Nils Egil Søvde

Optimization of Terrain Transportation Problems in Forestry

Molde University College
Specialized University in Logistics

PhD theses in Logistics 2013:6

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Nils Egil Søvde

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Specialized University in Logistics
for the degree of Philosophiae Doctor

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Preface

This dissertation presents research work performed to obtain a PhD degree in Logistics at Molde University College, Molde, Norway.

The work started in September 2008 when I received a scholarship (*stipendiat*) at The Norwegian Forest and Landscape Institute and ended in September 2013. Since February 2009 I have been a PhD student at Molde University College, when Professor Arne Løkketangen from Molde University College became my main supervisor. The place of work has been in Ås, Norway, where my forestry supervisor has been Bruce Talbot.

From July 2013 my main supervisor at Molde University College has been Professor Johan Oppen. I also received supervision from Graeme Bell of The Norwegian Forest and Landscape Institute during that time.

I have visited two foreign universities during the studies. For two months in the autumn of 2008 I visited Professor Karl Stampfer of the University of Natural Resources and Life Sciences in Vienna, for an introduction to mountainous harvesting. January - March 2012 I visited Professor Richard L. Church of the University of California, Santa Barbara.

In producing the papers, I have also worked with Magne Sætersdal of the Norwegian Forest and Landscape Institute, Fana, Norway.

The evaluation committee for this work is Professor Sophie D'Amours from Université Laval, Québec, Canada, Professor Asgeir Tomasgard, Norwegian University of Science and Technology, Trondheim, Norway, and Professor Halvard Arntzen, Molde University College, Molde, Norway.

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I would also like to thank colleagues and the management at the Norwegian Forest and Landscape Institute. This work has been multidisciplinary, and it takes courage to invest in new areas. Bruce Talbot has been my forestry supervisor, and Magne Sætersdal guided me through the environmental literature. Graeme Bell helped with end of project supervision and proofreading. A special thanks to Birger Vennesland for advocating further salary when needed.

I visited the University of Natural Resources and Life Sciences in Vienna during my PhD, and wish to thank Professor Karl Stampfer for hosting me. I also visited the University of California, Santa Barbara, and a special thanks goes to Professor Richard L. Church for hosting my visit and sharing his knowledge of location science.

I am also grateful for the good times I shared with past and present inmates at Villa Løkkeberg, my home for almost five years.

Ås, Norway
November, 2013

Nils Egil Søvde

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Glossary

ASD

Average Skidding Distance, a number describing the distance from a forest parcel (e.g. a stand) to the landing.

D-SPA

Dijkstra's Shortest Path Algorithm is an algorithm for finding the shortest paths between nodes in a network. It is commonly used in optimization.

DTM

Digital Terrain Model, a data structure where elevation (altitude) is given for coordinates.

E-CLP

The European Cableway Location Problem. A novel problem formulation for cableway placement including rigging time and yarding time, but not other aspects like landing selection or road location.

GRASP

Greedy Randomized Adaptive Search Procedure is a metaheuristic typically consisting of a constructive phase and a local search phase, which can be used to generate possible solutions during optimization.

HFS

Harvester–Forwarder System, consisting of two off-road machines. The harvester fells, limbs and cross-cuts the trees, and the forwarder transports the logs to the landing.

Retention patch

A retention patch is a part of a harvest area that is not harvested.

RSP

The Reserve Selection Problem is the problem of selecting a subset of candidate reserves for preservation. Various formulations are presented in the literature, but most formulations include preservation costs and environmental values.

TLP

The Trail Location Problem is the problem of selecting a subset of extraction trails covering a harvest area.

TTC

Terrain Transportation Cost is the cost of transporting timber in the terrain.

WKH

Woodland Key Habitat is a forest area with higher probability of finding rare or endangered species. In Norway, WKHs are registered by experts and stored in public databases.

Introduction

Chapter 1

Introduction

This thesis addresses the question of how numerical optimization methods can be used to improve the efficiency of forest logistics, in particular, addressing problems in terrain transportation of timber.

The structure of the thesis is as follows. The introduction chapter briefly outlines the two themes that are the central concern of the thesis: forestry and optimization. The following section, ‘Background and research context’, goes into more detail describing how researchers have applied optimization techniques within forest logistics, explaining the research context surrounding this thesis.

In the paper summary chapter, a process diagram highlights how each paper in this work addresses specific real world problems in forest operations, and shows visually how the papers relate to each other. Each paper is then summarized in a standard format for ease of reference. The conclusion chapter reflects on the work as a whole, and draws lessons from the common themes of the papers. A bibliography is given, which provides details of the material referenced throughout this research project, and is followed finally by copies of the individual research papers that have been produced.

1.1 Forest operations

Forests supply a wide range of products as well as immaterial goods such as recreation opportunities and environmental values. The first concern of most forest owners is profit, and wood production constitutes the major part of forest revenues. It takes considerable time to grow trees, but there are few costs incurred before the forest is harvested. On the other hand, the cost of harvesting operations may be high, and the terrain transportation cost (TTC) is a substantial part of the overall harvesting cost. Tree harvesting is also the forest activity with the largest impact on environmental and recreational values.

The focus of this work is forest operations in Norway, but the harvesting systems used in Norway are common in other parts of the world and many of the presented models and methods may be suitable for the systems of other countries.

A harvesting operation consists of several steps. The trees have to be felled and transported to a demand site. Depending on how the supply chain is organized, the trees may be limbed and cross cut in the forest or at the roadside. There are mainly two different harvesting systems operating in Norway: The Harvester–Forwarder System (HFS), and cable yarding systems. Harvesting using skidders is not a common harvesting system in Norway.

1.1.1 Wheel based harvesting

Wheel based harvesting systems harvest the major part of the world's annual forest harvest. The HFS is widely used in boreal forests. Some 90% of the harvested forest in Norway is harvested by HFS (Vennesland et al., 2006), and the system has a similar level of usage across the Nordic countries. A harvesting operation by HFS is highly productive and one of its main strengths is that it consists of independent operational steps. The system requires two terrain operating machines, a harvester and a forwarder.

The harvester is equipped with a crane and a processing head. It fells, limbs, cross cuts and sorts trees (referred to as *processing*), piling logs along the trail. When all the trees within reach have been processed, the harvester drives on a few meters, and the process is repeated. Occasionally, the harvester has to back up a distance to start harvesting along another trail. The forwarder subsequently transports the logs to roadside. This part of the operation can happen in parallel, or it can happen days or weeks later, depending on the operation and the requirements of the buyer of the timber.

Forwarding starts when the forwarder drives into the terrain, using the trails made by the harvester. At some point, the operator starts to sort and load using the crane mounted on the forwarder, and when the forwarder is fully loaded, it drives to the landing where the sorted logs are unloaded to different piles. The timber is loaded and transported by trucks at a later stage. The timing of operations is affected by factors such as landing size and buyer requirements.

The harvesting method used by HFS is referred to as the cut-to-length method. For this method, the length of a log is decided by the harvester operator, and the logs are in general not cross cut at later stages in the supply chain.

In the US and some other countries, skidding is more common and more studied in the literature. A skidder is a terrain operating machine which can be equipped with a winch, a grapple, or a clam-bank. Trees are typically not cross cut in the stand. Instead, the skidder drags the whole trees along the ground to the landing. The loads of a skidder are in general smaller than the loads of a forwarder, and the loading phase is simpler - both in a practical sense and for modeling.

1.1.2 Cable yarding harvesting

In steep or difficult terrain, harvesting relies principally on cable yarding systems. Although these systems only produce a small part of the harvested timber volumes in Norway, the volumes harvested by cable yarder systems are likely to increase in the near future (Vennesland et al., 2006). For example, in large areas along the coast of Norway, spruce was planted from the 1950s and onwards, and now these forests are rapidly maturing.

Cable yarding operations are labor intensive, and their harvesting costs are significantly higher than the harvesting costs for HFS.

A common cable yarding system in Norway and Europe uses a tower mounted on a truck, a set of cables and drums, and a carriage operating along the cables. A crane equipped with a harvesting head is either mounted on the truck or a secondary machine (an excavator or harvester). The cables are pulled into the harvesting area, and are elevated from the ground by the tower, by a tree used as a tail spar, and by intermediate supports if necessary. Trees are felled manually, choked manually, hauled along the cableway and then limbed and cross cut at the roadside. This system is flexible in the sense that any road location can be used as a landing. This flexibility was noted by Bont (2012), but other studies of cable yarding in research literature focus on larger yarding systems that require landings to be constructed.

1.1.3 Environmental issues

Forests include habitats for numerous species, and taking measures for preservation of biodiversity is important for forestry in general and harvesting operations in particular. Also, forests are sources of recreation opportunities and other public goods. It is important that forest operations and forest planning are environmentally friendly and in line with public opinion.

Tree removal is the forest operation that causes the greatest change to habitats and to the recreational values of a harvested area. It is also the most controversial aspect for the public. Timber sales are usually the largest source of income from forests, but maximizing profit may conflict with environmental values and the public interest. Sustainable forestry may be a wiser choice for the long term. For a discussion of these issues in more detail, see Bergseng et al. (2012).

Although this thesis focuses on profit modeling, Paper 3 directly addresses the problem of modeling environmental concerns and profit together.

1.2 Forest operations research

This work was originally motivated by the fact that the annual growth of Norwegian forests is significantly higher than the annual harvest (Vennesland et al., 2006). Forest operations research could help increase the annual harvest and make the harvest more environmentally friendly, by:

- *Planning and optimization of forest operations* can reduce the costs directly by finding better ways of organizing operations, and also indirectly, if rapid or early planning can reduce delays. The basic principles of economic theory indicate that a reduced cost of harvesting would lead to reduced timber prices and thus increased sales (Mansfield, 1993).

