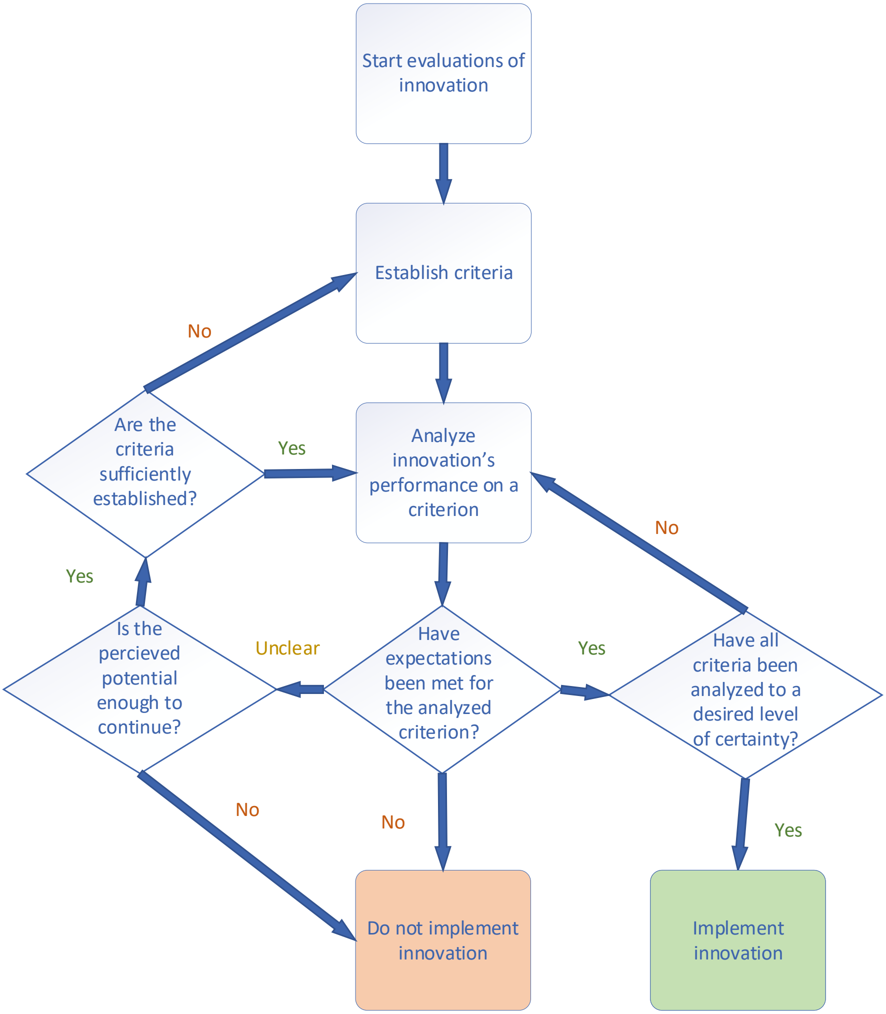

Figure 2. Conceptual flowchart for a structured decision process in strategic forest technology decision-making. The figure shows the principal connections between different actions and decisions in a decision process.

A decision process starts with the initiation of evaluations of an interesting innovation. As a first step, criteria should be established by asking questions about how the innovation could help the user achieve their organizational objectives. As shown in paper I, users consider economic criteria such as minimizing logging costs to be central, but they also aim to at least meet legal requirements or other threshold values relating to social and environmental criteria such as operator well-being and avoiding soil rutting.

Before proceeding towards analysis, the user should specify a target value for each criterion. For example, one target could be to reduce logging costs by 10 percent when compared to the established technology. However, a target of simply matching the cost of the established technology may also be chosen if it is believed that further cost reductions can be expected over time. Establishing clearly-defined criteria is an essential step but may be omitted in practice or may simply be treated as an unspoken expectation that is only considered when analyses become available (Lindroos et al. 2017).

Once criteria have been chosen, they should be analyzed. The order in which the criteria are analyzed should depend on their relative importance, the likely conclusions of the analyses (e.g., "the innovation will probably outperform the established option in terms of minimizing soil rutting"), and the ability to perform studies of impact by operators, stand conditions, and machines to an acceptable quality. The weight of each factor should be determined by the user, and the most important criterion is the one most likely to be analyzed first. The probable outcome should also be considered – if only a minor effort and investment are needed to achieve high quality when analyzing an innovation's performance with respect to some criterion, it becomes more attractive to perform extensive analyses. The ability to achieve a satisfactory quality of analysis is important because a key challenge at this stage of the process is to allocate the available resources in an optimal manner. Therefore, the priority of a given analysis should be increased if it is likely to substantially reduce uncertainty with respect to some criterion.

The results of an analysis may be positive, negative, or unclear and determines the proceeding for the innovation. If the result is negative, meaning that the innovation's performance does not meet the user's expectations (i.e., it fails to reach the satisfaction threshold), then its evaluation should be terminated and the user's resources should be reallocated to other working tasks. This should also be done if it is not clear whether the expectations have been met and the innovation is judged not to have sufficient potential to continue.

However, if the user considers the innovation's potential to be sufficient, the evaluations should continue. If the precision with which the criteria should be defined has increased since the previous analysis, the criteria should be refined accordingly and the refined criteria should then be reconsidered to determine which one should be analyzed next; this may necessitate an extension of the preceding analysis. Otherwise, the next criterion for analysis should be chosen as described above. This stepwise analytical approach in which each criterion is considered sequentially is justified and discussed in greater detail in section 5.4.

If an analysis yields a positive result, the user should perform additional analyses based on the remaining criteria until an acceptable level of certainty has been achieved for all criteria. Once this has been done, the implementation of the innovation should be taken forward. This may involve ordering units from an established serial production. However, if serial production has not yet been established, the next step would be to attempt to convince one or more manufacturers to set up such a production. Ordering from an existing series may be suitable in certain cases, such as those where a user identifies a machine that is established but not currently used in their market. This solution may require additional effort, such as modifying the machine to satisfy legislative requirements in the new market. However, this is normally much easier than starting a new serial production, as would otherwise be necessary. An innovation will inevitably evolve after a successful initial implementation (e.g., after the production and deployment of the first few machines) because of factors such as unexpected errors and ideas for improvement provided by an increasing number of forest machine operators and forestry professionals as they grow familiar with its capabilities and limitations (Kim & Chung 2017).

The presented conceptual model for decision processes in technology development has similarities with the 'structure of "unstructured" decision processes' of Mintzberg et al. (1976), which serves as the guiding framework for both this thesis as a whole and paper I in particular. Both models have the same core components, although some are described in different ways with different emphases – for example, the purpose and tasks of the "Analyze innovation's performance on a criterion" step in my model are similar to those of the "analysis" sub-process in the earlier model. Also, both models are relatively concise and include internal loops to reflect the fact that there are usually iterative elements within the overall flow of the decision process as it advances from its beginning to its conclusion. Early innovation models were linear (Narvekar & Jain 2006), unlike the model presented in Figure 2 and that of Mintzberg et al. (1976). However, the models differ in terms of the order in which alternatives are generated and criteria are established. In the model of Mintzberg et al. (1976), the criteria appear to be established through analysis, judgment, and bargaining after generating alternatives (Figure 1). Conversely, in the Figure 2 model, the criteria are established first and used to guide the analysis of alternatives. One could argue that this assumes that the alternatives have been defined before starting the process, making the order similar to that of Mintzberg et al. (1976). However, the analysis, which is central, is done after establishing the criteria. The order presented in Figure 2 was also suggested to be beneficial by authors such as Keeney (2009). A desire to start analyzing innovations even when the criteria for their evaluation have not been clearly established has been observed previously within forest technology development (Lindroos et al. 2017). The reason for the differences between the model by Mintzberg et al. (1976) and the model in Figure 2 is that the older model is descriptive whereas the Figure 2 is prescriptive despite being based on observations. That is to say, the model in Figure 2 describes how I would recommend users to work, with an emphasis on establishing criteria before undertaking any analysis.

5.3.2 A model for stepwise materialization of an innovation

The only way to determine whether an innovation's performance has been accurately analyzed is to implement and test it under conditions that encompass the full range of expected variation in all relevant sources of uncertainty, including variation between operators, stands, and machines. If it turns out that the analysis gave inaccurate results and led to bad decisions, measures should naturally be taken to evaluate and improve the decision-making process. However, such measures are beyond the scope of this thesis. Instead, the focus here is on providing a model of how to materialize an innovation in a stepwise fashion by progressively increasing the certainty in its analysis and the quantity of resources expended (Figure 3).

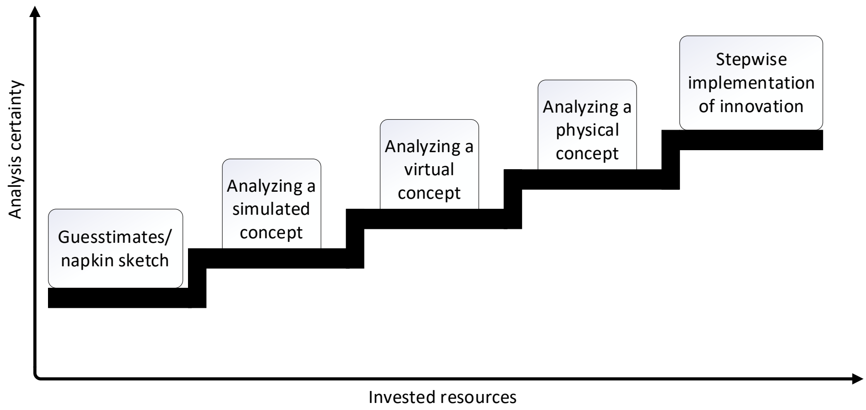

Figure 3. Conceptual stepwise progression of the materialization and implementation of an innovation, showing how the representation of the innovation changes over time as the uncertainty of the analysis is reduced and more resources are invested. Note that certain steps may be skipped and/or revisited in an actual decision process and that neither scale is linear.

When a decision process is initiated, the innovation may be no more than an abstract idea. Therefore, during the analysis it is represented by a simplified version of the final product such as a simulation model or a physical concept machine. It is recommended that the progression from analyzing (a) simplified version(s) of an innovation to analyzing a fully implemented machine/technology should occur in several steps except in cases where the potential is very high and the risk is low. Each step requires resources and there is generally a positive correlation between the quantity of resources invested and the certainty of the analysis. The suggested progression can be conceptualized as shown in Figure 3. For each step in the model, the analyses can be performed on scales ranging from a single stand to a particular region or even an entire country. These different scales are associated with different levels of variation in factors such as operator capabilities, stand conditions, and machines, as well as different levels of operational complexity (ranging from a single operation to a complete supply system). Consequently, they also differ in terms of their representability and the level of certainty that can be achieved in the analysis. Therefore, while iterating through the model shown in Figure 2, an innovation may be analyzed several times with respect to a particular criterion in accordance with the model shown in Figure 3, increasing the scale of the analysis each time. In any given step within the Figure 3 model, analysis that provide high representability are assumed to reduce uncertainty to a greater degree than those with lesser representability, and to therefore enable a larger step size. However, an increase in representability is also expected to increase the quantity of resources and time needed to take a given step.

In the first step, an emerging idea is tested by analyzing a theoretical innovation on the basis of assumptions, i.e. guesstimates, that can be compared to a "napkin sketch". The need for resources is low and experienced researchers with access to relevant information can perform such analysis using a spreadsheet in at most a few days. The certainty of such analyses depends strongly on the quality of the input data. High quality information may be available if an innovation has substantial similarities to established technology, but a more original innovation with low indata quality will require more sensitive judgment from the analyzing personnel.

In the next step, a simulated concept is constructed. As in the preceding step, the input data in this case is usually based on guesstimates. However, the capture of variation and stochastic elements during the analytical process will generally be greatly improved. This is especially valuable for systems with high machine dependency since random variation can have a strong impact on the results. A simulation also requires the analyst(s) to carefully think through how a typical working cycle is expected to proceed, which further increases the certainty of the analysis.

In the third step, a virtual concept is constructed. Here, the certainty of the analysis can be increased in several ways. If a model of the established technology is available in the virtual environment used to study the innovation, the two alternatives can be compared by having real operators operate both of them under varying stand conditions. Such virtual operations make it possible to perform comparative time studies. The refined input data also makes it possible to perform simulations and optimizations with extensive stand data such as those presented in papers III-IV. The innovation's potential in an actual supply situation can thus be evaluated, drawing on real observations.

In the fourth step, a physical concept is constructed, enabling studies on a real machine operated by real operators in real stands. This further increases the certainty of the analysis because it can provide additional information on the influence of operators and stand conditions. However, while this step also reduces the uncertainty relating to machine variation, large uncertainties remain in this area. In particular, the performance of a concept machine may differ substantially from that of a prototype or a serially produced machine. In particular, later machines may have improvements resulting from refinement of the design, an improved choice of components, better maintenance schemes, and so on.

The fifth step involves stepwise implementation of the innovation whereby it is gradually incorporated into the user's operations. Typically, one or a few units will be introduced to begin with, followed by a gradual increase to the final planned implementation. The risk attitudes of contractors may be very important during this upscaling process and must be managed by the user (Marra et al. 2003). In addition, the new data gathered during the implementation process will enable refined analyses and more accurate operational predictions as the machines are employed in a wider variety of stands by a greater number of operators and additional machines are added to the fleet.

An innovation that reaches this final step may do so by going through every single step described above. This route may be preferred for risk-averse users. However, some shortcuts may be taken and one or more steps may be skipped if the user is risk prone, the innovation is considered to have a high likelihood of meeting expectations, or substantial resources can be dedicated to the project.

5.3.3 The proceeding through the models for the case of the thesis

The case examined in this thesis – the development and testing of a new harwarder design – went through several iterations of the decision process shown in Figure 2. Additionally, it advanced through every step shown in Figure 3 except for the fifth, albeit not in the linear stepwise fashion described previously. When initiating work with a final felling harwarder, the users in the HCG decided that reducing logging costs was the main objective (Figure 2, Establish criteria), i.e. the most important criterion in the decision process. This is consistent with the remarks of the respondents in paper I. For the other criteria, the innovation was merely required to reach threshold values similar to those for the established TMS, and even a major improvement in performance with respect to these criteria would only moderately increase the users' interest in the innovation. It thus appeared that there was no appetite to trade reductions in logging costs off against increased operator well-being, for example. Having established the specific criteria, as described in paper I, an initial analysis was performed by the users and Skogforsk (Figure 3, step 1 - Guesstimates/napkin sketch). The following step did not involve analyzing a simulated or virtual concept (Figure 3), however – instead, the users discussed the concept with a manufacturer (Komatsu Forest AB) and made a deal for the production of a physical concept, which was designated the Komatsu X19. A possible reason for going directly from guesstimates/napkin sketches to a physical concept may be that the concept was considered to have substantial potential. Moreover, the users had operational experience from prior implementations of harwarders such as the Valmet 801 Combi, which entered serial production (along with a few other harwarders) for a few years in the 00s, although it was never produced on the same scale as harvesters and forwarders.