- *Opening new forest areas*. It has been observed that there is a need for new forest roads in the western parts of Norway (Øyen, 2008). Road network planning and road-building is required for those areas to be harvested. Road building costs are a significant part of Norwegian forestry costs. For a new forest road to be worthwhile, the savings from reduced harvesting costs or the profits from the opened forest should be greater than the costs of building the road[1].

- *Including environmental factors* when developing new models for terrain transportation, for example terms can be included in mathematical models that limit driving through terrain or restrict harvest areas.

A second motivation comes from the new opportunities provided by high accuracy remote sensing data. Airborne laser scanning is today the preferred method for surveying forest inventories and the technology is capable of locating single trees and other small objects. Digital Terrain Models (DTMs) generated from airborne laser scanning data are reported with an elevation accuracy of $\pm 10cm$ (Kraus and Pfeifer, 1998). However, such data has not found the same popularity within forest operations research as it has in inventory surveying, but the number of published applications is slowly increasing.

1.3 Optimization models

Optimization is the task of finding a solution $x \in \mathbb{X}$ that minimizes (or maximizes) an objective function $f : \mathbb{X} \to \mathbb{R}$, where $\mathbb{X}$ is the set of feasible solutions. Optimization problems can be categorized into classes according to the difficulty of finding a solution. For example, some problems are inherently intractable for large problem instances. In other words, at some problem size, the memory, the number of processors or the time required to find a solution approaches infinity. In contrast, other types of problems can be reliably solved for almost any imaginable problem instance size.

The definitions for solution methods depend on the aim. A practical definition which emphasizes that algorithms are different from heuristics and metaheuristics might be:

- An algorithm is a set of instructions which will return the solution for any instance.
- A heuristic is a set of instructions which may return a solution. The solution returned may be good or bad.
- A metaheuristic is a heuristic together with a set of instructions that guide the heuristic search.

By these definitions, algorithms are exact solution methods, whereas heuristics and metaheuristics are approximate solution methods. If the problem at hand is a difficult one, an algorithm can only solve instances of a certain size in a reasonable time. For larger instances, applying heuristics or metaheuristics is a possible option.

Real world optimization problems include the additional challenge of building an optimization model (Williams, 1990). A model is by definition a simplification of the real world. The choice of factors to include or omit, and how they are related, must be decided and formulated. However, if a real world problem is modeled and the model belongs to a class

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[1] Although road planning projects are beyond the scope of this thesis, the terrain transportation models presented here can be used as a foundation for future work in road planning.

which is difficult to solve, reformulation of the model could be considered. Sometimes a simpler model solved to optimality will yield better solutions than a difficult model optimized using a heuristic or a metaheuristic. In practice, a formulation is made based on analysis, qualified guessing, tradition and other criteria.

Another challenge when designing an optimization model is the choice of objective(s). A common objective is to maximize net profit, and this objective may be achieved by increasing revenues or decreasing costs. Although specifying objective functions for monetary values may be tricky, most businesses use cost and pricing on a daily basis. Some objectives can be hard to price (e.g. environmental values or public goods), and the benefits of these objectives may accrue to a third party. Typically, if several objectives are identified, they will conflict. In such cases, a multi-objective optimization model can be considered. In a multi-objective formulation, the objective function is replaced by $f : \mathbb{X} \rightarrow \mathbb{R}^n$. Such problems are generally difficult to solve (Serafini, 1987).

When optimizing for a real world problem, it can be worthwhile to design a specific heuristic for the problem at hand, or to modify or develop an existing metaheuristic. There are numerous metaheuristics (a comprehensive handbook is Glover and Kochenberger, 2003) and selection of technique is often a matter of personal preference. A popular approach is to analyze the problem at hand and consult the literature to select a method that performs well for the specific problem type. For example, online problem instance repositories may guide the selection of a heuristic or metaheuristic, or help in evaluation. For real world problems there are often no instance repositories available, and little literature may be available.

Evaluation of solution approaches can be difficult. One technique is to find solutions to similar problems and compare them. For example, removing one or more constraints is referred to as a relaxation of the original problem, and this may lead to a more computationally friendly problem. Alternatively, modifying the objective function can make the problem easier to solve. An example of such an approximation method is found in the calculations of net profit in Paper 3 of this thesis.

1.4 Summary

This chapter introduced the two distinct themes of forestry and optimization. In the next chapter, these two themes are connected in a survey of the literature addressing optimization in forest operations research.

Chapter 2

Background and research context

This chapter introduces the intersection of forest operations with optimization by providing short surveys of topics where the fields naturally overlap. These problems often have common features or similar solutions, but are not directly connected. The chapter is split into two categories: existing problems that predate this thesis (terrain transportation cost, extraction trail layouts, silvicultural treatments, the reserve selection problem and cableway layouts), and novel problems introduced by this thesis that draw on existing work (trail location problem for HFS, the European Cableway Location Problem (E-CLP) and the landing area evaluation problem).

2.1 Terrain transportation costs

The cost of harvesting is one of the largest costs in forestry, and the terrain transportation cost constitutes a significant part of the harvesting cost. Any forest planning including harvesting decisions thus require some estimate of these costs.

An intuitive idea is that terrain transportation cost is proportional to the distance from the forest stand to the landing. By calculating the average skidding distance ASD (some papers use the term average yarding distance), the cost of terrain transportation can be estimated from a function $f(ASD)$. This approach will be referred to as the ASD-method, and is commonly used in the literature. The method dates back to the textbook by Matthews (1942).

There are some challenges with the ASD-method. Firstly, driving a forest machine in uneven or non-flat terrain often result in detours, and corrections may be necessary to cater for this (Hughes, 1930). Including wander factors to increase the calculated TTC may improve the estimates. Another challenge is that the ASD is traditionally linked to the road density. The road density is the total length of roads in a forest, divided by the area of the forest. von Segebaden (1964) addressed the fact that forest roads are irregularly placed in the terrain, and found that corrections for non-parallel roads should also be included if the road density is included in the calculations.

Traditionally, a forest is viewed as a set of smaller parcels (stands). The forest inside each stand would ideally have the same characteristics (e.g. site index, tree size, age). Forest stands are the treatment units of practical forestry, and are commonly used in forest planning as the unit a decision variable is referring to.

The ASD-method may be a good choice for estimating TTC if corrections are carefully included. However, challenges due to uneven terrain and road layouts, together with more detailed DTMs from Airborne Laser Scannings, have led to attempts using another method. The terrain may be represented by a network $N = (V, E, w)$ where V is the set of vertices, E the set of edges and w is the costs of transportation along the edges E. By using standard graph algorithms (e.g. Dijkstra's shortest path algorithm, Dijkstra, 1959), a more detailed cost estimate can be found than by the ASD-method. This method will be referred to as the network method.

The network method was used by Tan (1992, 1999) for calculation of the opportunity cost (reduced TTC) for road location. The TTC was calculated as a function of distance and terrain class (i.e. a wander factor). Contreras and Chung (2007) calculated TTC using the network method for landing and spur road location, and used a TTC-function including distance and slope gradient uphill or downhill. More recently, Contreras and Chung (2011) refined the skidding model to also include a maximum roll limit, i.e. a maximum gradient perpendicular to the driving direction. The network method was also used by Chung et al. (2008) for calculation of reduced TTC for road location, using a TTC-function based on distance.

There are two challenges with the network method. The first one is that the method is increasingly used for TTC-estimates, but is not yet firmly placed in the literature. This problem is addressed in Paper 1. The second challenge is that productivity studies of how driving speed is affected by micro topography and other detailed terrain characteristics are lacking in the literature (Contreras and Chung, 2011). Such productivity studies are not within the scope of this thesis.

2.2 Extraction trail layout

The optimization of extraction trail layouts for wheel based systems is inherently linked with the calculations of TTC. There are three somewhat different approaches in the literature.

1. Earlier methods based on the Matthews method (Matthews, 1942) are largely analytical and return values for average road spacing or average trail spacing. Being based on the Matthews method, the same assumptions apply (e.g. flat or uniform terrain, and parallel and evenly spaced roads and trails) (e.g. Peters and Nieuwenhuis, 1990; Shishiuchi, 1993; Heinimann, 1998; Akay et al., 2007).

2. The network method can be used for more detailed calculations of the total TTC of a forest area, and returning extraction trail layouts as a bi-product. This approach was used by Contreras and Chung (2011), who developed a model for skidding operations and solved the model using a clustering heuristic to build skidder loads and a shortest path algorithm to find the location of the skidding trails. The same

method was also used by Contreras and Chung (2013) for estimating the cost of removing trees to reduce forest fire potential.

3. The network method can also be used with the aim of designing extraction trail layouts. This approach was used by Mohtashami et al. (2012), who designed main extraction trail layouts using cost indices for elevation, slope and soil class, but did not include the complete trail network.

There seems to be no studies describing optimization of a complete extraction trail network for HFS in the literature. The approach of Contreras and Chung (2011) is not directly applicable for the extraction of timber by forwarders. Forwarders can in general transport larger loads than a skidder, and the cut-to-length-method results in different assortments. Usually, a machine operator will limit the assortments to one or two per load, and the loading area for a forwarder will be larger than for a skidder.

2.2.1 The novel Trail Location Problem (TLP) for HFS

Modern remote sensing techniques can supply high resolution DTMs that have been used for the design of skidding extraction trail networks. An HFS operation is different from a skidding operation, and the differences leads to a novel problem formulation named the Trail Location Problem (TLP) for HFS. This problem was addressed in Paper 2, and the following observations were made:

- The trails are made by the harvester and used by the forwarder.
- The time used by the harvester for processing the trees and driving while processing is independent of the trail layout.
- The amount of idle harvester driving could be affected by trail layout. However, finding a route which minimizes idle harvester driving is similar to the *Chinese postman problem*, and including this while designing the trails would be a hierarchical problem. The cost of idle driving was assumed to be a small part of the total cost.
- Loading and unloading of forwarders has been modeled as a vehicle routing problem by Flisberg et al. (2007), and they used the trail layouts made by harvesters. Loading, unloading and routing of forwarders was considered to have little impact upon the desig of extraction trail layouts.

Hence, forwarder driving is the part of harvesting operations that influences trail layout the most.

2.3 Silvicultural treatments for retention patches

The increasing concern for preservation of biodiversity in the beginning of the 1990s also had an impact on forest harvesting. Setting aside forest land as nature reserves was the first approach, and several variants of The Reserve Selection Problem (RSP) were formulated and solved (e.g. Williams et al., 2004).

Another approach for preserving biodiversity is to include environmental considerations when harvesting a forest parcel, either as publicly registered Woodland Key Habitats (WKHs) deemed of high environmental value by experts (e.g. Gustafsson, 2000), or by requiring that a forest manager or contractor leave a part or parts of the harvest area as retention patches. The latter is referred to as Green Tree Retention (Franklin et al., 1997), and is becoming the dominant biodiversity management practice in boreal forests of North-America and Europe (Gustafsson and Perhans, 2010).

There are challenges when adapting the RSP to WKHs and retention patches. Firstly, a WKH or a Retention patch can be a very small part of a stand, and using the Matthews method for TTC-calculations may give inaccurate estimates. Secondly, nature reserves typically have unmanaged forests, whereas WKHs or retention patches may benefit from various silvicultural treatments (e.g. Fries et al., 1997; Götmark et al., 2005; Lõhmus, 2006; Franc and Götmark, 2008). The RSP has not been modified in the literature to include such silvicultural prescriptions, but there are some studies of the cost-benefit of different silvicultural treatments. Howard and Temesgen (1997) studied the estimated net profit of nine silvicultural prescriptions. Both the prescriptions and the harvesting cost calculations were based on the Matthews method and calculated for entire stands, and thus were not adapted to retention patches. Jonsson et al. (2006) did a cost-benefit simulation of how six types of coarse woody debris varied with seven management options. One of the management options was retention of small parts of the area, but their focus was the environmental values. Their cost estimates were based on the Matthews method and were calculated for entire stands.

Perhans et al. (2011) and Juutinen et al. (2004) both optimized RSP-formulations for retention patches and stands, respectively. However, they only included setting aside retention patches and stands for preservation, but not different silvicultural treatments. Their TTC-estimates were also based on the Matthews method.

A silvicultural treatment may increase or decrease the environmental values of retention patches or WKHs. In most cases, however, harvesting or partial harvesting reduce the environmental values. Maximizing profit and environmental values are thus conflicting objectives, and a multi-objective formulation may be appropriate. The problem of deciding silvicultural treatments for retention patches and WKHs using a more detailed TTC-calculation is the topic of Paper 3.

2.4 Cable yarding

Forest harvesting is commonly modeled as facility location problems. Such problems have been studied since the nineteenth century. Greulich (2003) is a review discussing some of the lesser known early contributions, and Mirchandani and Francis (1990) is a thorough textbook on discrete location theory. In forestry modeling, facilities may be e.g. trails, roads, landings or cableways, and have a building or rigging cost. The facilities are used for the transport of timber, and this use has a cost which may vary.

The uncapacitated facility location problem, or simple plant location problem (Krarup and Pruzan, 1983), is the problem of minimizing the total cost of using facilities and building the facilities. By defining the parameters

c_{ij} the cost of using facility j for transportation of timber from a grid point i (2.1)

f_j the building or setting-up cost of facility j (2.2)

(2.3)

and the variables

$$x_{ij} \begin{cases} 1 & \text{if timber from grid point } i \text{ is harvested using facility } j \\ 0 & \text{otherwise} \end{cases} \tag{2.4}$$

$$y_j \begin{cases} 1 & \text{if facility } j \text{ is set up} \\ 0 & \text{otherwise} \end{cases} \tag{2.5}$$

the problem can be formulated for timber transportation as

$$\min \quad \sum_i \sum_j c_{ij} x_{ij} + \sum_j f_j y_j \tag{2.6}$$

$$\text{s.t.} \quad x_{ij} \leq y_j \quad \forall i, j\,, \tag{2.7}$$

$$\sum_j x_{ij} \leq 1\,, \quad \forall i\,. \tag{2.8}$$

In this formulation, the double sum is the cost of using the facilities (the yarding cost) and the single sum in Equation (2.6) is the cost of building the facilities (the rigging up and down cost). Constraint (2.7) secures that only built facilities are used and Constraint (2.8) secures that timber is harvested only once.

The simple plant location problem is NP-hard (Krarup and Pruzan, 1983), but forest location problems are usually formulated as hierarchical (or multi-level) optimization problems. Hierarchical problem formulations are generally difficult to solve even if the problem at each level is easy (Tuy, 2002).

Dykstra (1976) included rigging and yarding costs, but also landing construction costs as well as different machine characteristics. The problem can be viewed as a hierarchical problem, as there are numerous combinations of landings to choose, and for each combination the cableway layout can be optimized. The problem is solved by a heuristic which first constructs a feasible solution, then iterates through a drop phase based on the drop-routine of Feldman et al. (1966) and an add phase based on the add-routine of Kuehn and Hamburger (1963), until the solution stops improving.

More recent research has included also road construction cost and road transportation cost, in addition to yarding cost, rigging cost and landing construction cost. Chung (2002) based the optimization on the method of Cooper and Drebes (1967), iteratively calculates the shortest path flows and modifies the variable costs. The locations of new forest roads are also included in Epstein et al. (2006), who describe the PLANEX software developed for Chilean forest industries. Their solution method consisted of three steps. First, a greedy, constructive heuristic which includes landings sequentially. Second, a heuristic solves the Steiner tree problem (the road network) (Promel and Steger, 2002), and the final step uses an evaluation by forest engineers.

Inclusion of road location options has shifted the focus from the problem of designing cableway layouts to the Steiner tree problem of connecting selected landings to an existing forest road network. This may be a reasonable approach, but the performance of the individual heuristics or the whole solution method are seldom discussed. However, there have been attempts at improving the cableway location subproblem in the PLANEX software. Vera et al. (2003) proposed two approximation methods, but they were unable to solve larger problem instances. Diaz et al. (2007) modified the greedy heuristic for the machine location sub-problem in PLANEX to a tabu-search metaheuristic. They reported "better solutions than those provided by state-of-the-art integer programming codes in limited computation times, with solution times significantly smaller".

Bont et al. (2012) also studied simultaneous optimization of road location and cableway location. They compared a mixed integer linear programming formulation with the heuristic used in the PLANEX software, and by reducing the set of candidate nodes, they solved the problem formulation to optimality.

2.4.1 The novel European Cableway Location Problem (E-CLP)

The optimization models presented in the literature for cable yarding operations are typically hierarchical models, including cableway locations, landing locations and road locations. Hierarchical problem formulations may lead to large problem instances, and most publications assume that possible landings are selected by experts. This reduces the size of problem instances, but also the size of the search space (compared to the real world). It disregards the flexibility of the cable yarding systems commonly used in Europe. European yarders can operate from any location on a forest road, unlike other yarders dependent on landing construction. One practical implication of the European systems is that the resulting cableway layout tends to be parallel (Bont et al., 2012), whereas the cableway layout of systems requiring construction of landings tends to be fan-shaped (Chung, 2002). Another issue is that cable yarding operations using European systems often are carried out without landing or road building, thus reducing the importance of including these factors in an optimization model.

The problem studied in Paper 4 is that of designing cableway layouts for the European cable yarding system, considering only a facility building cost (set-up and take-down of the tower) and a cost of using the facilities (the yarding). This leads to a problem formulation similar to the problem formulation given by Equations (2.6)–(2.8), and is called the European Cableway Location Problem (E-CLP).

2.4.2 The novel problem of landing suitability estimation by local area

Landing assessment is an important task in forestry. As already mentioned, the cited literature often assumes landings to be found and evaluated by experts. If the number of possible landings is small, this is a reasonable task for humans, but for larger instances or problems where expert evaluation is not possible, automation of landing evaluation may be necessary.

Chung (2002) analyzed possible landings by numerically calculating the feasibility of 36 cableways radiating from the possible landing in a star-shaped pattern, and graded the possible landing by the size of the area that could be harvested by the cableways, not by the size of the landing itself. This method was also used by Stückelberger (2008), who used the results for guiding the optimization of new forest road locations. Although the area a landing can cover is an important feature of a good landing, the method disregards the importance of the terrain close to the tower.

European tower yarders are flexible in terms of where they can operate, but a yarding operation collects timber from a large forest area, and landing space is bound to affect the operation. If a landing is filled with logs, the logs may be temporarily moved or picked up by trucks. This will lead to additional costs, both directly and indirectly, by slowing the work. In Paper 5, the problem of evaluating the quality of a possible landing at road grid points and terrain grid points is studied.

2.5 Summary

This chapter was a short survey of the research context of optimization in forest operations research. We have seen that although there is some history of applying optimization to forest operations, there are aspects where optimization has never been applied. This provides a motivation to introduce optimization to new areas of forest operations. In the next section the contribution of this thesis towards these themes is outlined.

Chapter 3

Summary of papers

This thesis was an applied study where terrain transportation problems were refined or modified to cater to improved input data, increased computational power or improved solution methods.

Figure 3.1 is a process diagram showing how the papers in the thesis contribute to different (but related) aspects of forest logistics.

Each paper is then separately summarized in a standard format describing the results, the roles of each co-author in producing the paper, and the theme of the paper within the context of the PhD.