When the X19 was ready, studies and trials were undertaken to analyze its performance with respect to the chosen criteria (Figure 2, Analyze innovation's performance on a criterion). The first study compared the time consumption and logging costs for the X19 (Figure 3, step 4 – Analyzing a physical concept) to those for the TMS (Jonsson et al. 2016). The TMS was represented using time consumption equations and costs based on earlier studies. It was found that the harwarder concept had considerable potential but several major uncertainties were also identified. In particular, the uncertainty concerning operator impact was considered to be too large, making it unclear whether expectations had been met (Figure 2, Have expectations been met for the analyzed criterion?). Despite this, the innovation's potential was judged sufficient to continue (Figure 2), and it was decided that the best way to reduce the uncertainty was to conduct further analyses rather than refining the criteria (Figure 2, Are the criteria sufficiently established?). A second study was therefore initiated in which the same questions relating to large-stem final felling were examined but two operators were included. In this case, both operators operated the X19 harwarder as well as a large harvester and forwarder (Figure 3, step 4). While this did reduce operator impact (Jonsson et al. 2016), the response remained unclear. Additionally, the harwarder's potential in small stem fellings remained to be investigated. The latter issue was initially addressed by simulating the innovation's time consumption and costs using input data from the first study on large stem fellings. That is to say, despite being simulation-based, the analysis examined a physical concept (Figure 3). Its purpose was to clarify the innovation's potential in small stem fellings in order to determine whether a time study analysis of such fellings could be justified. Promising results were obtained (Figure 2, Have expectations been met for the analyzed criterion), but there was a need to reduce a number of uncertainties (Figure 2, Have all criteria been analyzed to a desired level of certainty?). Therefore, a time study was undertaken (Figure 3, step 4) and its results proved to agree well with the output of the simulation (Manner et al. 2016).

In parallel to the discussions about stem size, the importance of the wood value criterion received increased attention. This revealed uncertainties concerning issues such as the harwarder's expected measurement quality and the proportion of bucking splits, and it was judged to be necessary to reduce these uncertainties. However, further studies on the X19 (Figure 3, step 4) showed that it did not offer clear difference with respect to any of the analyzed factors (Ågren et al. 2016). All six users' expectations concerning wood value were met, but one user's expectations concerning logging costs were not met, prompting that user to leave the HCG. The remaining five users judged the results obtained to be unclear, so additional studies were undertaken.

To move the harwarder further towards implementation, it was necessary to demonstrate a clear reduction in logging costs based on the discussions within the HCG and the chosen criteria. However, the exact cost reductions required by the users differed since one chose to end their evaluations and reprioritize their resources while the others chose to invest additional resources into further analysis and extended trials. The remaining users thus continued to focus on reducing uncertainty. However, refining the criteria may have been a better choice in this situation, as it could have revealed more appealing solutions such as a time study analysis focusing on large stem felling or a large-scale analysis of the innovation's potential such as those presented in papers III and IV. This illustrates the point that sufficiently well-established criteria are essential when seeking the best decision in a given situation. After one user left the HCG, the remaining users considered the criteria to be sufficiently established, and therefore conducted further analyses to reduce uncertainties relating to the chosen criteria.

The next study focused on describing the influence of assortments and showed that the predictive value of the number of assortments is much lower than that of the distribution between the assortments (Manner et al. 2019). Additionally, the harwarder proved better able to handle large and complex mixtures of assortments than was initially expected. Together with its competitive performance with larger stems, this prompted the group to evaluate its potential in southern Sweden (Figure 3, step 4). Since the harwarder had not been used at a scale even close to the TMS, the members of the HCG felt that uncertainties relating to operator impact could influence method development. Therefore, a new study was undertaken in which an established harwarder method was compared to a new one that achieved lower time consumption (Manner et al. 2020). These positive results encouraged the HCG members to continue reducing uncertainties despite the fact that the expected reductions in logging costs had yet to be achieved. The potential to reduce logging costs through further development was tested by evaluating automation sequences on a virtual harwarder (Figure 3, step 3). The decision to develop a virtual concept harwarder and automation sequences despite the existence of a physical machine was motivated by the much lower costs of performing such development work in a virtual environment. The study yielded no general time saving but revealed opportunities for further development (Manner et al. 2019). The final attempt to analyze potential improvements in the harwarder was done during a workshop involving the operators who had tested the X19 together with a forestry professional and some researchers. The subsequent analysis identified possibilities for reducing logging costs by implementing a number of technological improvements (Jonsson et al. 2020). To provide a detailed evaluation of the harwarder's ability to compete with the TMS on a larger scale, two final analysis was undertaken, the results of which are presented in papers III and IV. Overall, the studies indicated that the harwarder concept offered similar performance to the established TMS and did not meet all of the users' expectations, so additional steps towards implementation were not taken.

Although the automation sequences developed by Manner et al. (2019) were not taken further towards implementation, their development established a new knowledge base that will facilitate future efforts in this area.

5.3.4 Reflections and recommendations related to the conceptual models

Tests of an innovation often clearly show whether or not it meets expectations after one or two iterations. In such situations, it is fine to not carefully establish the criteria. However, if the result remains unclear after multiple iterations, I recommend refining the criteria to ensure that resources are deployed in the most efficient manner. Performing several further iterations of testing and studying then becomes a natural next step to fully explore the innovation's performance with respect to the refined criteria.

As shown in Figure 3, the quality and quantity of the input data should ideally increase as one advances from idea to implemented innovation. However, the size of the steps in this process (represented mainly by the quantity of resources invested) may vary depending on the level of uncertainty and the risk appetite of the DM(s). It may thus be preferable to take several small steps rather than a few large ones. Additionally, it may be helpful to structure the problem at hand before testing an innovation to ensure that the DMs have a clear view of what the problem to solve really is and what their values are. Doing this allows the innovation to be meaningfully compared to the status quo (i.e., the current solution). Once a 'go-decision' has been made, testing of the innovation can commence. If the innovation lacks a physical representation, its performance can be evaluated by applying and adapting existing data from similar innovations or technologies.

When evaluating the work described above, and considering the fact that the X19 has not yet been advanced to serial production, it is easy to conclude that it would have been more resource-efficient to proceed differently. However, while it appears that some aspects could have been improved, some aspects of the work were excellent. All groups in the 'development triangle', including users, a manufacturer, and a research organization participated in the process, and this was emphasized as a success factor by the respondents in paper I as well as by Ager (2017). The development of the X19 went according to plan, probably thanks to the good participation of these groups. After the X19 was delivered to one of the users, they and other users performed trials in their own organizations. Testing a concept in one's own organization has large benefits if a concept is advanced to serial production and implemented on large scale because both operators and forestry professionals such as team leaders and specialists get opportunities to ask questions about and become familiar with the new concept. This means that if the concept is subsequently implemented, many questions may already have been resolved and personnel will be better prepared for its introduction. Additionally, testing in diverse geographical areas with different stand conditions may reveal new problems and solutions. New problems can provide a basis for deciding to end evaluations or motivate analysis of potential solutions, while new solutions can make the concept more competitive with established technologies and increase its likelihood of advancing to implementation.

Since the X19 was produced (Figure 3, step 4) directly after creating an early 'napkin sketch' (Figure 3, step 1), one might argue that the decision not to implement it following the studies presented in papers III and IV could have been reached with far less expenditure of resources if the project had moved to step 2 or 3 after step 1 rather than advancing directly to the production of a concept machine. On the other hand, the input data available to construct a simulation model (in a putative step 2) was the same as that used in step 1. Moreover, since the harwarder is an independent system consisting of a single machine, the impact of variation and stochastic elements is relatively small. As such, omitting step 3 could also be justified. Additionally, earlier harwarders such as the Valmet 801 Combi had been taken through to the final step of the process, meaning that more information about their competitive ability could have been gathered as a basis for evaluation before considering the X19.

5.4 Strengths and weaknesses

The studies included in this thesis all provide unique lessons. The first paper captures the experiences of seven respondents representing six users. The respondents played key roles in the development efforts and their employers are among the largest and most influential organizations in the Swedish forest sector. The generalizability of the results concerning current technological decision-making in Swedish large-scale forestry is thus likely to be good. However, gathering more data would have made the results both deeper and wider. More users could have been included along with more respondents within each organization to reduce the influence of variation in individual respondents' ways of describing how they work. However, such variation is unlikely to have significantly affected the results because there were extensive similarities between the responses of the different interviewees. According to Creswell & Poth (2018), observation is a key source in qualitative studies, so complementing the interviews with observational studies and analyses of internal policies, guidelines, and routines could have increased the generalizability of the results. This approach was not adopted because the time required to collect such data and the costs of doing so are both substantial, but it could be worth investigating in a future study. Since paper I is one of only a few studies on decision-making in technological development processes within the forest sector, it is expected that there would be scope for increasing its generalizability. The decision process of Mintzberg et al. (1976) was used as a framework for analyzing the users' responses. This provided a good basis for interviews and analyses.

When designing paper I, it was expected that there would be clear decision processes and rules for choosing a suitable decision support tool. Many such tools have been described in different scientific publications, books, training programs, and courses. However, the processes lacked the expected clarity, suggesting that they could be made more effective by introducing well-adapted routines and checklists. It is also notable that most of the available tools focused largely on economic considerations, while Problem Structuring Methods, simulations, and optimization methods were less common, than expected. This reveals an opportunity to improve decision-making. When designing the study, the original plan was to distinguish between different kinds of uncertainties. However, the responses were not clear enough for this purpose, so all of the uncertainties were analyzed together. More careful definitions and follow-up questions will thus be needed in future studies on this topic.

Papers III and IV both conclude that both the DO and the AH could provide a better basis for decision-making. Moreover, the two approaches provide coherent outputs in terms of machine fleet composition and costs and can also be improved further. However, the DO also provides insight into where machine teams should be stationed and the scheduling of teams' work.

When adjusting the models, the AH approach was generally more sensitive to changes because there are fewer ways in which AH models can be automatically adjusted. For example, in the DO a single change in input data could change the area to which a team is deployed, which will in turn affect moving costs. However, with the AH approach, such a change would have a fixed moving cost that was independent of the other input data. The reaction of the DO to the change is thus more similar to that expected operationally. This is true for all possible changes, including changes in factors such as stand character, time functions, and cost parameters.

The conceptual models presented in Figures 2 and 3 are based on observations but can provide valuable support for strategic decision-making on forest technology. While both models are based on observations of Swedish forestry organizations, they are likely to be valuable for supporting decision-making processes in other countries and forestry contexts for a wide range of machine systems. It would however be interesting to develop and adapt the two models further to better reflect the characteristics of contexts other than that of Swedish forestry.

5.5 Implications for practice and future research

The focus of this study has been on the decision processes of technology users, namely large-scale forest companies and FOAs. However, as mentioned repeatedly, manufacturers and researchers are also important actors in strategic technology decision-making in large-scale forestry, so it would be interesting to investigate their decision processes. Manufacturers make decisions about whether to enable technologies for implementation, which could be analyzed using the model of Mintzberg et al. (1976) and an approach similar to that applied in paper I. The conceptual models presented in Figures 2 and 3 could also be applied in such studies because of their focus on forest technologies. However, it might be worth considering a framework with a greater emphasis on innovation, such as that of Narvekar & Jain (2006). A potential limitation is that manufacturers might see their decision processes as a source of competitive advantage that they would be unwilling to share fully, making full collaboration less likely than would be the case for users or research organizations. For research organizations, the model of Mintzberg et al. (1976) or those outlined in Figures 2 and 3 could be used. Since the purpose of research organizations is to conduct investigations and collaboration is important in their work, it is likely that different research organizations would collaborate in such a project and be keen to investigate and critically analyze their own decision processes to find ways of improving. Because collaboration between researchers, manufacturers, and users is seen as an important factor in their joint success, it would be interesting to investigate the overlaps between their decision processes.

As acknowledged by several respondents in paper I, the development triangle has been an important factor in the success of forest technology development, and before that in the development of mechanized harvesting methods (Ager 2017). After approximately three decades in which the TMS has dominated Swedish logging operations and improvements have mainly occurred through incremental innovations, the decision situations facing users, manufacturers, and other actors may be changing rapidly due to the increasing importance of environmental considerations, teleoperations, and automation as well as changing social criteria. The development triangle will therefore likely become increasingly important as a source of robust guidance for future efforts and development projects.

Another conclusion from paper I was that the responses were not clear enough to distinguish between uncertainties of knowledge, outcome, and value. Therefore, further research on the uncertainties associated with technological development decision-making in forestry organizations is warranted (Blennow & Sallnäs 2006). Paper I also indicated a need for greater use of decision support tools such as economic models, simulations and optimizations. Economic models are needed because logging costs are a central criterion for users, while simulations can provide deeper understanding (especially at the stand level) and optimizations can be used to evaluate the capacity of innovations to compete with established technologies. Since the establishment of the criteria appeared to be relatively vague, decision support tools such as Problem Structuring Methods could be beneficial.

These methods are likely to be applicable to all kinds of problems, but some barriers to their uptake were highlighted in paper II, which focused on how practitioners should think about choices concerning MCDA approaches. The most important message was that it is more important to carefully structure the problem before starting to consider alternatives than it is to use a particular MCDA. This is because there is no perfect MCDA method that is optimal for all forest operations problems. However, since MCDA approaches are sometimes seen as complex black boxes, I recommend using approaches that are comparatively simple and easy to grasp such as the popular AHP.

Groups of decision support tools such as MCDA, information systems, statistics, simulations, optimizations, and economic systems are applicable in different decision situations. Of these groups, MCDA and optimization were reviewed or applied in the papers included in this thesis. I have described the pros and cons with those tools here and with my co-authors in the papers, but choosing between all of the available decision support tool groups can be challenging. It would therefore be desirable to develop guidance to help users select an appropriate tool for their use case. Such guidance could be based on the fact that there are significant relationships between some decision support tools and decision characteristics (Segura et al. 2014). One notable contribution in this area was made by Eyvindson & Kangas (2018), who created a decision tree for choosing a suitable DSS for risk management in forest planning. It would be interesting to construct such a decision tree for general decision support tools. A general decision tree designed for use by researchers could be relatively detailed and could provide support for newcomers to the field who want to choose a decision support tool that is well-suited to their needs even if it requires them to learn new theories or software, or initiate a collaboration with someone who already has the necessary knowledge. Conversely, a decision tree for practitioners could include only one or just a few decision support tools within each group.

When implementing an innovation, an estimate of its optimal deployment within a region can be obtained using DO in conjunction with input data representing thinnings and final fellings as well as information on real teams' relative performance levels as well as their home bases. This approach is used by many forestry organizations today and has the potential to reduce the risk of making a suboptimal choice when deciding where to deploy the first examples of a new innovation or in which stands it should be applied. Both the DO and the AH are well suited for such analyses of large input data sets; I recommend using the DO when the need for precision is high and suitable input data are available, but to choose the AH otherwise. Conducting machine fleet analyses using either of these approaches requires specific competences - DO requires suitable software and personnel with advanced modelling and optimization expertise, whereas AH requires only the latter.

It was hard to determine whether alternative technical solutions were examined before or after deciding on the criteria for evaluating solutions in the development processes described by the participants of paper I. The respondents in the study of Mintzberg et al. (1976) frequently evaluated alternatives before determining criteria, showing that this approach is common. Keeney (2009) distinguishes between alternative-focused and value-focused decision-processes, the latter of which could equally well be described as being "criteria-focused" (author's comment). The main difference is that alternatives are identified at an early stage in the former case and used to clarify the values (i.e., criteria) that are then used in their evaluation. Such processes tend to be reactive. The opposite is true in value-focused processes, which enable a more active and creative way of selecting alternatives. Keeney (2009) has therefore argued strongly for the benefits of the value-focused approach. The conceptual model presented in Figure 2 has the same order as that advocated by Keeney (2009) and thus supports more active processes.

The absence of clear and well-rehearsed routines or guidelines may indicate a lack of suitable tools and decision processes. This lack could be addressed in several ways. First, decision-making in technological development could be improved by adopting scientifically supported decision processes such as that outlined in Figure 2. Second, one or a few easily grasped Problem-Structuring Methods could be introduced (Mingers & Rosenhead 2004). Third, insourcing of research competence could enable users to undertake more independent development efforts, while improvements in the competence of research and other expert organizations could enable deeper collaboration with users. Finally, more frequent collaboration on development projects could improve transparency when applying MCDA methods (Blagojević et al. 2019).