3.1 Contributions towards forest harvesting processes

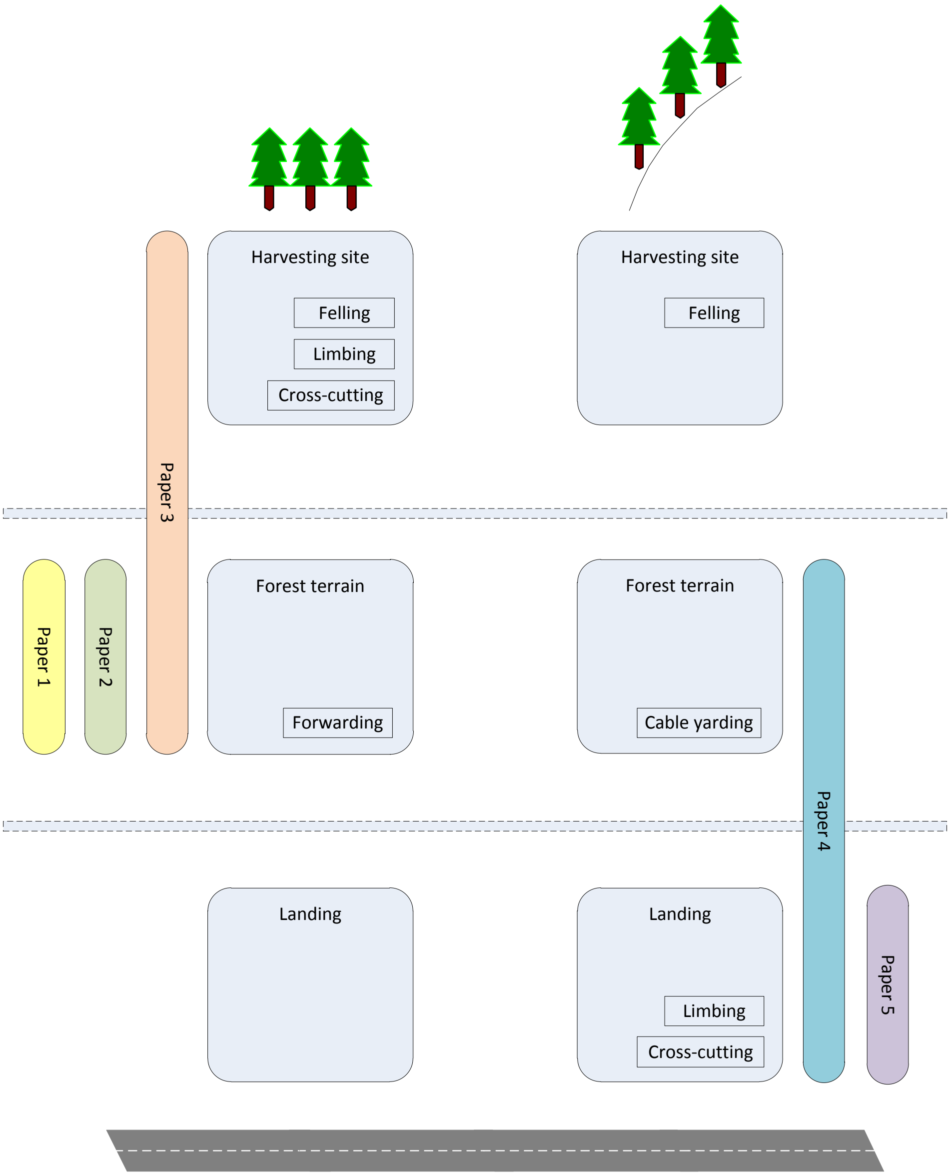

Figure 3.1: Graphical representation of two common forest harvesting processes, with coloured boxes indicating the aspects of the process that are directly relevant to the papers in this thesis.

3.2 Paper 1: Off road transportation costs for ground based systems

- **Paper name:** Off road transportation cost calculations for ground based forest harvesting systems.
- **Paper author:** Nils Egil Søvde.
- **Publication status:** Pending submission. The work has been accepted for oral presentation at the 46th International Symposium on Forestry Mechanisation – FORMEC 2013, Sept 30 - Oct 2 2013, Stralsund Germany.
- **Summary:** Some researchers have started using network methods for calculation of Terrain Transportation Costs (TTC), but such methods are not well discussed in research literature. Here, the network method is compared with earlier methods, bringing the literature up to date with practice.
- **Description:** This paper provides a review of how TTC has been calculated in the past. It also shows how the traditional method of calculating TTC from average skidding distance (ASD) is related to the more recent method of calculating TTC using the network method. The main conclusion is that the numerical network method is a more promising approach for detailed TTC calculations in uneven terrain.
- **Breakdown of work:** Nils Egil Søvde carried out the study and wrote the text as sole author.
- **Contribution to the thesis:** Any optimization model including harvesting of timber require estimates of the harvesting cost. As wheel based harvesting systems is the major harvesting system in Norway and the rest of the world, the impact of this study can be significant. Both Paper 2 and Paper 3 rely on the theme of this paper.

3.3 Paper 2: Optimizing trail layouts

- **Paper name:** Applicability of the GRASP metaheuristic method in designing machine trail layout.

- **Paper authors:** Nils Egil Søvde, Arne Løkketangen, Bruce Talbot.

- **Publication status:** Accepted for publication in the Journal of Forest Science and Technology. To appear September 2013. An earlier version of the work was also accepted and presented at the Fourth Forest Engineering Conference in White River, South Africa, April 5-7, 2011.

- **Summary:** This paper addresses optimization of extraction trail layout for forwarding.

- **Description:** In this paper the novel Trail Location Problem (TLP) for the harvester forwarder system is defined. A solution optimization approach is given. A model for calculating the cost of driving between neighboring grid points was developed and used to calculate the TTC of all grid points. It was observed that a trail is a two-dimensional facility and designing neighborhoods for local search could be difficult. The layout of a trail network can lead to ripple effects when moving in a local search. Thus, a greedy, constructive heuristic was designed, where trail segments were iteratively added from the existing forest road and the already added trail segments. The greedy heuristic was also modified into a GRASP metaheuristic. The results from the original and the modified method were compared. The basis of the solution methods was a greedy evaluation function measuring the improved net profit.

- **Breakdown of work:** Nils Egil Søvde designed the study, programmed the software and wrote most of the text. Arne Løkketangen suggested using the GRASP metaheuristic and supervised. Bruce Talbot supervised and also rearranged the paper from a method based approach to a case based approach.

- **Contribution to the thesis:** This paper's contribution to the theme of the thesis was the introduction of an applied metaheuristic optimization approach for forwarding operations. It was important to address this problem, because forwarder harvesting represents 90-95% of industrial timber harvesting in Norway. The technique appears to be effective, and the scientific contribution was accepted for journal publication. The ideas in this paper relate to the themes described in Paper 1, and were later extended further by the development of more advanced techniques in Paper 3. It represents a practical demonstration of optimization techniques for forest operations.

3.4 Paper 3: Optimizing retention patches

- **Paper name:** A scenario-based method for assessing the impact of retention patches on forest harvesting costs.

- **Paper authors:** Nils Egil Søvde, Magne Sætersdal, Arne Løkketangen.

- **Publication status:** Pending submission. An earlier version of the work was accepted and presented at the 44th International Symposium on Forestry Mechanisation -— FORMEC 2011: Pushing the Boundaries with Research and Innovation in Forest Engineering Conference date: Oct 9-13 2011 Conference place: Graz, Austria.

- **Summary:** This paper addresses the multi-objective problem of optimizing profit and environmental values for retention patches and woodland key habitats (WKHs).

- **Description:** In this paper the multi-objective problem of deciding silvicultural treatments for retention patches and WKHs was addressed. The net profit was given as an objective function, whereas the environmental values were given implicitly by a number of treatment scenarios. The solution method calculates the maximum net profit of each scenario using Dijkstra's Shortest Path Algorithm (D-SPA) (Dijkstra, 1959). This is an *a posteriori* solution method and as such is applicable if the number of scenarios is small and the environmental values of each scenario can be easily assessed after optimization.

  The net profit was calculated as timber value minus the minimum TTC. For the calculations of TTC, the model for driving between neighboring grid points in paper 2 was developed further, to yield a better estimate of the TTC. The choice of using D-SPA for the calculations of net profit instead of a heuristic solution method (e.g. Paper 2) was motivated by the reduced computational time costs.

  The method was applied to four real world terrains and the results indicate that the TTC may vary significantly depending on the micro topography. The traditional way of calculating TTC is to use ASD for each stand, whereas a Retention patch or a WKH may be a small part of a stand. For this reason, the costs of retention patches and WKHs reported in previous literature may be inaccurate. It was also found that prohibiting driving in an area may increase the cost of driving in areas beyond.

- **Breakdown of work:** Nils Egil Søvde designed and programmed the software, and wrote most of the text. Arne Løkketangen supervised. Magne Sætersdal supervised and wrote parts of the introduction in collaboration with Nils Egil Søvde. Bruce Talbot supervised, but felt he did not contribute enough to be a co-author.

- **Contribution to the thesis:** This paper extends and reapplies ideas first developed in Paper 1 and Paper 2. The network method for calculating TTC in paper 2 was developed further, and the use of an exact solver for simplified profit calculations in the problem formulation allowed larger problem instances. It was important to study how refined cost calculations affect environmental planning, as environmentally friendly forestry is a concern both for the industry and the public. This paper demonstrates that the ideas of this thesis can be applied to further areas beyond profit modeling.

3.5 Paper 4: Optimizing cableway layouts

- **Paper name:** A semi-greedy metaheuristic for the European cableway location problem.

- **Paper authors:** Nils Egil Søvde, Arne Løkketangen, Richard L. Church.

- **Publication status:** Pending submission. An earlier version of the work was also accepted at the 45th International Symposium on Forestry Mechanisation -– FORMEC 2012: Forest Engineering: Concern, Knowledge and Accountability in Today's Environment, Hotel Croatia, Dubrovnik (Cavtat), Croatia, Oct 8 - 12, 2012, but none of the authors could attend the conference.

- **Summary:** In this paper the European Cableway Location Problem (E-CLP) was formulated and a semi-greedy constructive metaheuristic was developed for solving the problem.

- **Description:** This paper develops a novel problem formulation, the E-CLP. Just as for the trail location problem, the two-dimensional facilities make neighborhoods difficult to construct. To solve the problem, a greedy constructive heuristic was designed where one cableway location is selected first, and then the next cableways are added from almost parallel cableways some distance from the last added cableway. The greedy heuristic was further developed to a semi-greedy metaheuristic.

  The two methods were tested with real world terrain, and the results show that the best calculated net profit from the greedy heuristic was always better than 96% of the best net profit from the semi-greedy metaheuristic. Since the greedy heuristic was considerably faster, but produced similar results, it could be used for solving parts of a hierarchical problem formulation where computational time is important.

  Lateral yarding was included in the calculations of the cost of using the cableways, yielding better solutions than reported in the literature.

- **Breakdown of work:** Nils Egil Søvde designed and programmed the software, and wrote most of the text. Part of the work was done at University of California, Santa Barbara, January – March 2012, visiting Richard L. Church who also supervised. Arne Løkketangen supervised. Bruce Talbot supervised, but felt he did not contribute enough to be a co-author.

- **Contribution to the thesis:** Rapidly growing mature forest areas in the coastal regions of Norway presents a challenge for the foresters and contractors. As cable yarding is the preferred harvesting method in steep terrain in Norway, it was natural to address this harvesting method in the thesis.

3.6 Paper 5: Automatic landing suitability estimation

- **Paper name:** Algorithms for estimating the suitability of potential landing sites.

- **Paper author:** Nils Egil Søvde.

- **Publication status:** Pending submission. An earlier version of this work was accepted and presented at the IUFRO 3.06.00 Conference Forest Operations in Mountainous Conditions, Honne/Biri (Lillehammer), Norway, June 2–5, 2013.

- **Summary:** This paper presents two algorithms for estimating the suitability of potential landing sites for use during harvesting operations. The main focus is cableway harvesting, but the algorithms can also be used for other harvesting systems.

- **Description:** This paper is a study of how a high resolution digital terrain model can be utilized for landing detection and evaluation. A yarding operation with a truck based tower yarder can operate continuously along a road, but the operation will be affected by the local terrain. In the paper, two algorithms for landing evaluation are presented and compared. The first algorithm is an estimate of the amount of timber that can be stored around a point on a forest road, whereas the second algorithm is a calculation of the average absolute elevation difference of an area around a point. The latter algorithm has the advantage of being useful away from forest roads.

  Both algorithms were tested with real world terrain and the results indicate that the simpler and more general algorithm gives similar results to the road-based algorithm. The result from either algorithm provides a fast, useful assessment of the cost of using a landing.

- **Breakdown of work:** Nils Egil Søvde carried out the study and wrote the text as sole author. Graeme Bell proofread the text and suggested some changes, but felt he did not contribute enough to be a co-author in the current draft.

- **Contribution to the thesis:** It is important to address landing suitability as costs due to delays and increased timber handling can be avoided by better planning. The algorithms presented in this paper can be used to improve the problem formulation and solution approach presented in Paper 4, and they are also suitable for use in other projects.

Chapter 4

Discussion and conclusion

This chapter should be read after reading the full text of the five papers.

4.1 Discussion

This thesis is a study of terrain transportation problems, with a focus on systems used in Norwegian forestry. This focus led to novel problem formulations and the development of heuristics and metaheuristics guided by key features of good solutions, as determined by problem analysis. For example, the constructive placement of cableways in the E-CLP solution was informed by studying the best practices established in industry.

An essential aim of this work has been to handle large problems instances. This has been addressed in several ways:

- By using heuristics and metaheuristics.
- By breaking down hierarchical problems through identifying and focusing on basic problems.
- By reformulating problems into alternative problems that can be solved using exact solvers.

4.1.1 Detailed remote sensing data

A major motivation for this work has been to investigate how data from modern remote sensing techniques can be used for optimization in forestry. Numerous applications for such data have been reported, and continuing development in this area may be considered a present research frontier of forestry. Remote sensing generate large data-sets of highly precise data, which allows detailed models that are best approached heuristically.

4.1.2 Model validity and computational efficiency

To a forester, the main concern might be the quality of the mathematical models. Is the model, including parameters, a true model of the real world? This question is a valid concern for a practitioner, but can be difficult to answer. The validation of a model may require extensive testing with real world cases, or even widespread use in the industry before confidence in the approach is developed. This is seldom possible within the scope of a research project. A recurring theme in this thesis is the discussion of model validity. In particular, a continual challenge throughout this project was that parameter value estimates for high resolution models were missing in the productivity studies presented in the literature, raising the difficulty of validation.

A mathematician, on the other hand, may be less concerned by validating the model against the real world. A model is by definition a simplification of the real world, and the behavior and solution methods can be interesting to study by themselves. For optimization of difficult problems using heuristics and metaheuristics, a mathematician may be more interested in the speed of the solver and the quality of the solutions on abstract problems.

In the research community, it may be most important to optimize as far as possible. In industry, the speed with which solutions are found might be more important than solution quality, e.g. a forest contractor may not have the time to wait weeks for a plan for cableway layouts.

Another challenging aspect of this work came from the novelty of the problems addressed. Comparing the solutions found to known solutions from problem instance repositories is not possible for new problems.

There are two aspects of forest operations for which computational speed and model validity is of minor importance. Firstly, most harvesting operations require manual planning by a forest manager or contractor. This planning will usually identify and mark the borders and main extraction trails or cable corridors, and is often carried out by visiting the harvesting site. Manual planning may be time consuming, and thus costly, but this cost is seldom discussed in the literature. Similarly, operational delays, their consequences and methods to reduce them are not usually considered. In practice, unpublished observations of cable yarding operations seem to indicate that delays due to difficult terrain may amount to days without productivity. For manual planning and operational delays, any tool that helps with planning may be useful.

4.1.3 Computers supporting humans, humans supporting computers

Applied operations research is often referred to as decision support. This name emphasizes the fact that computational solutions can support decision making and should be a guide for experts.

It is interesting to note that in most of the cited literature, the optimization relied on experts defining crucial input for the computer; e.g. candidate landings, mandatory road access points. This thesis has been guided by the hope of postponing and perhaps removing the need for expert input. Expert choices and expert data inputs were not needed as input to guide the algorithms in any of the papers of this thesis.

4.1.4 Wheel based systems

In this thesis the TTC for wheel based harvesting systems has been calculated using the network method described in Paper 1. Although Paper 1 is a discussion with just a few novel contributions, it may be the paper with the highest short term potential impact for research, public administration and the industry. The Matthews method is still the preferred method of calculating terrain transportation cost, and the analysis in the paper is an attempt to show that the network method provides a better model for describing real world terrain transportation.

For the Trail Location Problem (TLP) for HFS, a constructive heuristic was designed and developed to a metaheuristic in Paper 2. The problem formulation could be written

$$\max \quad \sum_i \sum_j U_i \left(\Pi - c_{ij} x_{ij}\right), \tag{4.1}$$

$$\text{s.t.} \quad x_{ij} \leq y_j\,, \quad \forall i, j\,, \tag{4.2}$$

$$\sum_j x_{ij} \leq 1\,, \quad \forall i\,. \tag{4.3}$$

where U_i is the timber volume at grid point i, Π is the timber price, c_{ij} is the unit cost of transporting timber from grid point i to road using trail j. There are no trail facility building costs in the formulation given by Equations (4.1)–(4.3). This is an inaccurate mathematical problem formulation for the TLP for HFS, as there are indirect costs of a trail layout. One such cost is that logs have to be stacked between the trails, possibly reducing the locations where a machine can drive. A non-monetary cost is the environmental impact of driving in the terrain. Another issue is that a forwarder can carry some 15 m^3 of wood, and will load logs from the area around the machine. It is faster and cheaper to move the crane than the machine. These issues could perhaps be addressed either by including an additional cost in the objective function or another constraint (e.g. a maximum trail length). However, in Paper 2 the solutions were directed towards a dispersed trail network by the constructive heuristic and the constructive metaheuristic. It would be interesting to explore those issues in a future project.

In Paper 3, the focus was not extraction trail location, but rather the profit of the modeled operation. To improve computation time and allow a larger area to be analyzed, the problem formulation was modified and solved by Dijkstra's shortest path algorithm (D-SPA), an exact solver. This method returned the optimal solution for the problem defined by Equations (4.1)–(4.3) without trail facility building cost. The result is a dense trail network, and although the dense trail layout can not be used for trail planning, the estimated forwarding cost is a lower bound for the forwarding cost. Parallel trails in the dense trail network as shown in Paper 3 have a TTC of similar magnitude, otherwise there would be more merging of trails. For some harvesting areas, the solution method used in Paper 3 can be used for generating main extraction trails and leaving the selection of smaller trails to the forest contractor.

Although the quality of the trail layout found in Paper 2 was not thoroughly analyzed, an upper bound for the net profit can be found by the solution method of Paper 3. Also, the shortest path solver is more promising for practical implementation in industry, due to the faster computation time.

Paper 3 could be developed to a RSP for retention patches and WKHs. WKHs were registered the past 15 years in Norway and a manual selection process was carried out. Such registrations and subsequent selections are a continuous process and in the future a multi-objective optimization approach based on Paper 3 may improve the selections, but this is going far beyond the intended scope of this thesis.

4.1.5 Cableway harvesting

The European Cableway Location Problem (E-CLP) was formulated to better describe cable yarding systems used in Europe. These systems often operate on existing road networks, and can use any part of a road as a landing. For this reason, road location and landing selection were not included in the model. This has the fortunate advantage of reduced problem complexity. Lateral yarding distance was included in the yarding cost calculations.