6. Conclusions

1. When making development decisions, respondents in paper I, representing six relatively large users of forest technology, aimed to maximize performance with respect to economic criteria without falling below threshold values for criteria such as operator well-being, soil rutting, and wood value.
2. Collaboration between users, manufacturers, and researchers was found to be important for successful decisions on forest technology development (papers I, III, IV).
3. There appeared to be a lack of proper diagnosis efforts among the respondents of paper I, so decision-making could be improved by using tools such as Problem-Structuring Methods (PSM).
4. Despite the growing importance of several criteria within forest operations, the review presented in paper II showed that Multi-Criteria Decision Analysis (MCDA) methods are rarely used in forest operations, probably due to lack of time to choose and perform analyses. To overcome this, practitioners are advised to focus on input data and alternatives because several methods can provide much more reliable answers than intuition, which is currently the most common basis for decision-making.
5. Both the Detailed Optimization (DO) and the Aggregated Heuristics (AH) approaches used in paper III are well suited for analysis of large input data sets with a single overall objective. I recommend using the DO when the need for precision is high and suitable input data are available. AH should be used when such data are unavailable or high precision is not needed.
6. Strategic forest technology development processes could be improved and streamlined by following the conceptual models

presented in Figures 2 and 3, making it possible to reduce resource expenditure and increase analytical certainty when going from project initiation to a final decision on whether or not to implement an innovation. It would therefore be interesting to further develop and refine these models.

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Popular science summary

The forest sector is a large contributor to Sweden's gross domestic product, accounting for around 10 percent of Sweden's yearly export of products. Technological development gives Swedish forest companies and forest owners' associations (FOAs) opportunities to maintain competitiveness in the highly cost-sensitive market for forest products. Such development efforts involve complex novel systems and are thus usually guided by unstructured decision processes. However, an organization's success is a product of its decisions, so the quality of those decisions is vitally important.

The main objectives of this thesis were to describe and critically analyze strategic forest technology decision-making. This was done by examining different aspects of the decision process using a variety of methods, including reviewing published research and directly examining the processes of forest companies and a FOA with a specific focus on decisions relating to the development of a new harwarder.

Study I investigated how forest technology decisions are made in forest companies and a FOA, and what support is used in the process. It was concluded that the participants value collaborations with manufacturers and researchers, that economic criteria often are the main objectives while other criteria are seen as constraints, and that large risks are managed by taking small steps rather than large ones where possible. Study II aimed to make Multi-Criteria Decision Analysis (MCDA) methods more intelligible for novice users and reviewed the use of MCDA methods in forest operations. Different methods were explained and grouped, and their strengths and weaknesses were presented. It was shown that the methods were used at strategic, tactical, and operational scales but were most commonly applied in strategic decisions. Study III developed and compared two modelling approaches for machine system analysis and concluded that they produced similar results despite having different levels of detail and demanding different competences. Moreover, their similarities were greater than in other analyses that have been reported in the scientific literature. Study IV used the previously developed modelling approaches to compare a new machine system to an established solution in Swedish final fellings and found the potential to reduce costs by implementing the new system. The analyses in papers III and IV were concluded to provide a suitable basis for strategic decision-making on innovations.

A conceptual flowchart for strategic decision-making on forest technology development was presented. This flowchart provides guidance for every step of the development process, from the first evaluations to the final decision about whether or not to implement the new technology. A conceptual model was presented, showing how an innovation can be stepwise evaluated by using different kinds of theoretical and physical representations, along with the different type of representations' pros and cons. Use of this flowchart and model could increase the decision efficiency of companies and other organizations within the forest sector.

Populärvetenskaplig sammanfattning

Skogssektorn står för en betydande del av Sveriges bruttonationalprodukt och står för cirka 10 procent av Sveriges årliga export av varor. Den tekniska utvecklingen ger svenska skogsbolag och skogsägarföreningar möjligheter att behålla konkurrenskraften på den mycket konkurrensutsatta marknaden för skogsprodukter. Sådana utvecklingsinsatser involverar komplexa nya system och styrs därför vanligtvis genom ostrukturerade beslutsprocesser. Men en organisations framgång är resultatet av dess beslut, så kvaliteten på dessa beslut är mycket viktiga.

Huvudsyftet med denna avhandling var att beskriva och kritiskt analysera strategiskt skogstekniskt beslutsfattande. Detta gjordes genom att undersöka olika aspekter av beslutsprocessen med hjälp av flera olika metoder, bland annat genom att granska publicerad forskning och direkt granska skogsbolagens och en skogsägarförenings processer med särskilt fokus på beslut som rör utvecklingen av en ny drivare.

I studie I undersöktes hur skogstekniska beslut fattas i skogsbolag och en skogsägarförening, och vilka stöd som används i processen. Det framkom att de intervjuade beslutsfattarna värdesätter samarbeten med tillverkare och forskare, att ekonomiska kriterier ofta är huvudmålen medan andra kriterier ses som ramar och att stora risker hanteras genom att ta små steg där det är möjligt, snarare än att ta stora steg. Studie II syftade till att göra multi-kriterie analysmetoder (MKA–metoder) mer begripliga för nybörjare samt att granska användningen av MKA-metoder i skoglig drift. Olika metoder förklarades och grupperades och deras styrkor och svagheter presenterades. Det visades att metoderna visserligen användes i såväl strategisk, taktisk och operativ tidsskala, men var vanligast i strategiska beslut. I studie III utvecklades och jämfördes två metoder för maskinsystemanalys, som gav liknande resultat trots att de hade olika detaljnivåer och krävde olika kompetenser. Dessutom var deras likheter större än i andra analyser som har rapporterats i den vetenskapliga litteraturen. I studie IV användes de utvecklade metoderna för att jämföra ett nytt maskinsystem med en etablerad lösning i svenska slutavverkningar, och resultaten visade på potential att minska kostnaderna genom att implementera det nya systemet. Analyserna i studie III och IV genomfördes för att ge ett lämpligt underlag för strategiskt beslutsfattande om innovationer.

Ett konceptuellt flödesschema för strategiskt beslutsfattande om skogsteknisk utveckling presenteras i avhandlingen. Detta flödesschema ger vägledning för de olika stegen i utvecklingsprocessen, från de första utvärderingarna till det slutliga beslutet om huruvida den nya tekniken ska implementeras eller inte. Dessutom presenteras en konceptuell modell över hur en innovation stegvis kan utvärderas med hjälp av olika former av teoretisk och fysisk representation av innovationen, tillsammans med de olika representationernas för- och nackdelar. Användning av flödesschemat och modellen förväntas öka beslutseffektiviteten för företag och andra organisationer inom skogssektorn.

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II

Subject review

Multi-Criteria Decision Analysis (MCDA) in Forest Operations – an Introductional Review

Boško Blagojević, Rikard Jonsson, Rolf Björheden, Eva-Maria Nordström, Ola Lindroos

Abstract

Decision making in forestry is very complex and requires consideration of trade-offs among economic, environmental, and social criteria. Different multi-criteria decision analysis (MCDA) methods have been developed for structuring and exploring the decision-making process of such problems. Although MCDA methods are often used for forest management problems, they are rarely used for forest operation problems. This indicates that scholars and practitioners working with forest operations are either unaware of MCDA methods, or see no benefit in using these methods. Therefore, the prime objective of this review was to make MCDA methods more intelligible (compared with current level of understanding) to novice users within the field of forest operations. For that purpose, basic ideas as well as the strengths and limitations of selected MCDA methods are presented. The second objective was to review applications of MCDA methods in forest operations. The review showed that MCDA applications are suitable for forest operation problems on all three planning levels – strategic, tactical, and operational – but with least use on the operational level. This is attributed to: 1) limited availability of temporally relevant and correct data, 2) lack of time (execution of MCDA methods is time consuming), and 3) many operational planning problems are solved with regards to an economic criterion, with other criteria serving more as frames. However, with increased importance of environmental and social aspects, incorporating MCDA methods into the decision-making process on the operational planning horizon (e.g., by developing MCDA-based guidelines for forestry work) is essential.

Keywords: multi-criteria decision analysis, decision-making, forest operations

1. Introduction

The complexity of forestry decision making is associated with dimensions and categories, which range from: long term (strategic) to short term (operational) on a temporal scale, stand level to national level in a spatial scale, and individual to group decision making in a stakeholder scale (Segura et al. 2014). Previously, forestry decision making was often performed by a single, empowered decision maker (forest owner or forest officer) and, thus, the decision-making process was less complex than present-day processes. However, after the UN Conference on the Environment and Development in Rio (UNCED 1992), public participation through involvement of different groups of stakeholders gained relevance and wide acceptance (Mendoza and Martins 2006). In addition, forestry decision making is a very complex issue that requires consideration of trade-offs among economic (e.g., timber, forage, livestock, hunting), environmental (e.g., soil erosion, carbon sequestration, biodiversity conservation), and social criteria (e.g., recreational activities, level of employment, population settlement) (Diaz-Balteiro and Romero 2008). Another issue is that various stakeholders participating in the decision-making process can have different or opposite priorities, objectives, and goals, which may lead to conflicts.

The complexity of decision problems in forestry is ever increasing. Correspondingly, the difficulty faced by decision-makers in searching a solution that considers all criteria, examines tradeoffs, reduces conflicts, in an optimizing framework (Ananda and Herath 2009), without the help of decision support systems (DSS) has also increased. Segura et al. (2014) classified DSS for forest management problems into six groups: multiple criteria decision analysis (MCDA), optimization, simulation, economic models, statistical methods, and information systems. Usually, these groups are combined in DSS in a way such that simulations, information systems, statistical models and/or economic models provide input data for MCDA or optimization. For example, geographic information systems (GIS) and strengths, weaknesses, opportunities, and threats (SWOT analysis, economic model) are often used in conjunction with MCDA methods. Similarly, life cycle assessment (LCA) can be used to assess the environmental pillar in sustainability analysis, while MCDA covers more pillars (e.g., economic and social) and can be used to compare alternatives from a product to a policy level (Cinelli et al. 2014). Segura et al. (2014) reviewed 120 forest management problems; MCDA was used in 31%, while optimization appeared in 59% of the papers; the total number of operational problems (29) was less than the number of tactical (39) and strategic (52) forest management problems. Moreover, MCDA methods were more often used in strategic problems than in tactical and operational problems, but almost the opposite was true for forest management decisions concerned primarily with environmental questions. For example, for a total of 179 forest management problems with biodiversity objectives, MCDA, MCDA combined with voting methods, and optimization methods were applied in 41.9%, 52.7%, and 20.5% of the research papers, respectively (Ezquerro et al. 2016).

The trend of increasing MCDA application will most likely continue as today's forestry decision problems (with multiple criteria, functions, and stakeholders (typically) with conflicting interests) call for highly flexible and versatile DSS, which require tools complementary to simulation and optimization tools (Kangas and Kangas 2005). Belton and Stewart (2002) and Mendoza and Martins (2006) described several inherent properties that render MCDA appealing and practically useful for decision making in forestry, namely MCDA:

⇒ explicitly considers multiple, conflicting criteria

⇒ helps to structure the management problem

⇒ provides a model that can serve as a basis of discussion

⇒ offers a process that leads to rational, justifiable, and explainable decisions

⇒ can deal with mixed sets of data (quantitative and qualitative) including expert opinions

⇒ is conveniently structured to enable a collaborative planning and decision-making environment

⇒ provides a participatory environment that accommodates the involvement and participation of multiple experts and stakeholders (Mendoza and Prabhu 2003).

Overall, the framework of MCDA is supposed to aid in decision making and aims to integrate objective measurement with value judgment. By doing this explicitly, the inbound subjectivity of decision making can be managed in a more clear and precise way (than that achieved without MCDA applications). MCDA is intended for complex decisions and aims to aid in the decision-making process by providing decision-makers with tools for improved knowledge about their decisions. This means that the content will change only modestly, but the understanding of the process will increase, and their priority will be clarified. Therefore, at the time of decision making, the decision-maker will know more about the issue (than previously) but must still make one or several decision(s) (Belton and Stewart 2002). These useful properties of MCDA have recently been recognized by scholars and researchers worldwide. Indeed, whereas only a handful of scientific papers within the environmental field mentioned MCDA methods in the early 1990s, several hundreds of papers using MCDA methods were published annually in the late 2000s (Huang et al. 2011). In fact, in the last four decades, MCDA has been an efficient and often used approach for solving forest resource management problems (Ananda and Herath 2009) for both individual and group (participatory) context (Nordström et al. 2010, Acosta and Corral 2017).

However, some scholars have highlighted the weaknesses of applying MCDA in forestry. According to Kangas et al. (2006), MCDA methods are sometimes too complex, demand significant amounts of data, consist of excessive number questions to be answered by decision makers, and are usually time consuming. Decision makers may, therefore, struggle in understanding the principles underlying the ranking of various options, i.e., the method can seem like a »black-box« and this can lead to distrust (Gregory 2002). According to those authors, voting methods can be a credible alternative in forest decision making. Segura et al. (2014), as in the case of this paper, included voting methods in the MCDA group, since they are used more frequently than MCDA.

Although MCDA methods are often used for forest management problems, they are rarely used for forest operation problems. Therefore, the prime objective of this paper was to present and elucidate MCDA methods (together with Multi-criteria approval and Delphi voting methods) to novice users within the field of forest operations. For that purpose, basic ideas as well as the strengths and limitations of selected MCDA methods are presented. The second objective was to review existing applications of MCDA methods in forest operations.

2. General definition of time perspectives in forestry

Decision problems related to forestry are often divided into strategical, tactical, and operational time levels (Carlsson et al. 2006, Borges et al. 2013, Segura et al. 2014). However, the definitions of these three perspectives vary in the literature (Church 2007, Epstein et al. 2007, Gunn 2007). Moreover, the time perspectives may differ widely within an organization, as strategic planning may be performed on a 100 year-horizon for some organizational units and on a 10 year-horizon for others. Comparisons between such time perspectives must, therefore, account for these potential differences. Nevertheless, the focus within the planning perspectives is connected to the aim of the planning processes and could, hence, be considered common to most organizations and branches. Therefore, in this paper the perspectives have been defined as follows:

Strategic planning focuses on producing policies and organizational goals, as well as helping the organization to function and make decisions that are favorable to the organization. This level can and should include all parts of the organization and may include re-definition of these parts through financial adjustment. The perspective has no upper time limit, but border on the tactical planning stage at the lower end.

In the *Tactical planning* stage, implementation of the strategic plan for the upcoming period (e.g., on a yearly basis) is considered. The strategic plan is enacted, using the resources required for accordance with the strategic plan. The tactical planning stage follows the strategic planning stage in the upper time end and precedes the operational planning in the lower end.

The *Operational planning* stage is aimed at executing the tasks defined in the tactical plan. Hence, planning on the operational level focuses on the use of the available resources.

The selected definition is expected to capture (at a resolution suitable for the objective of this paper) the nature of the planning and its dependence on the time perspective. A proper definition is considered crucial, as the suitability of MCDA methods and their applications may vary with the time perspective.

3. Forest operations and associated problems

Forest operation problems have been described in many ways. This paper focuses on forest operations, in general, with a broad view of the area. Thus, Sundberg's (1988, 110 p.) description of forest operations frames the area in focus rather well: »…the interaction of labour and machines with the forest. It involves an understanding of the relationships between labour, technology, the forest resource, forest industries, people and the environment«.

Forest operation problems may be categorized in many ways (Epstein et al. 2007, D'Amours et al. 2008, Rönnqvist et al. 2015). We have divided forest operations into five categories, depending on the type of operation and the influence of the time perspective. Categories 1–2 focus on cultivation, 3 on procurement till roadside and 4–5 on transportation issues from roadside to industry.

⇒ regeneration (site preparation, establishment of a new stand)
⇒ pre-commercial thinning, i.e., harvesting without extraction of trees
⇒ harvesting and extraction, i.e., harvesting with extraction and procurement of trees
⇒ access to forest stands (e.g., road construction and maintenance)
⇒ logistics.