Cableways for European cable yarders are typically laid out in parallel along a forest road, and this was the basis for designing a greedy constructive heuristic for the E-CLP. By guiding the search towards a parallel pattern, the solutions were likely to be good. The greedy heuristic was also modified to a semi-greedy metaheuristic, and the two methods were compared. The greedy heuristic suggested solutions with net profit better than 96% of the solution found by the semi-greedy metaheuristic, and was much faster. The greedy heuristic may thus be preferred if computing time is essential, e.g. for industrial applications or for hierarchical problem formulations including other types of facilities such as landing selection and road network layouts.

The novel E-CLP and especially the landing assessment may be important for Norwegian cable yarding harvesting. Cable yarding harvesting in Norway is presently going through a revival, and any tools for reducing costs and delays will help contractors.

4.1.6 Implications for the forest sector

One implication of this work is that TTC-calculation by the network method gives better cost estimates than methods based on average skidding distance. Thus, the network method should be the preferred method for TTC-calculations in the industry, for the public administration and in research.

The presented methods for solving forest planning problems could also be very useful for agents in both the forest sector and the public administration. However, such agents will require that the planning software run quickly, and for this reason the fast solution methods presented in this thesis may be preferred.

There is one minor and two major issues that have to be resolved before the work presented in this thesis can be industrialized:

- A user friendly interface for the software must be designed.
- High resolution DTMs or data from airborne laser scannings in Norway must be readily available.
- Productivity studies in forestry are in general not reporting parameters and cost functions for high resolution optimization models. Such studies would make the results of optimization more reliable and less controversial.

4.2 Future work

This work was multidisciplinary, and the implications for further work are both multidisciplinary and for each discipline.

The improved remote sensing techniques enables DTMs and other maps with high resolution, and also detailed problem formulations. When the problem formulations change, the parameters and functions of the formulations also change, and this is not yet incorporated in forestry productivity studies. For wheel based harvesting, no productivity studies report how terrain driving speed is affected by micro terrain. There are more studies of cable yarding productivity, but some parameters used for optimizing cableway location are also missing or dubious. Few studies of yarding productivity report lateral yarding distance, and some studies have few observations. A cableway is rigged one or two times per week, making traditional time studies costly; Stampfer et al. (2006) seems to be the only such study in the literature. Rigging of support jacks are time consuming, but studies are not reported. Finally, landing usage costs are not reported in the literature.

There are also other input data that could be included in the models if the quality improved. One such example is soil data. The soil maps in Norway are not of high accuracy, and perhaps new remote sensing techniques can be developed to improve the maps. Such data could in turn be used for improving productivity models, as driving speed may vary depending on the soil.

The optimization models can also be developed further. A landing usage cost could be included in the E-CLP formulation, and all or some of the methods could be adjusted and included in a hierarchical road location problem.

The world is complex, and models of real world problems are simplifications. However, research and improved technology allows constant evolution of models. The models presented in this thesis are attempts to postpone or reduce the need for expert assessment, and this idea may be valuable to keep in mind for future research. Present forest operations research generally still relies on expert input early in the analysis.

The problems studied in this work are real world problems, and they are not well studied in research literature. The techniques used today for solving these types of problems can most likely be improved further. A problem repository should be set up to evaluate and compare solution methods across optimization in forestry, to help future research and development progress faster.

4.3 Conclusion

In conclusion, this thesis has demonstrated that optimization has the potential to improve the efficiency of forest logistics, and is a promising approach for future forest operations research. It fills some gaps in the literature by adapting and improving forest planning problems to Norwegian conditions, identifying new problems drawn from the real world, and showing that high resolution data from modern remote sensing techniques can be valuable input for forestry optimization models.

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Paper 1

Off road transportation cost calculations for ground based forest harvesting system

Off road transportation cost calculations for ground based forest harvesting systems

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Abstract

Ground based systems are the main approach used for off-road timber transportation throughout the world. Estimates of terrain transportation costs are required for several forest planning problems and for assessment of harvesting contracts and forest land values. Methods for these calculations can be categorized into two groups. Methods based on average transportation distance predate computers, are analytical, and based on manual calculations. Network methods are based on a digital raster representation and are solved with numerical computations. Here, the two categories are compared and linked. Analytical methods in the literature have been limited to flat terrain and including detail is difficult. The network method can be extended to include uneven terrain or detailed input data.

Keywords: terrain transportation, terrain transportation cost, forest planning, forest operations, harvesting.

1 Introduction

Ground based systems are the dominant systems used for off road timber transportation throughout the world, either using forwarders or skidders. A harvesting operation consists of several steps. The trees have to be felled, limbed, cross cut and transported to roadside. The terrain transportation cost (TTC) is a significant part of the total harvesting cost. However, there has not been much focus on the cost calculations of off road driving in the research lately. Such calculations are required for e.g. planning of forest operations, forest planning in general or environmental planning, but seldom discussed in detail. Computational power, remote sensing techniques and optimization techniques have significantly improved the past 25 years, and a revisiting of this topic seems appropriate.

The TTC can be calculated analytically or numerically. Early methods that predate computers are in general analytical and based on average skidding distance (ASD), sometimes

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referred to as average yarding distance. Although such ASD-methods also can be numerical, computers and numerical methods can handle more complex and detailed models. Such methods will in this work be referred to as the network method and are the main focus of this work, as ASD-methods have been discussed elsewhere (e.g. Sundberg and Silversides, 1988; Greulich, 2003). In a real world case there are several factors that may influence the TTC. Detours increasing the skidding distance may be necessary due to e.g. steep slopes, rock outcrops, soil types or environmental values. Varying volume density may also affect the actual average skidding distance. Another issue is that skidding time may be varying due to terrain and soil type. Nurminen et al. (2006) found driving speeds from $14.5m \cdot \text{min}^{-1}$ to $87.3m \cdot \text{min}^{-1}$ (loaded and empty), but did not relate this to terrain types. The ASD-method and the network method are compared and their limitations are analyzed in light of how they can be developed further.

A forest parcel is a forest area which is meaningful to consider as a whole. Reasons can be equal site index, uniform or uniformly aged forest or simply that the parcel is a suitable silvicultural or computational treatment unit. A forest parcel may thus be a stand, a forest compartment, a grid point (or mesh) or other units used in model formulations. It is noteworthy that e.g. a mathematical model in general will be valid for different sizes of forest parcels, but the parcel size has impact on how the model parameters should be calculated.

2 Early methods based on average skidding distance

The calculation of harvesting and forwarding costs in forestry literature has been limited by the technology and techniques of each era. Advances in maps and surveying techniques, and in software and hardware have improved calculations. Early approaches predate computers and were designed for calculation by humans. Greulich (2003) describes some of the early literature refering to the ASD.

Matthews (1942) treats ASD-estimates analytically. His work is a commonly cited reference for harvesting cost calculations. It describes cost calculations and optimization for varying cases (e.g. skidding and yarding, uphill and downhill, different road and landing layouts) and problems (e.g. road and landing location, choice of equipment). In this paper the focus is on TTC, and the method for calculating TTC described by Matthews (1942) will be referred to as the Matthew's method. The Matthew's method is simple in the sense that it is designed for hand calculations and relies on the geometric shape of the forest parcel under consideration. The mean unit TTC for a parcel, $\bar{c}$, is given by

$$\bar{c} = c_d d_c, \tag{1}$$

where c_d is the mean unit distance dependent cost and d_c is Matthew's estimate of the ASD. The calculations of d_c vary according to the assumptions made. If all the wood is assumed to be transported to one landing, $d_c = d(x_c, y_c)$ where the function $d(x, y) = \sqrt{(x - x_l)^2 + (y - y_l)^2}$ is the distance from (x, y) to a landing (x_l, y_l). If continuous landings are used, d_c is found by dividing the parcel in smaller parts according to the shape of the parcel.

Suddarth and Herrick (1964) derived another estimate of ASD by integrating the function $d(x,y)$ across the parcel. If A_p is the area of the parcel p, the ASD is given by

$$\text{ASD} = \frac{1}{A_p} \iint_p d(x,y)\,\mathrm{d}A. \tag{2}$$

The ASD is in general not the same as the d_c in Equation (1). By replacing d_c in Equation (1) with the ASD, $\bar{c}$ is given by

$$\bar{c} = c_d \cdot \text{ASD}. \tag{3}$$

The total TTC of harvesting a parcel is

$$c = \bar{c} \cdot V, \tag{4}$$

where V is the timber volume of the parcel.

The integral in Equation (2) can be formulated for any parcel shape. Analytical solutions have been reported for some shapes (e.g. Suddarth and Herrick, 1964; Peters, 1978), but the derivations are in general cumbersome or lengthy or both. Equation (2) has also been further extended for side slope (Greulich, 1980, 1987, 1989), for rectilinear thinnings (Greulich, 1994a) and continuous landings (Greulich, 1994b,c). The basis for TTC in the above references is Equation (3). Greulich (1991) modified the TTC by replacing Equation (3) with

$$\bar{c} = \beta_0 + \beta_1 \text{ASD} + \beta_2 \text{ASD}^2. \tag{5}$$

The right hand side of Equation (5) is a truncated power series, and this Equation is addressing the fact that the ASD-method assumes that TTC is a linear function of ASD. This assumption may be too simple, and earlier attempts has been made to correct the TTC found by only considering distance to landings. An extraction trail rarely follows the straight line to a landing, and throughout the forestry literature a wander factor (w) has been used for correcting the relation between TTC and ASD. Although von Segebaden (1964) included the wander factor and is frequently credited the invention, the concept was mentioned earlier by Hughes (1930). Usually, it is assumed that the harvest area is divided in parcels with uniform wander factor.