The categories cover both methods and technology and are subsequently divided into the time perspectives (see the following paragraphs). The categories cover only some issues related to forest operations but serve as a basis for further interpretation of MCDA application to the field. A comparison of the categories on the basis of time perspectives yields clear patterns. The *strategic planning* stage typically includes the long-term plans necessary for the prolonged time perspectives (e.g., choice of silvicultural regimes and harvesting methods, such as whole-stem or cut-to-length, and suitable technology for implementation of these methods). *Tactical planning* typically includes investment in the technology necessary to execute the subsequent operational plans, and planning of specific actions (e.g., number of machines, in varied sizes, for meeting the strategic plan requirements). *Operational planning* consists of measures required for the execution of actions. For the sake of the MCDA review, the operational planning stage is divided into three levels:

⇒ scheduling of resources to planned actions (e.g., identifying machines that should be used for planned stands)

⇒ detailed planning of actions (e.g., pre-planning of the trees that should be harvested, where to drive the machines in the stand, and adjustment of the scheduling plan)

⇒ on-site and real-time planning in direct connection to the execution, which might include adjustments of pre-made plans or the execution of work according to routines (e.g., operator chooses the trees for thinning, how to buck stems, and how to prevent rutting).

4. MCDA

4.1 General MCDA methodology

Multi-Criteria Decision Analysis (MCDA) is described by Belton and Stewart (2002) »as an umbrella term to describe a collection of formal approaches, which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter«. In other words, MCDA handles the process of making decisions in the presence of multiple, usually conflicting, criteria. The methodology of MCDA can be classified into four basic phases:

⇒ structuring the decision problem

⇒ assessing the possible impact of each alternative

⇒ determining the preferences (values) of decision-makers

⇒ evaluating and comparing the alternatives (Raiffa 1968, Keeney 1982, Belton and Stewart 2002, Nordström 2010).

In the first phase, identifying decision makers and defining the criteria and alternatives of the decision-making problem are essential. This phase is essential for the quality of the decision-making process, because poor structuring of a decision-making problem will probably lead to poor decisions, irrespective of the MCDA method employed. Therefore, in this paper, the first phase (where the type of decision-making problem is identified as either an individual or a group problem) is described in more detail than the other phases. Most decisions, whether personal or organizational, may involve multiple stakeholders, i.e., those affected by a decision and those tasked with implementing this decision (Belton and Stewart 2010). Identifying stakeholders and selecting those who will be involved in the process as decision makers (DMs) are therefore necessary. In group decision making, the weights of DMs reflect their expertise and/or importance and must be defined. Should the vote of all DMs be considered equally important, and if not – how should they differ? Several methods, ranging from the decisions of one DM, the entire group or mathematical methods may be used to establish DM weights. In the first case, weights are defined by a specific DM (i.e., a supra decision-maker with supreme expertise or authority) who is given the power to decide the level of influence of the other DMs. Finding a supra decision-maker, who is accepted by everyone, can be difficult (Ishizaka and Nemery 2013). In contrast, the entire group can be involved in allocated DM weights, in what is referred to as a participatory approach. In that approach, each DM evaluates all other group members (including him- or herself) using pairwise comparisons (Ramanathan and Ganesh 1994) or by choosing a value between a lower and an upper limit (Lootsma 1997). This implies that the DM can tacitly judge the weights of certain members of the group to form a decisional coalition (Van Den Honer 2001). Other approaches, which are more mathematical than this approach, can be used to define the weight between DMs. For example, weights can be obtained on the basis of the: demonstrated individual consistencies of each DM (Chiclana et al. 2007, Cho and Cho 2008, Srdjevic et al. 2011), agreement between individual decisions made by a DM and the group decision (group consistencies) (Regan et al. 2006, Yue 2012, Ju and Wang 2013, Blagojevic et al. 2016), or on the basis of past performance of DMs (Cooke 1991).

Afterward, a decision hierarchy must be structured, where the goal or overall objective (statement of what DM(s) wants to achieve via the decision), criteria, sub-criteria (if any), and alternatives should be defined (Keeney, 1992). This is usually done by previously selected DMs (from above) with the help of a decision analyst. An alternative approach, although rarely applied, is to have one person with supreme expertise or authority who will define all content of the decision hierarchy. Selected criteria should fulfill several requirements; they should be essential, controllable, complete, measurable, operational, decomposable, independent, concise, and understandable (for more details see: Keeney 1992, Kangas et al. 2015). Hence, finding qualified DMs may be difficult and, therefore, the selected criteria may correspond to those easily managed by the analyst. Some criteria that DMs are interested in may be omitted due to lack of data or models, but a laissez-faire attitude to criteria selection can influence the decision process. For example, if criteria were non-independent, they would yield an over-evaluated weight in the decision (Ishizaka and Nemery 2013). Moreover, exploring and including all relevant decision alternatives in the analysis, especially when the decision space is represented by a continuous rather than discrete (i.e., unlimited vs. limited) set of alternatives, may be difficult. Lack of alternatives that perform at a satisfactory level on all criteria may create dissatisfaction and conflict among DMs, resulting in a need for further alternatives (Belton and Stewart 2010). Several methods, such as Strategic Options Development and Analysis (SODA) (Eden and Ackermann 2001), Soft Systems Methodology (SSM) (Checkland 2001), Strategic Choice Approach (SCA) (Friend 2001), Robustness Analysis (Rosenhead 2001), and Drama Theory (Bennett et al. 2001), can be used for problem structuring; a thorough description of these methods is beyond the scope of this paper. However, in this phase, DMs may be susceptible to many cognitive and motivational biases (Montibeller and von Winterfeldt 2015) that can be avoided, with the help of a decision analyst. For example, criteria with many sub-criteria tend to receive higher weights than criteria with few sub-criteria (Morton and Fasolo 2009), and *desirability bias* may lead to the exclusion of alternatives that compete with the preferred one.

In the second phase, performance data of alternatives with respect to all selected criteria must be obtained. This data can be quantitative – e.g., measured, calculated, estimated, simulated with a model – or qualitative (descriptive). Similarly, in the third phase, the importance (i.e., weights) of criteria must be defined. This definition can be made via several quantitative (statistical) methods, for e.g., the Entropy Method (Shannon and Weaver 1947, Srdjevic et al. 2004) or the Criteria Importance Through Inter-criteria Correlation (CRITIC) (Diakoulaki et al. 1995) method. Such methods are less frequently used than other methods, since they are *blind* to problem reality, i.e., weights are allocated based on the observed level of variation within each criterion (rather than on problem-related values). A common way to define criteria weights is to elicit preference values from decision makers. The preferences are subjective judgments (made by the decision maker), which can be expressed as cardinal values (e.g., the weight of criterion *j* is 0.300) or ordinal values (criterion *j* is ranked as second most important). They can be expressed either directly or in a pairwise manner. In group decision making, the criteria weights will be the sum of the weight preferences associated with each DM's criteria adjusted for the DM's individual weight within the group (established in the first phase). In the fourth and final phase, alternatives will be evaluated and compared using the selected MCDA method. The last two phases, which differ between the methods, are described in detail below.

4.2 MCDA methods

MCDA methods have been classified in several ways depending on the perspective and purpose of classification (Hajkowicz et al. 2000, Nordström 2010). The classification in this paper is based on the way the preferences are modeled (Belton and Stewart 2002), where all MCDA methods are divided into three different categories:

⇒ goal, aspiration or reference level methods
⇒ outranking methods
⇒ value measurement methods.

Goal aspiration or *reference level methods* rely on establishing desirable or satisfactory levels of achievement for each criterion (Linkov et al. 2004). All criteria should be quantitative, as these methods are aimed at minimizing the distance between a certain point and the actual achievement for each of several criteria under consideration (Romero et al. 1998). Methods from this group allow trade-off between criteria and are, therefore, compensatory. They are especially well-suited for problems with continuous or many alternatives and are non-demanding for DMs, who must only define weights of criteria and desired criteria level. Goal Programming (GP) (Charnes and Cooper 1961), Compromise Programming (CP) (Zeleny 1982), and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) (Hwang and Yoon 1981) methods represent three of the most widely used goal, aspiration or reference level methods. GP, which is used to handle multiple conflicting objectives, is an extension of Linear Programming (LP). In LP, an objective function is optimized (maximized or minimized) within the feasible region defined by the rigid LP constraints. These constraints can (indirectly) be more important than the objective, thereby leading to infeasibility problems (Kangas et al. 2015). In GP, this issue is resolved by considering an objective that is composed of several goals with hard and soft constraints. A goal with a soft constraint has a threshold that is an ideal point, which can be exceeded as solutions greater than this point are feasible even if they are undesirable (Ishizaka and Nemery 2013). Although there are various types of GP (Diaz-Balteiro et al. 2016), this continuous method is aimed at identifying an optimal solution from an infinite number of alternatives and can, hence, be very useful for generating alternatives. In contrast, CP and TOPSIS represent discrete MCDA methods aimed at selecting a solution from a finite number of alternatives. CP ranks alternatives according to their closeness to the ideal point (Zeleny 1982). The best alternative is the one occurring at the least distance from an ideal point in the set of efficient solutions. Similarly, in the TOPSIS method, the preferred alternative lies closest to the »ideal« solution, and farthest from the »negative-ideal« solution.

Outranking methods (or French school) are based on the pairwise comparison of alternatives along each selected criterion and the extent to which the preference for one alternative over the other can be asserted (Linkov et al. 2004). For each criterion, the preference function translates the difference between the two alternatives into a preference degree ranging from zero to one (Behzadian 2010). Outranking methods are non-compensatory and, hence, criteria weights are interpreted as votes given to different criteria (rather than as importance, as in compensatory methods). The weights can be obtained, for example, by assigning scores from 1 (least important) to 7 (most important) to the criteria (Hokkanen and Salminen 1997). However, the weights can also be obtained from pairwise comparisons, as in the AHP method (Kangas et al. 2015). Preference functions and threshold values must be selected and defined, respectively, for Outranking methods, which are therefore more demanding for DMs than Goal Aspiration methods. Furthermore, in outranking methods, complete ranking of alternatives is only achieved in some cases.

The PROMETHEE family (Brans et al. 1986) of outranking methods includes the PROMETHEE I and the PROMETHEE II methods for partial ranking and complete ranking, respectively, of the alternatives. Brans et al. (1986) proposed several criteria functions for measuring the difference between two alternatives associated with any criterion. For these measurements, decision maker(s) must select the type of criterion function and define the corresponding indifference and preference thresholds. Two alternatives are considered indifferent for a criterion if the difference between these alternatives is lower than the indifference threshold. A strict preference is revealed if the difference exceeds the preference threshold (Pohekar and Ramachandran 2004). Subsequently, positive and negative preference flows for each alternative are calculated using previously obtained outranking degrees. The positive flow quantifies the global preference for a given alternative compared with all the other alternatives, while the negative flow quantifies the global preference for a given alternative by all the other alternatives. In PROMETHEE I, if one alternative is better than another with respect to both negative and positive flow, then this alternative is determined to be better overall. If one alternative is deemed better according to positive flow and another is considered better with respect to negative flow, these two alternatives are interpreted as incomparable. In PROMETHEE II, the net flow is used and, hence, complete ranking of the alternatives is achieved (Hokkanen and Salminen 1997, Kangas et al. 2015).

The ELECTRE methods (Roy 1968) are similar to the PROMETHEE methods, in the sense that ELECTRE III uses both an indifference threshold and a preference threshold. However, a veto threshold, which is used to eliminate alternatives that perform excessively bad in any criteria, is also employed. Therefore, ELECTRE III can be considered a non-compensatory method (Rogers and Bruen 1998), where a bad score of any alternative with respect to one criterion cannot be compensated with good scores in other criteria. Nevertheless, given similar thresholds, and a sufficiently high veto threshold in ELECTRE III, these two methods (PROMETHEE II and ELECTRE) have produced identical results (Salminen et al. 1998). As previously mentioned, ELECTRE are non-compensatory methods and are, therefore, applicable to decision-making problems focused on environmental sustainability (Cinelli et al. 2014).

A third category, *Value Measurement* methods, may also be referred to as a full aggregation approach (or American school) (Ishizaka and Nemery 2013). This category consists of diverse methods, such as Multi-Attribute Utility Theory (MAUT), Simple Additive Weighting (SAW), Simple Multi-Attribute Rating Technique (SMART), Analytic Hierarchy Process (AHP), and Analytic Network Process (ANP). Multi-Criteria Approval (MA) and Delphi methods are considered more voting than MCDA methods but are also described here. Although these methods are based on diverse philosophies, most (except for MA) are compensatory, thereby allowing complete rankings of alternatives. Some of these methods (MAUT, AHP, ANP) are very demanding and time consuming for DMs, whereas others (AHP, SMART, MA, Delphi) are user friendly, more easily understandable, and likely to be used in group decision making.

In MAUT (Keeney and Raiffa 1976), the underlying assumption is that the decision maker's preferences for each criterion can be represented by a function, referred to as the sub-utility function. This sub-function(s) is usually unknown at the beginning of the decision process and, hence, must be constructed by the DM(s) (Ishizaka and Nemery 2013). Using utility sub-functions, diverse criteria (such as costs, risks, benefits, stakeholder values) are transformed into one common dimension-less scale (utility/value) (Linkov et al. 2004). These sub-utility functions are then aggregated to describe the overall utility of the alternatives. The relations between the weights of different criteria describe the trade-offs between the criteria (Kangas et al. 2015). The overall utility of each alternative is calculated by summing the products of the sub-utilities multiplied with the corresponding weights of the criteria. The SAW (Hwang and Yoon 1981) method, where the scores of alternatives with respect to the criteria are normalized to values of 0–1 rather than forming a utility function, is basically the simplest case of MAUT. In the SMART method (Edwards 1977), criteria and alternatives are both evaluated with a direct rating, on a scale ranging from 0 (alternative has no merit according to the given criterion) to 100 (ideal alternative). This rating incorporates all the criteria on the same units and, therefore, allows aggregation of all partial scores into a single score. For this aggregation, the weights of the decision criteria are also acquired on the 0 to 100 scale (Ishizaka and Siraj 2018). Once all the partial scores and criteria weights are obtained, the overall score for each alternative is calculated using the weighted sum.

The AHP (Saaty 1980) method enables decomposition of a complex decision problem into a hierarchy, where the goal is at the top level, while criteria and alternatives occupy the lower levels. This method determines the preferences among a set of alternatives by employing pairwise comparisons of the elements comprising the hierarchy at all levels. Using Saaty's importance scale, the elements at a given level of the hierarchy are compared with the elements at a higher level (Table 1).

Table 1 Saaty's importance scale

Definition	Importance
Equal importance	1
Weak dominance	3
Strong dominance	5
Demonstrated dominance	7
Absolute dominance	9
Intermediate values	(2, 4, 6, 8)

Numerical values that are equivalent to linguistic values are placed in appropriate comparison matrices. The local priorities of the criteria and the alternatives are then calculated using one of the existing prioritization methods. In addition, the consistency of the decision maker judgments is calculated for each comparison matrix. Subsequently, the synthesis is performed by:

⇒ multiplying the criteria-specific priority vector of the alternatives with the corresponding criterion weight

⇒ appraising the results to obtain the final composite alternative priorities with respect to the goal. The highest value of the priority vector indicates the best-ranked alternative.

As previously mentioned, in AHP (as with the aforementioned MCDA methods), independent criteria must be employed. However, ANP provides a general framework for dealing with decisions without making assumptions about the independence of:

⇒ higher-level elements from lower level elements

⇒ elements within a level as in AHP hierarchy (Saaty 2004).

Decision elements in ANP are evaluated using pairwise comparisons (using the Saaty scale) and local priorities of compared elements are computed as in the original AHP. In contrast to AHP, ANP employs non-linear hierarchy consisting of a (non-linear) network of clusters (for example, cluster of criteria, cluster of alternatives), nodes (elements in a cluster), and dependencies (arcs) (Kadoic et al. 2017). Intra-cluster correlation of elements and inter-cluster correlation constitute dependency and outer dependency (or feedback), respectively. The computed local priorities are placed in a so-called supermatrix calculation that handles interactions among the network of criteria and decision alternatives. The main weaknesses of the ANP are related to the complexity of the method, duration of implementation, and uncertainty in making judgments, especially those on the cluster level (Kadoic et al. 2017). However, according to Saaty (2004), ANP is more objective than AHP and will provide a truer representation of real-world scenarios.

In the MA (Fraser and Hauge 1998), criteria are ranked according to their importance, and then approval limits or thresholds are defined for each criterion (Laukkanen et al. 2004). The threshold is usually defined as the average evaluation of the alternatives with respect to the criterion considered, although other threshold values can be used. For example, in maximization problems, each alternative is approved with respect to each criterion, if the criterion value is above average, and disapproved otherwise (Kangas et al. 2006). Five classes of voting result are possible, namely: unanimous, majority, ordinally dominant, deadlocked, and indeterminate. The voting result is unanimous if only one alternative has been approved with respect to all criteria. The majority result occurs when one alternative has been approved with respect to the majority of the most important criteria. If one alternative has been deemed superior based on the order of the criteria and the dichotomous preferences, the result is ordinally dominant (for more details see Fraser and Hauge 1998). The result is deadlocked if two or more alternatives are approved and disapproved with respect to the same criteria and, hence, determination of a single superior alternative is impossible. Similarly, if one alternative is approved with respect to the most important criterion, but another is approved with respect to more criteria, the voting result is indeterminate. In that case, further preference information is needed (Fraser and Hauge 1998, Kangas et al. 2006).

The Delphi method (Dalkey and Helmer 1963) is used to obtain consensus from a group of experts (Okoli and Pawlowski 2004) and is primarily used in situations where expert judgments are required. The answers from the experts are gathered via two or more rounds of questionnaires and group feedback is obtained between the rounds. The process is stopped when the stop condition (usually the number of rounds or consensus) is achieved. A key advantage of the Delphi method is that direct confrontation with the experts is avoided. Correspondingly, these experts are encouraged to revise their previous answers in light of the replies of other group members. A detailed description of methodology (e.g., guidelines for data collection, data analysis, reporting of results) is provided elsewhere (Schmidt 1997).

Fundamental and practical descriptions of MCDA methods are provided by Belton and Stewart (2002), Ishizaka and Nemery (2013), and Kangas et al. (2015). Ishizaka and Nemery (2013) have provided examples of the software available for all MCDA methods, which may be of interest to new users.

5. MCDA in forest operations – literature review

Scientific peer-reviewed papers with MCDA methods applied to forest operation problems were found through a literature search. Most of the literature was found in previous reviews (Diaz-Balteiro and Romero 2008, Segura et al. 2014, Ezquerro et al. 2016), as well as in the Web of Knowledge and Google Scholar databases or as a result of the snowballing approach also applied. Considering only papers published in English (regardless of publication year) yielded 23 papers about MCDA in forest operations. Several aspects of these papers, such as time perspectives as well as the type of problems, criteria, and MCDA methods employed, were analyzed (Table 2). The selection of a timber harvesting system was a common type of problem, and the choice of MCDA methods, as solutions, aided in decision situations with conflicting objectives (where gut feeling would have otherwise sufficed). The harvesting and extraction category were clearly dominant, probably owing to the large amount of resources used and the value created by these activities.

From the data presented in Table 2, all three types of sustainability criteria (economic, environmental, and social) were addressed in 15 of 23 (65%) of the papers. AHP (most used MCDA method), MAUT, ANP, MA, and PROMETHEE were employed in 52% (i.e., 12), 22%, 13%, 13%, and 9% of the studies, respectively.

As Table 2 shows, group decision making occurs frequently in studies (i.e., in 16 (70%) of the papers) focused on forest operation applications of MCDA. Geographically, most of the studies (65%) were applied in Europe (Table 2), and considering time perspectives, six, fifteen, and nine papers addressed operational, tactical, and strategic issues, respectively. Some of the papers contained two perspectives and have thereby been counted twice. Practitioners in collaboration with researchers have found MCDA applications suitable for forest operation issues in all three planning levels, but the operational level was associated with the fewest papers. Indeed, within the operational time perspective, most papers addressed the longest time horizon (L1), whereas no paper addressed the on-site and real-time decision process in direct connection to the execution (i.e., L3) stage.

6. Discussion

6.1 Is there a »best« MCDA method that can be used?

Different authors have tried to answer this question from a theoretical perspective (Guitouni et al. 1998, Roy and Słowiński 2013) and in relation to particular application areas (Cinelli et al. 2014, Mulliner et al. 2016, Diaz-Balteiro et al. 2017). Selection of an appropriate MCDA method for a given problem is itself an MCDA problem and, hence, this selection creates a meta-problem, which is difficult to resolve (Triantaphyllou 2000, Mulliner et al. 2016). Guitouni et al. (1998) and Roy and Słowiński (2013) proposed questions that may help an analyst choose a MCDA method well-adapted to the decision context. We agree with Ishizaka and Nemery (2013) that this approach is intended for experienced researchers and may be too complex for forest practitioners. Practitioners should still be familiar with at least basic properties of different MCDA methods.

Methods such as SAW, SMART, AHP, and MA are simple to use and, more importantly, easier to understand than other methods, which are more mathemat-

Table 2 Summary of MCDA in forest operation papers, ordered by time perspective, forest operations category, type of problem and MCDA method used

Paper	Time	Forest operations category	Type of problem	MCDA method	Type and number of DMs	Number and type of criteria	Number of sub-criteria	Number of alternatives	Country of case study
Huth et al. (2005)	Strategical	Harvesting and extraction	Selection of harvesting system	PROMETHEE	Single	3; EC, EN, S	–	64	Malaysia
Dimou and Malivitsi (2015)	Strategical	Harvesting and extraction	Selection of harvesting system	Delphi	Group	3; EC, EN, S	15	5	Greece
Kühmaier et al. (2014)	Strategical	Logistics	Identification of energy wood terminal locations	AHP	Group (15)	8; EC, EN, S	15	–	Austria
Ghaffariyan and Brown (2013)	Strategical and tactical	Harvesting and extraction	Selection of harvesting system	PROMETHEE	Group (30)	5; O, EN	10	4	Australia
Horodnic (2015)	Strategical and tactical	Harvesting and extraction	Selection of harvesting system	AHP	Group (17)	7; EC, EN, S	28	4	Romania
Jaafari et al. (2015)	Strategical and tactical	Harvesting and extraction	Selection of harvesting system	ANP	Group (7)	3; EC, EN, S	10	4	Iran
Gerasimov and Sokolov (2014)	Strategical and tactical	Harvesting and extraction	Selection of harvesting system	HL rule	Group (51)	12; ER	–	14	Russia
Ghajar and Najafi (2012)	Strategical and tactical	Harvesting and extraction	Selection of harvesting method	ANP	Group	3; EC, EN, S	8	3	Iran
Kühmaier and Stampfer (2012)	Strategical and tactical	Logistics	Selection of energy wood supply	AHP and MAUT	Group	3; EC, EN, S	8	48	Austria
Stampfer and Lexer (2001)	Tactical	Harvesting and extraction	Selection of harvesting system	AHP and MAUT	Single	3; EC, EN, S	4	2	Austria
Kühmaier and Stampfer (2010)	Tactical	Harvesting and extraction	Selection of harvesting system	AHP, SMART and MAUT	Group	3; EC, EN, S	7	10	Austria
Wang (1997)	Tactical	Harvesting and extraction	Selection of skidding technology	AHP	No data	4; EC, EN, S	–	3	China
Ghaffarian (2008)	Tactical	Harvesting and extraction	Selection of skidding technology	AHP	Single	3; EC, EN, S	18	3	Iran
Synek and Klimánek (2015)	Tactical	Harvesting and extraction	Selection of skidding technology	AHP	Single	4; EN	–	5	Czech Republic
Talbot et al. (2014)	Tactical	Harvesting and extraction	Selection of excavator-based yarder technology	AHP	Group (40)	3; O	10	4	Norway
Melemez (2015)	Tactical	Harvesting and extraction	Risk analysis	AHP	Group	5	4	4	Turkey
Enache et al. (2013)	Tactical	Access to forest stands	Selection of forest road types	MAUT	Group	4; EC, EN, S	15	4	Romania
Diaz Balteiro et al. (2016)	Tactical and operational (L1)	Regeneration	Selection of forest plantations	AHP and GP	Group (12)	3; EC, EN, S	11	30	Spain
Laukkanen et al. (2004)	Operational (L1)	Harvesting and extraction	Selection of harvesting plan	MA	Group (7)	7; EC, EN, S	–	9	Finland
Laukkanen et al. (2005)	Operational (L1)	Harvesting and extraction	Selection of harvesting plan	MA	Group (3)	5; EC, EN, S	–	30	Finland
Palander and Laukkanen (2006)	Operational (L1)	Harvesting and extraction	Selection of harvesting system	MA	Group (3)	5; EC, EN, S	–	18	Finland
Coulter et al. (2006)	Operational (L1)	Access to forest stands	Prioritizing forest road investments	AHP	Single	3; EC, EN	12	20	USA
Olsson et al. (2017)	Operational (L2)	Regeneration	Spatial evaluation of stump suitability for harvesting	MAUT	Single	2; EC, EN	–	–	Sweden

EC – economic; EN – environmental; S – social; O – operational; ER – ergonomic;
L1 – scheduling of resources to planned actions; L2 – detailed planning of the action; L3 – real-time planning

ically complex. In addition, SAW requires minimal input parameters from decision makers. Conversely, in MAUT, ELECTRE, and ANP, DMs must define more input data (including utility functions, preference functions, indifference, preference, veto thresholds, pairwise comparisons), which is complicated and time consuming. The use of simple methods prevents the concealment of value judgments and promotes trust in the method, which is very important, especially in group decision making (Howard 1991). However, SAW (for example) assumes linearity of preferences, which may differ from the decision maker's preferences, and is therefore unrefined (Ishizaka and Nemery 2013). For example, can we assume that a forest company profit of $2M is twice as good as a profit of $1M?

Diaz-Balteiro et al. (2017) stated that characteristics, such as number of criteria and DMs, of the problem under consideration are crucial for the selection of a method. For example, the MAUT method may be suitable if the aim is to solve a problem with a small number of criteria and a few well-prepared DMs. Conversely, more pragmatic methods (compared with MAUT), such as AHP or Outranking methods, should be considered if there are many criteria and a set of DMs without any specific training in decision analysis (Diaz-Balteiro et al. 2017). Similarly, AHP, SMART, MA or Delphi are (compared with other methods) better suited for group decision making, as they are user friendly and more easily understandable. These comparisons suggest that non-complex methods should be employed for large non-expert groups. As previously explained, for problems where complete ranking of alternatives is required, outranking methods should be avoided in favor of methods with a compensatory nature. In addition, ANP should be used for decision-making problems involving dependent criteria.

There is no a »golden« MCDA method that suits all types of forest operations problems. Therefore, a general recommendation to practitioners is to concentrate on the selection of criteria and definition of alternatives, which will be essential for the outcome from all methods. If all relevant criteria and alternatives are included, with reliable data, then the output of most MCDA methods will yield substantial reduction in the risk of making decisions that lead to undesired outcomes.

6.2 Can MCDA methods be further used at operational levels?

The literature review indicates that a few publications have addressed MCDA application in forest operations. The MCDA methods used were similar to those employed in similar fields. A review of studies within the environmental field revealed that AHP, MAUT, PROMETHEE, ELECTRE, and TOPSIS were used in 48%, 16%, 8%, 5%, and 2% of the studies, respectively. The remaining papers were reviews and combinations of several MCDA methods (Huang et al. 2011). Diaz-Balteiro and Romero (2008) reported similar ranking for MCDA applications to forestry problems in the last 30 years, with AHP (22%), MAUT (17%), and GP (17%) representing the most commonly used methods. Hence, AHP is the dominant MCDA method for problems associated with environmental, forest management, and forest operation decisions. This is attributed to the fact that AHP is understandable and user-friendly, easy to use in group settings, and has the ability to combine qualitative and quantitative data in an effective manner.

Few publications address MCDA application in forest operations, which indicates that most of the forest scholars and practitioners working with forest operations have limited knowledge about MCDA methods. This paper can help fill the knowledge gap regarding these methods. However, scholars and practitioners may be aware of MCDA, but simply avoid using these methods. For example, a survey of information technology (IT) companies (Bernroider and Schmollerl 2013) reported that 71.9% of those companies were aware of MCDA methods, but only 33.3% used these methods (Ishizaka and Siraj 2018). There are no similar data for forestry, but the results may be similar. In general, the use of MCDA methods may be limited by several factors (Davis 1989, Venkatesh and Bala 2008, Giannoulis and Ishizaka 2010, Ishizaka and Nemery 2013, Ishizaka and Siraj 2018), including:

⇒ practitioners lack a clear perception of the added value (perceived usefulness)

⇒ non-experts struggle with understanding the MCDA methods

⇒ different MCDA methods may result in different solutions for the same problem, which adds to the confusion about which method to choose for a particular type of problem (Ishizaka and Siraj 2018).

MCDA can be subject to several behavioral and procedural biases (Montibeller and von Winterfeldt 2015), which can occur in all phases of the decision-making process, leading to incorrect recommendations (Marttunen et al. 2018).

The review also reveals that MCDA methods are less often used to address applications on the operational level, especially on the levels close to the execution of a decision (L2 and L3), than on other levels. This may be attributed to several factors. First, operational problems (in general) and everyday type problems, which are solved through routines and rules of thumb, occur more frequently than strategic problems (i.e., the one-off type, which are perceived as more complex). These strategic problems represent the »classical« MCDA problem setting. Second, on the operational level the need for concrete, precise, and updated data, is greater than on the strategic and tactical levels. For example, consider the selection of the most appropriate route for forestry machines in the terrain. Detailed and up-to-date data on factors related to soil damage (e.g., soil type, moisture content, slope, streams, daily precipitation data) are required if one of the criteria is aimed at minimizing soil damage. In contrast, descriptive or qualitative data (which can be less precise than quantitative data) is sometimes sufficient for the strategic level. Third, scholars may be more motivated and interested to write papers, which consider strategic and tactical problems as they might be perceived as *bigger* and more *important* issues (than other issues). Fourth, structuring a MCDA problem is a complex task (see Section 4), which requires certain methodological knowledge. The MCDA applications are, however, case-specific, and conditions may differ substantially on the operational level, possibly preventing the transfer of results from such case studies into general practice (Erler 2017). Fifth, many operational planning issues, such as planning of logging operations, are solved with one key criterion (economic) and the rest of the criteria serve more as frames. Therefore, the problem may be seen more as a profit-optimization problem (with environmental and social constraints) than a MCDA problem.

Conformation to the ongoing transformation of forestry (environmental and social aspects have become increasingly important) requires further development and incorporation of MCDA methods into decision-making on the operational planning horizon of forest operations. For example, one possible future direction could be to develop and use general MCDA models for certain types of forest operation problems. Erler (2017) described a general DSS for the selection of harvesting system with characteristics that can be transferred to local conditions. This DSS lacks the precision and detail required to fit the diverse conditions in normal forestry. However, this DSS can be considered a compromise solution between a complex DSS, which requires practitioners with high MCDA skills, and decision making through routines and rules of thumb. Moreover, with potential technological innovation (i.e., capture of Big data) in timber harvesting (see Lindroos et al. 2017), relevant and correct data would be expected. The use of MCDA, even for real-time operational problems, may then be required.