3 The network method

Whereas early attempts of modeling terrain transportation and harvesting operations were analytical and based on hand calculations, a more recent approach is based on discrete mathematics. Tan (1992) assumed that the terrain could be modeled as a network of grid points. Instead of calculating the ASD of each grid point (the ASD-method), the wood is assumed to be transported to one of the neighboring grid points and recursively through grid point until a landing is reached. There is a large number of possible paths between two grid points, but finding the cheapest one is referred to as the shortest path problem.

More precisely, the problem can be defined as follows. Let the terrain be given by a weighted graph $G = (V, E)$, where each vertex (grid point) $v_i \in V$ represents a point in the terrain. The edges E link each vertex with its neighbors, and the unit cost of transport between the neighbors v_i and v_j is $c(v_i, v_j)$. A path from vertex v_0 to vertex v_n is given by $p = \langle v_0, v_1, \dots, v_n \rangle$, and the unit cost of transporting timber on this path is the sum of its constituent edges, given by Equation (6).

$$c(p) = \sum_{i=1}^{n} c(v_{i-1}, v_i) \tag{6}$$

The mean unit TTC of grid point v_i can be found by minimizing Equation (7), i.e. the shortest/cheapest path from v_i to a vertex v_0 that is a landing.

$$c_j = \begin{cases} \min\left\{c(p) : v_j \overset{p}{\rightsquigarrow} v_0\right\} & \text{if there is a path from } v_j \text{ to } v_0 \\ \infty & \text{otherwise} \end{cases} \tag{7}$$

This problem formulation can be solved fast by standard combinatorial mathematics (e.g. by Dijkstra's shortest path algorithm (Dijkstra, 1959)).

The total TTC of harvesting a parcel is given by

$$c = \sum_{j} V_j c_j, \tag{8}$$

where V_i is the timber volume at grid point i. There are some studies in the literature using the shortest path formulation given by Equation (6)–(7). Although the method is largely the same, there are some variations of how the cost $c(v_i, v_j)$ of transport to a neighbor (Equation (6)) is calculated. Tan (1992) calculated the cost as a function of distance and terrain class. Contreras and Chung (2007) used a skidding cost derived from the regression model by Han and Renzie (2005), including distance and slope gradient uphill or downhill. In a more recent paper, Contreras and Chung (2011) refined the skidding model to also include a maximum roll limit. Chung et al. (2008) used a cost based on distance. Søvde et al. (2013) used a cost based on distance and penalties for roll and pitch.

One advantage of the network method is that as long as the distance between neighboring grid points is small, there is no need for introducing a wander factor.

4 Discussion

Although the network method has been in use for more than 20 years, the method has not been analyzed in depth. The topics of the cited literature are: road planning (Tan, 1992; Chung et al., 2008), landing location (Contreras and Chung, 2007) and extraction trail layout (Contreras and Chung, 2011; Søvde et al., 2013). As the calculation of TTC is only a part of the studied problems, the network method is not discussed much.

4.1 The impact of uneven terrain

Let $f(x, y)$ be a function of the TTC per area, incorporating all the irregularities that may influence the TTC and also the timber volume. Without loss of generality, the parcel p is assumed to be rectangular. The parcel can be partitioned into $n \times m$ sub-rectangles in the

x and y direction. The TTC of a parcel is given by the sum of the cost of harvesting each sub-rectangle,

$$\hat{c} = \sum_{k=1}^{n} \sum_{l=1}^{m} f(x_k^*, y_l^*) \Delta A, \tag{9}$$

where (x^*, y^*) is the center point of each sub-rectangle. By increasing the number of sub-rectangles, the double sum approaches the integral.

$$\begin{aligned} c &= \lim_{n,m \to \infty} \sum_{k=1}^{n} \sum_{l=1}^{m} f(x_k^*, y_l^*) \Delta A && (10) \\ &= \iint_p f(x,y) \, \mathrm{d}A && (11) \end{aligned}$$

Equation (4) follows directly from Equation (11) if $f(x,y) = V \cdot c_d / A_p \cdot d(x,y)$. Finding the analytical function $f(x,y)$ is not straightforward. The timber from a point (x,y) can be transported along many extraction trails, maybe also to different landings. One possibility is that the value of $f(x,y)$ is the cost of using the cheapest extraction trail to the point (x,y). The ASD-method assumes that the skidding distance is the straight line to a landing. If there are obstacles, and the trail follows a known curve $(x(t), y(t))$, the length of the curve can be found by integrating along the curve. Also, finding the shortest curve of all the possible extraction trail curves is possible. However, if the driving speed varies, the problem of finding the fastest path turns into *the problem of the brachistochrone*, a more difficult problem of variational calculus. The interested reader may find more details in Troutman (1996). Whether the integral in Equation (11) can be solved easily is a matter of the function $f(x,y)$ and the shape of the parcel.

Equation (7) is the same as Equation (9) if the sums and indices are rearranged and $f(x_k^*, y_l^*) = c_j$. If c_j in Equation (7) is a good estimate of $f(x,y)$, the problem of finding the TTC in uneven terrain can readily be solved with the network method.

4.2 Input data

A model formulation or a method such as the ASD-method or the network method relies on the input data. There are numerous ground based harvesting systems operating around the world and the productivity varies. Traditionally, productivity studies in forestry are based on time studies. A harvesting operation is observed and the operation at hand is partitioned into part operations. Typically, the harvesting operation is repetitive and the data is analyzed as cycles. Time studies are time consuming and has some limitations, though. There is a limit to how much information a person can register, as well as to how detailed the data can be. Although data such as position or terrain can be registered or maybe assessed afterwards, a study relies on the predefined areas of interest. Recent productivity studies of terrain transport (e.g. Han and Renzie, 2005; Nurminen et al., 2006) still report cycle times. Such data are suitable for the ASD-method, but not directly applicable for the network method. Cycle times are average values where the observed distances are larger than the raster size used in some of the later publications using the network method and the estimates of driving speed may be smoothed.

An interesting question is whether c_j in Equation (7) is a good estimate of $f(x,y)$. This is in fact an open research question. Neither Contreras and Chung (2011) nor Søvde et al.

(2013) found studies on how driving speed is affected by the micro terrain. Hopefully, such studies will appear soon. Sensors (e.g. accelerometers, gyros and gps) are available at budget prices, and high accuracy DTMs and inventories are widely used in forestry. Some other data that may influence the TTC (e.g. soil data) is not available at the same level of accuracy, but nevertheless, the prospects for future improvements are good.

5 Conclusion

The ASD-method predates computers and was designed for hand calculations. The method often yields lengthy derivations (e.g. Greulich, 1989) and adaptations according to landing layout and parcel shape. Improving the method to include uneven terrain may be difficult or impossible in practice, at least there seems to be no attempts at this in the literature. However, there are reasons for still using the ASD-method. Most of the productivity studies in the literature are reporting cycle times, suitable for the ASD-method. Also, the method can be used by forest managers, forest owner or contractors when estimating harvesting costs or negotiating contracts. Ironically, the average skidding or forwarding distance in such cases will probably be estimated using Matthews' method.

The network method is a promising method for the calculation of TTC. It is easy to implement and different parcel shapes can readily be calculated. In addition, the method is more flexible than the ASD-method. More complex TTC-functions $f(x, y)$ in Equation (11) can be handled without affecting the computation time much. Unfortunately, studies correlating driving speed with e.g. micro topography and detailed inventories are lacking in the literature.

The network method is a more promising method than the ASD-method. However, one of the disadvantages of the ASD-method is cumbersome integral calculations. Such integrals can be estimated numerically (i.e. by Equation (9) on a grid of the parcel). This approach was suggested by Suddarth and Herrick (1964), who also found that dividing the parcel in eight parts yielded estimates deviating less than 1% from the ASD. Future productivity studies can perhaps determin which method is most effective.

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Paper 2

Applicability of the GRASP metaheuristic method in designing machine trail layout

Applicability of the GRASP metaheuristic method in designing machine trail layout[*]

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Abstract

The ground based harvesting system consisting of a harvester and a forwarder is the dominant harvesting system in parts of the world, due to its high productivity. Both machines usually operate along extraction trails, and are equipped with cranes that can reach some distance from the extraction trail. In this work we optimize the layout of an extraction trail network by considering how terrain topography influences the cost of forwarding.

Given the complexity of finding optimal machine trails for terrain transportation, traditional optimization methods might be limited due to the problem size. In this study, the optimization is done with a greedy constructive heuristic and a Greedy Randomized Adaptive Search Procedure (GRASP) metaheuristic, and the results of the two solution techniques are compared. Both the greedy heuristic and the GRASP metaheuristic were examined for a semi-random terrain and a smooth cone-shaped terrain, and provided useable extraction trail layouts in terms of how a forest machine operates on slopes.

The objective value of the solution found by the GRASP metaheuristic was 5.6% better than the greedy heuristic in the semi-random terrain, and 2.3% better in the cone-shaped terrain. The result of this study showed that the GRASP meta-heuristic is useful for finding feasible routes in the terrain, increasing efficiency.

The method could be useful for planning feasible routes in the terrain, thereby increasing efficiency, or for acquiring a better estimate of the cost of terrain transport in price setting.

Keywords: forwarding, GRASP, harvesting, metaheuristic, transportation.

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1 Introduction

The planning of access trails for ground based harvesting operations receives little concern in forestry planning. Sometimes the access trails are manually planned by a forester, but the location of forest machine trails are usually decided by the machine operator, often in an ad hoc fashion. The reasons may be that forestry planning traditionally is a labour intensive task, requiring field work to make good plans, and that the forest machine operators do a satisfactory job at no extra cost.

There are several issues for planning of access trails for harvesting. First, the introduction of high accuracy airborne laser scanning may give more precise data than traditional forest operations management tools (Krogstad and Schiess, 2004), and at a lower cost.

Also, a forest operation has economic, environmental and social impacts. The evaluation of these impacts is often a complex task, and is prone to be subjective and random. Modern optimization techniques could handle this task in a more rational manner.