Furthermore, the addition of other criteria and application of MCDA yield a rather cumbersome process of structuring the decision problem, assessing the possible impact of each alternative, determining the preferences of DMs, and evaluating and comparing alternatives. Performing this process is, therefore, easier at lower operational levels (L1), where the decisions are further away from execution, than at higher operational levels. Indeed, there is no possibility for an operator to implement a full MCDA method for each decision of which tree to harvest and which to leave in thinning. However, the operator would benefit from a DSS in the form of a work-methodology that has been developed with MCDA methods. The operator would then assess the alternatives and determine the decisions required under certain well-defined conditions, without having to execute the MCDA methods. This is similar to well-established concepts, such as eco-driving, where fuel consumption, costs, and/or travel time are combined and a DSS is presented to drivers in the form of behavioral guidelines (Barkenbus 2010). Therefore, we see a future need for incorporating MCDA into forest operations on operational level L3 (i.e., real-time planning immediately preceding execution via MCDA incorporation in the development of new work methods). Future guidelines for conducting forest work should benefit from the use of MCDA, which would provide operators with rules that incorporate possibly conflicting goals related to economic, environmental, and social factors. The challenge will be to develop rules that are accepted by the operators. The acceptance of (new) rules and the corresponding behavioral change are often difficult to achieve (e.g., Barkenbus 2010), irrespective of the methods used to develop those rules. With MCDA, the rule-development process will be rather transparent and may in fact facilitate acceptance, if the work is performed with appropriate criteria and weights, as well as engagement of suitable DM.

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III

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Comparison of modeling approaches for evaluation of machine fleets in central Sweden forest operations

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ABSTRACT

There are many factors to consider when deciding which technologies to use in forest operations and how to plan their use. One important factor is the overall cost when choosing between the established two-machine system (TMS) with a harvester and a forwarder, and a one-machine system with a harwarder in final fellings. Such considerations can be done with different model approaches, all of which have their strengths and weaknesses. The aim of this study was to analyze and compare the TMS and harwarder potential using a Detailed Optimization (DO) approach and an Aggregated Heuristic (AH) approach. The main differences are the aggregation of seasons, including machine system teams, and spatial considerations. The analyses were done for one full year of final fellings for a large forest company's region in central Sweden, containing information necessary for calculating costs for logging, relocation between stands and traveling between the operator's home bases and the stands. The approaches were tested for two scenarios; when only TMS were available, and when both TMS and harwarders were available. The main results were that the approaches coincided well in both potential to decrease total costs when harwarders where available, and distribution of TMS and harwarders. There were some differences in the results, which can be explained by differences in thecalculation approach. It was concluded that the DO approach is more suitable when detailed analyses are prioritized, and the AH approach is more suitable when a more approximate analysis will suffice or the available resources for making the analysis are more limited.

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Introduction

Globally as well as locally, forest operations are conducted with different methods and by use of many different kind of machine systems (Lundbäck et al. 2018). When managing forest operations, many decisions must be made, including the choice of which machine system to use and how to plan its operation. There are many factors to be considered. The choice must take account of the key aspects of meeting the expectations for quality and production levels at the lowest possible cost. Such analyses can be carried out at various levels of applications. They include: 1) finding the ideal work conditions for a system by studying individual stands, 2) evaluation of a system's performance in the existing work conditions by applying performance functions to several known or fictional stands and, finally 3) matching supply and industry demand and estimating relocation costs by finding ideal scheduling using geographical analysis of known or fictional stands and industry demand. The three levels contribute, respectively, to evaluate how machine systems perform in different stand conditions and in typical combinations of stand conditions, and in a situation when machine systems need to meet the requirement of a functional forest supply system.

Regardless of operation type, machine system comparisons need to take account of three distinct parts of the operations: the relocation of machines between the stands they operate in, the operators traveling back-and-forth between the stands and their home bases during operations, and the operation in the stands. Hence, such comparison demands input data about, for example, stand characteristics, stand locations, operators' home bases and descriptions of machine performance in various conditions. The comparison can be carried out using different modeling approaches (Ringdahl et al. 2012). When there are physical machines available, time studies can be used to model the time consumption of the elements of the operation under various conditions (Eriksson and Lindroos 2014) and can, together with cost analysis, provide comparative analysis of machine systems (Di Fulvio and Bergström 2013). When there is a shortage of information on machine system performance, due to, for example, lack of data or that the analysis is done on machine systems that have not yet been built, theoretical machine system comparisons can be done based on available data (Ringdahl et al. 2012). Irrespective of whether the data used were derived from actual machines or from theoretical ones, modeling of the systems can be carried out using different approaches. For instance, constructing heuristics to find a near optimal solution is one approach; using optimization methods to find the best solution of all feasible ones is another. These can be combined as in Bredström et al. (2010) where an annual harvesting problem is expressed in an optimization model and where an heuristic is used to solve the integrated problem in two phases, both using

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optimization models. Dems et al. (2017) developed an optimization model for an annual harvesting problem and two customized heuristics for faster solution time. Frisk et al. (2016) studied an operational harvesting problem where detailed sequences of harvest areas for each team are built gradually using a decomposition heuristic based on rolling horizon planning.

In ground-based, mechanized cut-to-length operations, the two-machine system (TMS), with a single-grip harvester and a forwarder, has been the most common method of logging in the Nordic countries since the 1990s (Eriksson 2016; Nordfjell et al. 2019). It is common for a TMS team to work on both final fellings and thinnings, although many teams are specialized in either operation. The machine operators usually live nearby and travel to the stand and back home every working day. However, there is a persistent desire to replace the TMS with a one-machine system (Andersson 1989; Silversides 1997). Several studies have been conducted on one-machine systems (a single harwarder), with a focus on evaluating its performance (productivity and/or cost) in different stand conditions. The analyses have been made on both thinning operations (Lilleberg 1997; Hallonborg 1998; Talbot et al. 2003; Väätäinen et al. 2006; Codd and Nieuwenhuis 2008; Kärhä et al. 2008) and final felling operations (Hallonborg and Nordén 2000; Wester and Eliasson 2003; Väätäinen et al. 2006; Bergkvist 2010; Manner et al. 2016; Jonsson 2020). Generally, the harwarder has shown greatest potential to compete with the TMS in final fellings with relatively small stand volumes and short extraction distances. The benefit when used for final felling rather than thinning operations is that it is easier to load logs directly onto the load bunk in final felling because there is more space. The benefit when logging small stand volumes is that only one machine needs to be relocated rather than two, and relocation costs get a larger proportion of the total costs compared with large stand volumes. Long extraction distances are beneficial for the TMS because it moves faster and has lower operational costs, and there is more forwarding work to do. Hence, short distances are beneficial for the harwarder. These benefits have been shown by many previous studies of harwarders, and also for the Komatsu X19, which is the latest harwarder machine developed for Nordic forest operations (Manner et al. 2016).

When deciding on whether to invest in a new machine system, it is beneficial to have information on how the system performs in the likely combinations of stand conditions that will be experienced, as well as how well it will manage to meet the requirement of a functional supply system. However, there is only a limited number of studies that have included these strategic considerations.

Both Lindroos (2012) and Ringdahl et al. (2012) made theoretical comparisons between use of harwarders and TMS: s in three different regions in Sweden with typical stand conditions. They found that the harwarder had the greatest potential for direct loading of logs for extraction of several different systems and was also comparable to the TMS over a large part of the harvested volume. However, due to the focus on comparing direct loading systems, the analysis did not consider the work of unloading logs at the landing. The potential in relation to the TMS was therefore assumed to be overestimated. Bredström et al. (2010) optimized a machine fleet for using a TMS in a forest company's region in central Sweden, and compared the results to when harwarders were also available. They used an optimization model to construct a machine fleet, assign stands to the machine system teams and schedule the stands for each team while solving an annual planning problem. It was found that there was potential to decrease the total costs by using some harwarders. This optimization approach is suitable for such large-scale analyses in which the requirements for supply and demand are addressed but requires special competence and detailed input data. This complexity also leads to relatively high analysis costs, and requires specialized software. Even though optimization approaches using specialized software commonly produce more reliable estimations, it is also possible to produce comparable results from analysis using standard software with well-constructed models (Asikainen 2010; Ringdahl et al. 2012). However, previous comparisons of modeling approaches have not addressed such a complex problem as finding a machine fleet in which the chosen machine systems together need to meet the requirement of a functional supply system.

Therefore, the aim of this study was to compare the outcome of two proposed modeling approaches for analyses of machine fleet composition. Both required extensive analysis of large input data, but requiring different types of competence and software: more specialized software with detailed input data was used for one, called Detailed Optimization (DO), whereas standard software and more aggregated data were used for the other, called Aggregated Heuristics (AH). Both approaches were applied to a specific case, and, since there is no correct answer as to how the machine fleet should be composed, the evaluation focused on how similar the output was from the two approaches.

Materials and methods

Description of the main areas and questions for a machine fleet analysis

A machine fleet analysis aims at finding the optimal machine fleet configuration which can carry out the desired operations within the required time with the expected quality and with the lowest possible costs. The costs are minimized by finding the most suitable configuration for the total machine fleet for a certain task (i.e. work in a specific geographical region). The analysis consists of assigning the available teams to the most suitable stands and determining the time of operations, including the movement of machines. The total costs include the activities associated with forest operations, relocation of the machine systems teams between the stands, and the operators' travel back-and-forth between the home base while working in the stand. Configuration concerns determining the number of machines of a specific type (e.g. sizes) within a given machine system and/or between different machine systems. In such an analysis, there are constraints regarding quality and flow. Quality relates to factors, such as legislation, certification, and wood value. Flow relates to delivering the right product within the required time – commonly referred to as logistics or supply chain management. To do this, input data about the machines' time consumption (in different operational environments), costs, the stands' characteristics and supply and demand are needed. The desired outputs from a machine fleet analysis are the total costs, the number of teams within each machine system type, and an assignment and scheduling description of the machine fleet. Such outputs can then be used as a basis for deciding the machine fleet for a forestry organization.

In this study, we used two approaches to compare two scenarios. The first approach was a revised version of the annual optimization model used by Bredström et al. (2010), here called Detailed Optimization (DO), and the second was a static spreadsheet analysis, here called Aggregated Heuristic (AH). The first scenario involved a forest company's regions' final fellings for one year, where only one type of machine system was available – a TMS consisting of extra-large harvesters and forwarders. In the second scenario, an additional machine system was available – an extra-large harwarder in competition with the TMS. The differences between the two scenarios were then the basis for estimating the potential for decreasing total costs using harwarders, and the fleet's composition. A sensitivity analysis was performed to account for data uncertainty associated with time consumption equations and machine costs for the harwarder. The qualitative aspects of the machine systems' performances were not addressed in the analyses, since it was assumed that the input data fully (or at least equally well) covered quality requirements for both TMS and harwarders.

The model approaches in brief

To estimate the total costs of a machine fleet, we made two types of estimations: those which were the same for both modeling approaches, and those which were unique to each approach. Those that were the same for both approaches were time consumption equations for the machines, as well as the equations for estimating costs for machine relocation and operator traveling. To carry out such estimations, interest rate, investment costs, stand conditions, distance between stands (see eq. 1–7) were used as input to the models. For those equations that were unique for each of the two approaches, different equations and/or parameter values were used. Also, the supply and demand relating to harvested roundwood were matched with higher precision in the DO than in the AH.

Detailed optimization

The Detailed Optimization was built using explicit equations for the spatial impact of relocation and traveling, and explicit equations regarding the matching between demand and supply per assortment and season. We used the Machine Resource Optimization approach, as described in Bredström et al. (2010), and developed it further in this study. It is an optimization model, which constructs a machine fleet in the first phase, assign stands to the machine system teams (an assignment problem) in the second phase, and schedules the teams' set of stands (a traveling salesperson problem for each team) in the third phase.

The model constructed a fleet of fictional machines connected to fictional home bases and did so for a specified geographical level, a region. The stand data relating to the assortment distribution of historical harvests were interpreted as the demand, such as the harvested volume of a certain assortment (e.g. pulpwood of spruce) during a specific season (e.g. spring, March to April). The whole input data material is used as supply. The available machines had a specified amount of work time that was possible to achieve over a particular season, and the use of a machine was connected to a cost. When estimating the logging costs within each stand, the machines were available with up to 100% utilization; if they were used less, the costs increased due to charges for downtime. Within the TMS, the use of the fastest machines was decreased to keep the balance with the slowest. The hourly costs increased as the machine ulitization decreased from 100%.

For each team, the model scheduled the order in which stands were harvested, so the actual distances between stands were used to calculate the relocation costs. The model used the actual driving distance between stands' locations and the teams' home bases to estimate traveling costs.

Aggregated heuristic

The Aggregated Heuristic was a static spreadsheet analysis, estimating how many machine teams of the TMS and/or the harwarder were needed to meet the demand. Instead of the specific relocation and travel input data as used in the DO, input data in the form of average values within a specific geographical district was used, which then were aggregated at a regional level together with the logging costs. The TMS and harwarder were first compared on each stand, and the system with the lowest total costs was assigned to the stand. The stands' volumes allocated to each system were summarized for each district. If the volume was sufficient for a machine system team 100% of the time, it was used in the district, otherwise it was not available. It was then estimated how many teams would be needed to harvest the volumes.

The stand data were, just as for the DO, interpreted as supply but here they were also interpreted as demand, i.e., matching between supply and demand was realized for the whole analyzed time at once, without separating into different seasons. The estimations of machine utilization allowed the machines to be used 100% of the time, which is always the case for the harwarder and the least productive machine within the TMS. The fastest machine in the TMS was allocated a lower utilization to match the slowest, with increased costs to compensate for downtime-related costs – just as with the DO. There was no scheduling in the AH but to simplify, the model instead used a fixed assumed average distance between the stands to estimate the relocation costs, and also fixed the assumed average distance between stands and home bases to estimate traveling costs.

Model approach equations

Same equations in both model approaches

All time consumption equations are in productive minutes, with breaks up to 15 minutes included, per cubic meters solid under bark (PM_{15}-min/m^3). The equations for the harvester and forwarder were from Eriksson and Lindroos (2014), which is the most current study. These do not include breaks, and so, here, the equations were divided by 0.917 for the harvester and 0.942 for the forwarder to give time with breaks up to 15 minutes (2019 conversation between the corresponding author and Magnus Bergman at the forest company SCA; unreferenced).

Harvester time consumption (t^h, in PM_{15}-min/m^3) was estimated with an equation from Eriksson and Lindroos (2014), where mean stem volume was used to predict time consumption (Eq. 1).

$$t^h = 60/e^{(3.704+0.134*Ln(m)-0.161(Ln(m))^2}/0.917 \quad (1)$$

m = mean stem volume, m^3 solid under bark (m^3sub)/stem

Forwarder time consumption (t^f, PM_{15}-min/m^3) was estimated with mean forwarding distance, mean stem volume and load size as predictors (Eq. 2).

$$t^f = 60/e^{\left(0.327-0.073*Ln\left(d^f\right)^2+0.188*Ln(m)+0.636*Ln\left(d^f*21.3\right)\right)}/0.942 \quad (2)$$

d^f = mean forwarding distance, meters

In Eq. (2), the value 21.3 is the load capacity (in m^3sub) assumed in this study, based on Manner et al. (2016). Eq. (2) is not recommended to be used for very short mean forwarding distance values, since it then gives unrealistically low productivities according to the authors Eriksson and Lindroos (2014). In the analysis, the distance was therefore kept at a distance before the estimated productivity radically dropped, if the stand's distance was smaller than 78 meters.

Harwarder time consumption (t^{hw}, PM_{15}-min/m^3) was estimated as the total time consumption for the harvester and forwarder ($t^h + t^f$) multiplied by the difference between the two systems as defined by Manner et al. (2016). The equations by Manner et al. (2016) are particularly sensitive to changes in mean stem volume and mean forwarding distance (Eq. 3).

$$t^{hw} = \left(t^h + t^f\right) * \left(\frac{t^{hw\ Manner}}{t^{h\ Manner} + t^{f\ Manner}}\right) \quad (3)$$

$t^{hwManner}$ = Time consumption for the harwarder, according to Eq. 13 in Manner et al. (2016).
$t^{hManner}$ = Time consumption for the harvester, according to Eq. 11 in Manner et al. (2016).
$t^{fManner}$ = Time consumption for the forwarder, according to Eq. 12, but without "q" and "+0.05-x," in Manner et al. (2016).

The machines time consumption estimations (Eq. 1–3) (PM_{15}-min/m^3) were recalculated to productivity (m^3/ PM_{15}-h), by dividing 60 with the time consumption, before they are presented in the *Results* section.

All costs were calculated in Euros. At the time for the study, 1 Euro had the value of 1.1 US Dollars or 10 SEK (XE 2021). Machine costs were calculated using the model SkogforskFLIS (Hofsten et al. 2005) with inputs including fixed costs and variable costs. The model is similar to the model in Ackerman et al. (2014). Fixed costs included repayment of loans based on interest rate, depreciation, insurance, costs for machine trolley (a wagon with, for example, space for lunch, basic service, and repairs), and operators' salaries. Variable costs included fuel, maintenance, relocation between stands and the operators traveling between their home base and the stands.

Costs for relocating the machines and machine trolleys between the stands were calculated based on information from forest companies. A machine trolley usually has a fuel tank, a small room for meals and basic service and repair equipment. One relocation is needed per stand. On short distances, it is common to drive the machine between stands, whereas it is transported on a low-bed trailer when relocated across longer distances.

The costs for relocation across distances of more than 5 km ($g^{>5}$, in EURO/relocation) were calculated as (Eq. 4)

$$g^{>5} = c^{i\ trail} + \left(t^{p\ trail} + t^{trolley} + \frac{d^{re}_{ij}}{s}\right) * c^{trail} + c^{op} \quad (4)$$

c^{itrail} = Initial cost for the trailer, i.e., driving to the stand.
t^{ptrail} = Time for transport preparation, securing the machine on the trailer and unloading the machine when arriving at the next stand.
$t^{trolley}$ = Time for coupling the machine trolley and parking it by the next stand.
s = Speed of the trailer, when driving loaded with a machine and trailer, km/h.
d^{re}_{ij} = Distance of relocation between stand i and j, km.
c^{trail} = Cost of the trailer, per scheduled machine hour (SM-h).
c^{op} = Cost of the machine operator, per SM-h.

The speed when driving a trailer (s, km/h), loaded with a machine and a trolley, can be compared to the speed of a timber truck. Our estimations were based on studies on timber trucks (Ranta and Rinne 2006), but the speed was multiplied by 0.8 to give a better comparison with a slower trailer. The factor 0.8 was chosen after discussion with an experienced trailer operator (Eq. 5).

$$s = \left(9.3 + 12.7 * \ln\left(d^{move}_{ij}\right)\right) * 0.8 \quad (5)$$

The costs for relocating on distances of 5 km or less ($g^{\leq 5}_m$, in EURO/relocation), for machine m. 12 is the assumed average driving speed for a forest machine (km/h) while driving between stands (2019 conversation between the corresponding author and Robert Johansson at the forest company Holmen Forest; unreferenced) (Eq. 6).

$$g^{\leq 5}_m = \left(t^{tracks} + \frac{d^{move}_{ij}}{12} + t^{trolley}\right) * c_m \quad (6)$$

t^{tracks} = Time taken to remove tracks and mount them at the next stand.
c_m = Cost of machine m, EURO per hour.

The costs for operators' travel between home base i and stand k one way (h_{ik}, EURO/one way travel) depend on the distance and the costs per km. Each work shift requires one journey there and back, and the number of shifts depends on how many shifts are needed to finish the logging operation (Eq. 7).

$$h_{ik} = d_{ik}^{home} * c^{home} \quad (7)$$

d_{ik}^{home} = Distance between stand i and home base k, km.
c^{home} = Cost of the operators driving between stand and home base, EURO per km.

The TMS has a balance challenge, typically, the harvester produces more per time unit. To manage this imbalance, the faster machine can be used less or the slower used more. In our calculations, all machines were limited to, at maximum, 100% utilization and, for the TMS, the fastest machine (most often the harvester) was used less.

Specific in detailed optimization

The optimization model used was defined using decision variables, parameters, objective function, and constraints. The objective function (8) gives the overall harvesting cost, forwarding cost, operator traveling cost, the machine relocation cost, and a penalty in case an aggregated demand is not met during the season. Constraint (9) states that each stand is assigned a machine system team. Constraint (10) states that an assignment can only be made if a team is selected to operate. Constraint (11) states the available time for each machine in each season. This includes any overtime used. Constraints (12) to (16) describe how overtime can be used with the TMS machines. More specifically, constraints (12) and (13) state that the overall capacity including overtime is limited to harvesting and forwarding time. Constraints (14) and (15) give the limit of overtime for each harvester and forwarder. Constraints (16) to (18) describe the relocation between stands for each machine. More specifically, constraints (16) and (17) give the relationship between relocation and specific stands that have been assigned to the machine. Constraint (18) and (19) gives the subtour elimination constraints generated using the Miller-Tucker-Zemlin formulation for VRP problems (Miller et al. 1960). Constraint (20) states the overall aggregated demand for all assortments over the seasons. Constraint (21) states that the selected machines' operators must start and end at their home bases. Constraints (22) to (25) define the binary restrictions. Constraint (26) gives the nonnegativity constraints for the continuous variables.

This problem is a general large-scale mixed integer programming (MIP) problem. It consists of an allocation part, where machine systems are allocated to stands, and a traveling salesman problem (TSP) part, where the sequence for each machine system team is determined. The overall problem is very hard to solve directly. Hence, we applied a heuristic approach similar to that of Bredström et al. (2010). It is different in that we incorporated seasonal demand, allowed overtime and set the capacity of all machines to be substantially higher. In Phase 1, we removed all variables and constraints relating to the TSP part (16) to (19), and relaxed all binary constraints except for whether a machine is used or not, z_m, and the overtime variable, v_{mt} . The solution to this phase produced the set of machines to use in Phase 2. In Phase 2, we used the set of machines generated in Phase 1 but with binary restrictions on the assignment, that is, y_{mit}, and relaxed overtime variables. This phase gave the actual assignments for each machine. In Phase 3, we included the TSP constraints for each machine given the stands assigned for each season. This phase was solved by the MIP formulation given above for the TSP part and for each machine.

Sets and parameters used.

I: set of stands
H: set of home bases
T: set of seasons
M: set of machine systems (subsets M_{TMS}, M_H for TMS and harwarders respectively)
A: set of assortments
h_m= home base for machine system m
d_{ij}= distance between stand i and stand j
f_m= fixed cost to use machine system m
c_{mij}= cost to relocate machine in machine system m between stand i and stand j
t_{mi}^h= harvesting time in machine system m in stand i
t_{mi}^f= forwarding time in machine system m in stand i
a_{mt}^h= harvest time available in machine system m in season t
t_{mt}^{af}= forwarding time available in machine system m in season t
g_{mt}^h= maximum harvesting overtime in machine system m in season t
g_{mt}^f= maximum forwarding overtime in machine system m in
season t
a_m= available time for machine system m
c_{mi}^h= harvesting cost in machine system m in stand i
c_m^o= overtime cost in machine system m
c_{mi}^f= forwarding cost in machine system m in stand i
c_{mi}^m= operators' traveling cost for machine system m in stand i
c_t^o= penalty cost for missing accumulated demand satisfaction
until season t
g_{ia}= volume of assortment a at stand i
d_{at}= volume of assortment a demanded in season t

Decision variables are as follows.

$$z_m \begin{cases} 1, \mathit{if\ machine\ system\ m\ is\ used} \\ 0, \mathit{otherwise} \end{cases}$$

$$ymit \begin{cases} 1, \text{if machine system } m \text{ is used in stand } i \text{ or} \\ \text{home base during season } t \\ 0, \text{otherwise} \end{cases}$$

$$x_{mij} \begin{cases} 1, \mathit{if\ machine\ system\ m\ relocates\ from\ stand\ i\ or} \\ \mathit{home\ base\ to\ stand\ j\ or\ home\ base} \\ 0, \mathit{otherwise} \end{cases}$$

$$v_{mt}\begin{cases}1, if\ harvester\ in\ machine\ system\ m\\ uses\ overtime\ during\ season\ t\\ 0, otherwise\end{cases}$$

$$o_t = missedoveralldemandrequirementuntilandincludingseasont$$

$$w^h_{mt} = \text{overtimeusedforharvesterinmachinesystem}m\text{inseason}t, m \in M_{TMS}$$

$$w^f_{mt} = \text{overtimeusedforforwarderinmachinesystem}m\text{inseason}t, m \in M_{TMS}$$

$$u_{im} = \text{capacityutilizationuntilstand}i\text{formachinesystem}m$$

The full DO model can now be stated as

$$\min z = \sum_{m\in M} f_m z_m + \sum_{m\in M, i\in I, t\in T}\left(c^h_{mi} + c^f_{mi} + c^m_{mi}\right)y_{mit} + \sum_{m\in M, t\in T} c^o_m\left(w^f_{mt} + w^h_{mt}\right) + \sum_{m\in M, i\in I, j\in I}\left(c^m_{mij}\right)x_{mij} + \sum_{t\in T} c^o_t o_t \quad (8)$$

Subject to.

$$\sum\nolimits_{m\in M}\sum\nolimits_{t\in T} y_{mit} = 1, \quad i\in I \quad (9)$$

$$\sum\nolimits_{i\in I\cup^{h_m}}\sum\nolimits_{t\in T} y_{mit} \le M z_m, \quad m\in M \quad (10)$$

$$\sum\nolimits_{i\in I}\left(t^h_{mi} + t^f_{mi}\right)y_{mit} \le \left(a^h_{mt} + a^f_{mt}\right), \quad m\in M_H, t\in T \quad (11)$$

$$\sum\nolimits_{i\in I} t^h_{mi} y_{mit} \le a^h_{mt} + w^h_{mt}, \quad m\in M_{TMS}, t\in T \quad (12)$$

$$\sum\nolimits_{i\in I} t^f_{mi} y_{mit} \le a^f_{mt} + w^f_{mt}, \quad m\in M_{TMS}, t\in T \quad (13)$$

$$w^h_{mt} \le g^h_{mt} v_{mt}, \quad \text{harvester}m\in M_{TMS}, t\in T \quad (14)$$

$$w^f_{mt} \le g^f_{mt}(1 - v_{mt}), \quad \text{forwarder}m\in M_{TMS}, t\in T \quad (15)$$

$$\sum\nolimits_{i\in I\cup^{h_m}} x_{mij} = \sum\nolimits_{t\in T} y_{mjt}, \quad m\in M, j\in I\cup\ h_m \quad (16)$$

$$\sum\nolimits_{j\in I\cup^{h_m}} x_{mij} = \sum\nolimits_{t\in T} y_{mit}, \quad m\in M, i\in I\cup\ h_m \quad (17)$$

$$u_{jm} - u_{im} \ge t^h_{mi} - a_m\left(1 - x_{mij}\right), \quad i,j\in I, m\in M \quad (18)$$

$$0 \le u_{im} \le a_m, \quad i\in I, m\in M \quad (19)$$

$$\sum\nolimits_{m\in M, I\in I, a\in A, t\in T: t\le t'} g_{ia} y_{mit} = \sum\nolimits_{a\in A, t\in T: t\le t'} d_{at} +, \quad t'\in T \quad (20)$$

$$y_{mit} = z_m, \quad m\in M, i = h_m, t = first(T)\ and\ t = last(T) \quad (21)$$

$$y_{mit}\in\{0,1\}, \quad m\in M, I\in I\cup\ h_m, t\in T \quad (22)$$

$$x_{mij}\in\{0,1\}, \quad m\in M, i,j\in I\cup\ h_m, j\in J \quad (23)$$

$$v_{mt}\in\{0,1\}, \quad m\in M, t\in T \quad (24)$$

$$z_m\in\{0,1\}, \quad m\in M \quad (25)$$

$$o_t, w_{mt}, w^h_{mt}, w^f_{mt}, u_{im} \ge 0, \quad m\in M, t\in T \quad (26)$$

Specific in aggregated heuristic

Based on the total costs for each system, the given stand is defined as either a TMS stand or a harwarder stand. If the accumulated volumes for a system type (TMS or harwarder) in a district is enough for one whole system or more (≥1 TMS or harwarder), it is available in the machine fleet for the district. The number of the machine system teams is, however, not an integer in the AH but aggregated which simplifies the problem to be solved.

All available stands are included in the cost calculation, which means that supply and demand is balanced – not for separate seasons – but for the whole planning period. However, if the volume is not enough for the other system, it is made unavailable. Last, if the volumes for each system are not enough for either of the systems, the system that has the lowest total costs in the whole district is made available.

The costs for relocating between stands and traveling between home base and the stands were estimated using Eq. (4-7) with the same assumed averages as input for distances regardless of machine system. The distance between the stands (d^{move}_{ij}) and the distance between home base and the stands (d^{home}_{ik}) were determined after discussions with forest company representatives who had a good knowledge of machine fleet management.

Table 1. Input data for machine costs calculations.

Input data	Harvester	Forwarder	Harwarder
Investment cost, million Euro	0.493	0.399	0.669
Value at the end of the life cycle, %	10	20	10
Interest rate*, %	2.99	2.99	2.99
Insurance costs, thousand EURO/year	2.5	1.6	2.5
Trolley, thousand Euro/year	5.25 *2	5.25 *2	7
Salary, EURO/hour	25.1	25.1	25.1
Extra salary for uncomfortable hours, EURO/hour	3.468	3.468	3.468
Working days/year	205	205	205
Shifts per working day	2	2	2
Hours/shift	7.6	7.6	7.6
Uncomfortable hours/working day	4.7	4.7	4.7
Diesel consumption, liters/PM_{15}-h	17	17	17
Diesel price, EURO/liter	1.02	1.02	1.02
Oil consumption, liter/PM_{15}-h	0.75	0.4	0.7
Technical Utility (TU), %	83	86	83
Machine cost, EURO/PM_{15}-h	108.1	91.5	119

* Stibor 90 for January 2019 (Riksbank 2019) + 3%.
*2 one trolley is assumed to cost 7 thousand EURO per year, and a TMS is expected to need, on average, 1.5 trolleys.

Table 2. Input data for the region's four districts, as used in the AH. In the DO, all stands were used irrespective of district borders. All mean values are volume weighted.

District	Number of stands	Total volume, m^3	Total net area, hectare	Volume/stand, m^3		Mean stem volume, m^3		Mean forwarding distance, meters	
				Mean	SD	Mean	SD	Mean	SD
1	135	128 326	528	951	886	0.37	0.11	387	272
2	265	407 852	1 908	1 539	1 812	0.36	0.14	416	253
3	255	550 774	2 731	2 160	2 093	0.34	0.11	410	252
4	389	497 371	1 948	1 279	1 236	0.43	0.15	372	214
All pooled	1 044	1 584 323	7 115	1 625	1 655	0.38	0.14	398	243

SD = standard deviation

Case study

The source of the interest rate was Stibor 90, plus 3% (Sveriges Riksbank 2019). Costs for insurance, machine trolley, operator salary, available days per year were obtained from a group of Swedish forest companies. All machines were assumed to operate with two shifts, with extra payment for overtime (extra time beyond agreed normal time per shift) and uncomfortable hours (working time early mornings, late evenings, or weekends) according to collective agreement (SLA-GS 2013). Machine investment costs, diesel consumption, and oil consumption were obtained from a machine manufacturer (Manner et al. 2016) (Table 1).

Technical utility (TU) is connected to a machine's technical complexity and the maturity of its technology, and a high TU indicates a well functioning machine, which is connected with a lower cost impact. Both the harvester and the forwarder are technologically mature, and hence have high TU. The harvester is more complex than the forwarder. The harwarder is assumed to have a similar maturity of technology as the harvester and the forwarder, but also has a tilt and rotatable load carrier and quick hitch and so might be expected to have a higher TU than both because of its complexity. On the other hand, the technology for harvesting is only used until the load carrier is filled. Then, the harwarder transports its load to the roadside and unloads using a forwarder grapple. Therefore, the harvester and the harwarder were assigned the same TU (Table 1).

The distance between the stands (d_{ij}^{move}) and the distance between home base and the stands (d_{ik}^{home}) were determined in discussions with forest company representatives who had a good knowledge of machine fleet management.

The analysis was carried out using final felling input data from a forest company's region in central Sweden, harvested during 2017. To ensure realistic information, stands were only included if they had a net felling area >0.5 hectare, a total volume >99.9 m^3sub per stand, and extracted volume <803 m^3sub per hectare. These levels were chosen in discussions with the forest company. Six assortments were, on average, harvested per stand. No information about the company's operators' home bases was available. The AH used the input data divided into four districts (Table 2).

In the DO, the relocating distance was estimated from the stand's coordinates. In the AH, the distance was fixed and, in discussions with the company, assumed to be 25 km. In the DO, a network of available positions for home bases was constructed, with the distance between each position 37 km north-south and 63 km east-west. In the AH, the distance for traveling between home base and stands was fixed and, after discussions with the company, assumed to be 35 km. The forest company mostly use contractors but also manage their own logging machines. All results were validated by the company.

Analysis

The main results from the analysis are total costs and the fleet composition with scenario 1 (only TMS) and scenario 2 (TMS and harwarder).

The DO was carried out using a standard laptop with the AMPL modeling language and the CPLEX 12.6 solver. We used the default MIP gap in CPLEX for all problems, that is, 0.00001.

The DO model used three seasons, nine assortments, 72 potential TMSs, 72 potential harwarders, and 1044 stands. The maximum allowed solution time was 24 hours for Phase 1 and Phase 2. For Phase 3, we used a maximum time of 20 seconds for each machine. After preprocessing, the Phase 1 problem had 154269constraints and 452233variables (1008 binary). The solution was found after about an hour (3747 seconds). After preprocessing, the Phase 2 problem had 36072constraints and 104029variables (103 044 binary). The solution terminated after the maximum solution time of 23 hours with a gap of 0.05%. The solution after one hour had a gap of 0.09%. The Phase 3 problem to find the TSP solution for each machine was solved within 20 seconds for most of the problems. The size of Phase 3 depended on how many stands were assigned to each machine; we note that the average size for the TSP (one for each selected team) was about 30 stands.

The AH was carried out using a standard laptop running Microsoft Excel. The model consisted of eight columns of input data and 191 columns of calculations in one worksheet, and eight columns in another worksheet where the results were gathered.

Since the time consumption functions and cost levels for the TMS originated from large input data sources, and the harwarders originated from much smaller data sources, we were not as confident of the time consumption function and cost levels for the harwarder. To cover, we performed a sensitivity analysis of how the results changed for each approach and between them, while we adjusted harwarder time and costs within a reasonable interval.

Results

Machine fleet composition when only using the two-machine system

When analyzing the first scenario, the two modeling approaches gave a very similar number of machines required, with slightly more with the DO. Moreover, both approaches found that, of the two machine types, the forwarders were closest to full utilization which shows that the harvesters produced more volume per time unit. However, the level of utilization was higher with the AH than with the DO. The mean relocation distance was 37 km with the DO (Table 3).

Both modeling approaches also gave very similar distributions between cost components (Table 4).

Two-machine system and harwarders in competition

When analyzing the second scenario, the results from the two approaches were also very similar. When rounding the number of machine system teams with the AH, the results were in fact identical with the DO. The AH gave slightly lower total costs and utilization than the DO, the difference being only 0.45 million EURO. The estimated savings were 1.5% between the approaches (Table 5).

The costs for relocations and traveling in relation to total costs were generally a little lower with the AH than with the DO, and the logging costs were higher. The total costs were still very similar (Table 5). The relocation distance was 13 km for the TMS and 11 km for the harwarder with the DO, compared with the assumed 25 km with the AH. The traveling distance was 26 km for the TMS and 27 km for the harwarder (Table 6).

Table 3. Analysus results from the two approaches when only one machine type (the two-machine system (TMS)) was available.

Variable	Detailed Optimization	Aggregated Heuristic
Number of TMS teams (n)	26	25.5
Mean utilization, %	90	92
harvester	94	100
forwarder		
Total costs, million EURO	14.44	13.76

Table 4. Relative distribution (%) of costs for the two approaches.

Variable	Detailed Optimization	Aggregated Heuristic
Logging	90.6	89.5
Relocation	6.2	7.6
Traveling	3.2	2.9

Table 5. Results from the analysis of the two approaches when two machine systems (TMS and harwarders) were competing.

Variable	Detailed Optimization	Aggregated Heuristic
Number of		
TMS	15	14.5
harwarders	18	18.2
Mean utilization, %		
harvester	87	90
forwarder	93	100
harwarder	94	100
Total costs TMS and harwarder, million EURO	13.92	13.47
Savings with harwarder, %	3.6	2.1

Table 6. Cost distribution in percentage (%) for the two approaches.

	Detailed Optimization		Aggregated Heuristic	
Cost part	TMS	Harwarder	TMS	Harwarder
Logging costs	93.2	92.4	92.2	91.3
Relocation costs	4.5	5.5	4.8	6.1
Traveling costs	2.3	2.1	3	2.6

Sensitivity analysis

Productivity

When adjusting the harwarders' productivity from 95% to 105%, the total costs with the AH were consistently lower than with the DO (3.2–4.7%). At low productivity levels, the total costs were mainly attributable to the TMS, which corresponds to more TMS teams; with high productivity levels, the total costs were attributable more to the harwarder and hence to a greater number of harwarders (Figure 1).

Costs

When adjusting the harwarders costs from 95% to 105%, the total costs with the AH were consistently lower than with the DO (3.2–3.9%). At low harwarder cost levels, the total costs were attributable more to the harwarder, which corresponds to a greater number of harwarders; with high harwarder cost levels, the total costs were mainly attributable to the TMS, corresponding with a greater number of TMS teams. The impact on total costs when adjusting the harwarder costs were slightly greater than when adjusting the productivity (Figure 2).

Discussion

This study aimed to propose and compare the results from a Detailed Optimization model approach and an Aggregated Heuristics model approach, by analyzing similarities and differences in a case study.

The estimated total costs were consistently lower with the AH compared with the DO. In the sensitivity analysis, the difference was at most 4.7%, when the harwarders' productivity was decreased by 5%. More commonly, it was around 3.6% for the two sensitivity analyses. Asikainen (2010) compared a static model approach to a dynamic one and found a 10% cost difference, on average. Our results are hence clearly closer. Even though the approaches give concurrent results, there are some differences with logical reasons.

The machine utilization was generally higher with the AH than with the DO, because of the different model assumptions, such as regarding relocations and traveling. The AH, therefore, shows potential for lower total costs because the number of teams are aggregated per district, but the DO better reflects what to expect operationally, since it estimates fictional teams. The difference is, however, relatively small, with at most 4.7% between the approaches in the sensitivity analysis, which is clearly lower than shown in similar comparisons (Asikainen

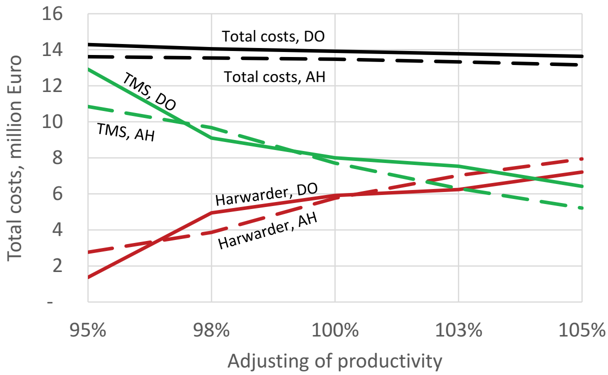

Figure 1. Total costs when the harwarder productivity was adjusted from 95% to 105%.

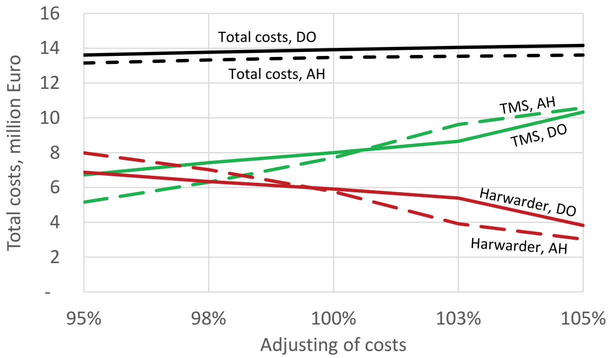

Figure 2. Total costs while the harwarder costs are adjusted from 95% to 105%.

2010). The balance calculations with the DO generally led to higher logging costs because all machines were used less than 100%. On the other hand, the relocation costs and the traveling costs were lower, because the DO found better solutions than the assumed average values used in the AH. This indicates a potential to use the DO strategically to choose the borders between districts better. The AH shows the potential for machine systems within existing district borders. The logging costs are, however, the dominating cost component. The dynamics of the stand characteristics contributes to the non-linear cost change when the harwarder productivity or costs are changed.

In the DO, the supply and demand were matched per season during the analyzed year, which gives a good reflection of operational reality. The AH only matched for the whole case and not on individual machine systems, which is a large simplification. Both approaches can be used for suggesting how many machine system teams are needed within a region, that is, support decisions on a tactical level. However, the DO can also provide information on where the teams should be located and how they should work operationally.

In the AH, the relocation and traveling costs are estimated based on assumptions, which were chosen in discussions with the forest company. The AH results can, therefore, represent what to expect operationally. In the DO, the relocation and traveling costs were calculated based on known locations of the stands and suggested home bases. Since the DO returned lower costs for relocation and traveling, it shows a potential to decrease the costs by improved planning with such an approach. However, there might naturally be challenges to persuade machine operators to decide where to live, since the short travel distance value will be considered in competition with other values relevant for the operators and their families.

o carry out machine fleet analyses using either of the approaches compared, sufficient competence is required. The DO requires suitable software and personnel with advanced modeling and optimization expertise. The AH requires personnel with modeling expertise. We used Microsoft Excel™ but other software might be used, such as Matlab or R. The DO requires more precise input data. When choosing which stand to harvest, different assortments' volumes per stand and harvesting dates are necessary. In the AH, the total volume is enough, because the matching between supply and demand is only carried out for the whole case without accounting for the assortment's delivery in shorter time periods. The DO problem is very large. However, by splitting the solution into three phases, where each is considerably easier to solve, it is possible to find high-quality solutions. The splitting of the solution can be viewed as making strategic decisions in Phase 1, that is, selecting the machine system teams, tactical in Phase 2, that is, assigning stands to teams, and finally operational in Phase 3, that is, determining the schedule for each team. The splitting of the solution can also be viewed as an approach to avoid symmetry. There is a huge number of solutions and, as teams are similar, there are many similar solutions. By selecting the machine systems in Phase 1, we remove a large degree of the symmetry in the model. Large symmetry is known to make the branch and bound technique very slow. In Phase 2, the problem has a fixed set of machine system teams to choose from and, here, the number of binary variables is at its largest. However, as there is some structure to the assignments, it is relatively efficient to solve the problem although we use the maximum time. The solution quality of 0.09% is very close to the optimal solution. An alternative would be to solve only the DO model's linear programming relaxation. This solution only takes a few seconds, and the aggregated solution could be used, like the AH, to obtain an approximate required size of a machine fleet.

Both approaches handled spatial variation within a geographical region, but in different ways. In the DO, the geographical sublevel of districts was not included, resulting in an optimization of the machine fleet and its work for the region. This is valuable from a top-level strategic point of view, but might be challenging to implement if district borders are strongly adhered to in daily operational work. In the AH, on the other hand, the district borders were the key element for handling the spatial aspect, since there had to be enough work for at least one team of a machine system in a district. So even if it was not addressed in this study, it can be expected that the DO approach would handle regions better in which the stand condition variations are not well matched with the district borders. These expectations would be interesting to evaluate further with larger input data.

In this comparison, both the number of systems was very limited and all teams within each system were considered identical. If desiring to increase the number of systems, or to differentiate teams within systems in a machine fleet analysis, it is possible with both approaches but they offer different possibilities and limitations. The difference between teams would consist in differentiating input related to the team's time consumption and costs. Reasons for doing so in an analysis could be to, for instance, represent different sizes of the machines within the system (e.g. to have "sub-systems" with teams consisting of small-, medium-, and large-sized harvesters and forwarders). It could also be to represent the known unique performance of actual teams of a machine system that is under consideration for being replaced with another system. With the AH, both increased number of systems and differentiated teams can be added, and is then handled in the same way – like the machine systems in this analysis. So in the AH it does not matter if it truly is new machine systems or just differentiations with a machine system. Hence, to add "subsystems" like machine sizes is quite easy irrespective of the total number of teams in the analysis, whereas the problem design grows rapidly if each team within a system should be considered unique. Also with the DO, it would be possible to both increase the number of systems and to differentiate teams within systems. However, in contrast to the AH, it would be easier to differentiate teams than to add systems. With the DO, there was more than one team of each machine system available from each home base with equal time equations and cost estimations for each machine, adding a symmetry challenge, and it is therefore faster to optimize with differentiated time equations and cost estimations for each team's machine(s). This is an advantage for the DO when preparing a tactical plan with variations due to differences between individual machine system teams. Adding new systems to the DO would be possible, but each system would considerably increase the problem to solve.

Neither one of the model approaches' results could be validated as correct. However, we involved the forest company in the project and they viewed the results from the scenario with only TMS, which is comparable with their operations, as realistic.

This study focused on comparing the results from two model approaches, when two machine systems compete within a forest company region. With reliable time equations and cost estimations for new or even as yet non-existent machine systems, our approaches can provide a basis for comparison with the established machine system. The approaches can also be used for comparisons in other geographical regions, and specifically with other stand characteristics.

Conclusions

Among the advantages with the DO, we can conclude that it is a detailed model approach, which gives a good view of the operational reality. It also takes reasonable machine utilization into account. On the other hand, it is resource demanding and needs more input data.

Among the advantages for the AH, we can see that it is resource efficient, requires less input data and can be constructed using standard software. As it requires less input data, it reflects the operational reality less well compared with the DO, for instance, regarding machine utilization, supply, and demand.

Both approaches are dependent on the quality of the input data, since high input data quality gives high output quality, whereas low input data quality produces no useful results. Both approaches have the potential to develop and provide a better decision basis, and give coherent results in terms of the machine fleet's number of machines and costs. However, the DO also provide additional results in terms of where machine teams should be stationed as well as the scheduling of teams' work.

Both approaches are well suited for analysis of large input data, and we recommend using the DO when the need for precision is high and suitable input data are available, but to choose the AH when those are not required or available. However, the results of this study relate to one case region in central Sweden and it would be interesting to see how the two approaches work with other case conditions.

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Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2022:53

The quality of forestry organizations' decisions regarding technology development are crucial to maintain competitiveness. The main objectives of this thesis were therefore to describe and critically analyze strategic decision-making about forest technology. This was addressed with four studies and the general conclusions were that strategic forest technology development processes could be improved and streamlined by following the conceptual models presented in the thesis.

Rikard Jonsson received his doctoral education at the Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, in Umeå. This is also where he received his Master of Science in Forestry.

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