In addition, the profit of the operation may increase by using optimization techniques to make the harvesting more efficient, and a machine operator could benefit from having a draft plan suggested from terrain data that is difficult to assess behind standing trees.

This study focuses on optimization of the location of extraction trails made and used by a harvester and a forwarder, primarily considering terrain accessibility constraints. It thereby differs from optimal machine trail layout work by e.g. Shishiuchi (1993) and Akay et al. (2007), which are based on a number of assumptions including flat or uniform terrain, and parallel and evenly spaced roads. If the terrain is more difficult, forest operations requires planning tools that can evaluate the degree of accessibility to ground based harvesting systems.

When optimizing real world problems, the choice of model will depend on the objective, as well as available input data and computational resources. The model will be a simplification of the real world. Martell et al. (1998) give a review on forest management challenges, and classify optimization problems as strategic, tactical or operational, depending on level of aggregation and planning horizon. The problem we are addressing is that of finding the location of a machine trail network, from which the crane of a harvester or forwarder can reach any tree. This optimization problem is an operational problem, and could be called the Trail Location Problem (TLP).

Traditionally, planning of forest extraction trails is done using a trail density formulation (e.g. Peters, 1978; Shishiuchi, 1993; Heinimann, 1998), or on stand level (e.g. Church et al., 1998; Baskent and Keles, 2005). Optimization of extraction trail layout necessarily requires a stand level model. Although an optimization model designed for forest level could be used on a finer scale, the model presumably will have to be modified or tuned. In particular, parameters of the model must be supplied. In our case, the crucial parameter is the cost of forwarding. In the literature, early models using trail density linked skidding distance to productivity, possibly using corrections for difficult terrain or wandering (e.g. von Segebaden, 1964; Fjeld et al., 2000). Another approach is to time study forwarder operations and develop a regression model for the time consumption or cost (e.g. Han and Renzie, 2005; Nurminen et al., 2006). However, studies correlating a high accuracy digital terrain model with forwarder productivity seem to be lacking in the literature. Analytical models for the static stability of forwarders on slopes are well developed (Hunter, 1993). A forest machine can handle steeper slopes in the driving direction (pitch) than slopes perpendicular to the driving direction (roll), but the machine overturn angles vary with load and steering angle (Hunter, 1993; Frønsdal, 1985).

A real world terrain is a continuous surface, and there are an infinite number of extraction trail layouts that will cover the area. A discrete subset is used in a computerized model of the terrain, which reduce the number of possible solutions. However, the number of possible layouts is still exponential, and at some problem size, exact solution methods will be intractable by computers (Garey and Johnson, 1979). One way of optimizing such difficult problems is to use a heuristic or metaheuristic.

To our knowledge, there are few studies in the literature about the trail location problem. Contreras and Chung (2007) use Dijkstra's shortest path algorithm (D-SPA) (Dijkstra, 1959) to calculate the terrain transportation cost to a landing within the forest compartment, and then D-SPA to find the cheapest road from there to existing road. This procedure is repeated for each vertex of the forest compartment. They use a grid with the resolution of both $10m \times 10m$ and $1m \times 1m$, and their skidding cost is derived from the regression model developed by Han and Renzie (2005).

However, the trail location problem is similar to the forest road location problem (FRLP). The main difference between trail and road layout is that a road segment has some construction cost, a trail segment does not. Also, adaptations made in the literature usually give a different formulation of the FRLP. In particular, one adaptation is to optimize the road location from some n mandatory access points to existing roads. Dean (1997) called this problem the multiple target access problem (MTAP). Dean (1997) also described the single target access problem (STAP), where one vertex ought to be connected. The latter problem can be solved using Dijkstra's shortest path algorithm, and utilized in a heuristic to find a solution for the FRLP. Tan (1992, 1999) iteratively calculated the cost and benefit of a road from each vertex to an existing road using D-SPA, and connected the road with the best ratio until the cost was higher than the benefit.

Anderson and Nelson (2004) generated a set of landings randomly, corresponding to different maximum skidding distances, and used D-SPA to connect each landing sequentially.

The goal of this study is to optimize the layout of extraction trails for a forwarder. We compare a greedy heuristic with the well tested metaheuristic Greedy Randomized Adaptive Search Procedure (GRASP) (Feo and Resende, 1995). In order to achieve this goal, we introduce a novel way of calculating terrain transportation cost.

2 Materials and Methods

We present a constructive, greedy heuristic model that iteratively adds a short trail segment to existing machine trails and forest roads. This greedy heuristic model is subsequently slightly modified to utilize the metaheuristic Greedy Randomized Adaptive Search Procedure.

In the model, a forest road is assumed to be a permanent and maintained road that can be accessed by a timber truck. A machine trail is a path in the terrain topography suitable for driving with a harvester or forwarder fitted with a crane that can reach an area surrounding the machine. From a forest operations perspective, terrain is generally classified according to three main categories: steepness, roughness and bearing capacity (Berg, 1992). In this study, the focus is how the terrain topography affects forwarding cost, and only steepness and surface roughness are considered.

The terrain is represented by a square grid of vertices with a resolution of $1m \times 1m$. Each grid point has some constants and variables associated with it, as listed in Table 1. Timber at vertices within a given reach of trail vertices can be felled, processed and stacked by a harvester on the machine trails, and then forwarded to the roadside. The forwarder is assumed to use the same machine trails as the harvester.

Table 1: Data representation for vertices

Element	Type	Description
`elevation`	Constant	Height above sea level
`volume`	Constant	Volume of timber harvestable from vertex
`isroad`	Constant	True if vertex is on a road
`x_pos, y_pos`	Constant	Geographic coordinates
`istrail`	Variable	True if vertex is part of an extraction trail
`tt_cost`	Variable	Cost of terrain transport from this trail vertex to road
`covered_by_list`	Variable	Vector of vertices that are road or trail from which this vertex can be reached with a machine's crane

In representing the terrain by a regularly spaced grid, this grid is a network $N = (V, E, w)$ where V is the set of vertices, E the set of edges and w is the costs of transportation along the edges E. The trail location problem is to find a set of vertices V from which harvesters and forwarders can obtain the economically viable timber at minimum cost, and connect the vertices to existing roads. This problem is similar to the Steiner Minimal Tree Problem (SMTP), a known NP-hard problem (Promel and Steger, 2002). The class of NP-hard optimization problems consists of problems that are difficult to solve in the sense that there is no known solution method that can solve large problems to optimality. For such problems, heuristics or metaheuristics are commonly used when trying to solve large problems.

The main concern in this work is to use numerical calculations to evaluate where we can operate a forest machine, and generate a near optimal extraction trail plan automatically. To do this, we calculate pitch and roll, and use this to penalize a trail segment if the terrain is steep. Pitch is the inclination in the driving direction, whereas roll is the inclination perpendicular to the driving direction.

2.1 Objective function and calculation of distance dependent forwarding cost

We use the net profit of the operation as an objective function, f, to be maximised, given by Equation (1).

$$f = \sum_i V_i \left(\Pi - (C_h + C_f + C_i)\right) \tag{1}$$

The net profit is the sum of net profit of all grid points, i.e. timber revenue Π [$\$m^{-3}$] (at roadside) minus harvesting and forwarding costs, multiplied by the timber volume V_i [m^3] at grid point i. C_h [$\$m^{-3}$] is the cost of felling, delimbing and cross cutting, while C_f [$\$m^{-3}$] is the part of the forwarding cost that is independent of transportation distance (i.e. loading and unloading). C_i [$\$m^{-3}$] is the variable cost of forwarding timber from grid point i to roadside, and is given by the cheapest terrain transportation cost of any trail vertex within crane reach of the vertex i.

The terrain transportation cost of a vertex B is found by Equation (2), where C_B [$\$m^{-3}$] is the terrain transportation cost of vertex B and C_A [$\$m^{-3}$] is the terrain transportation cost of the vertex A, the vertex that is closer to the forest road. If vertex A is a forest road, the terrain transportation cost is equal to zero. C_{AB} [$\$m^{-3}$] is the cost of driving from vertex A to vertex B.

$$C_B = C_A + C_{AB} \tag{2}$$

The cost C_{AB} [$\$m^{-3}$] of forwarding from B to A along an extraction trail is calculated using Equation (3).

$$C_{AB} = C_0 d_{AB} P_r P_p \tag{3}$$

C_0 [$\$m^{-4}$] is the cost of transportation per m^3 per m traveled in flat terrain. This longitudinal method of representing the transportation cost ($\$m^{-4}$) avoids the need to build or monitor discrete forwarder loads. The parameter d_{AB} [m] is the distance from A to B. P_r is a penalty factor for roll, calculated using Equations (4) - (5), and P_p is a penalty factor for pitch, calculated using Equations (6) - (7)

$$P_r = 1 + (10r)^4 \tag{4}$$

$$r = \frac{|e_l - e_r|}{d_{lr}} \tag{5}$$

$$P_p = 1 + (2p)^4 \tag{6}$$

$$p = \frac{|e_A - e_B|}{d_{AB}} \tag{7}$$

The pitch p when going from A to B, given by Equation (7), is the inclination (in percent) of the terrain in the driving direction. e_A [m] and e_B [m] are the terrain elevation at A and B, and d_{AB} [m] is the distance between the points. The roll, given by Equation (5), is the inclination between a vertex l to the left and a vertex r to the right. e_l [m] is the elevation at the left vertex, and e_r [m] is the terrain elevation at the right vertex. d_{lr} [m] is the distance between the vertices. These vertices are selected differently depending on the driving direction. If we go from vertex A to vertex D in Figure 1, the left vertex is vertex C and the right vertex is B.

The penalty factors P_r and P_p, Equations (4) and (6), respectively, are close to one if the terrain is flat, but grow rapidly if the terrain is steep. The penalty factors were selected in

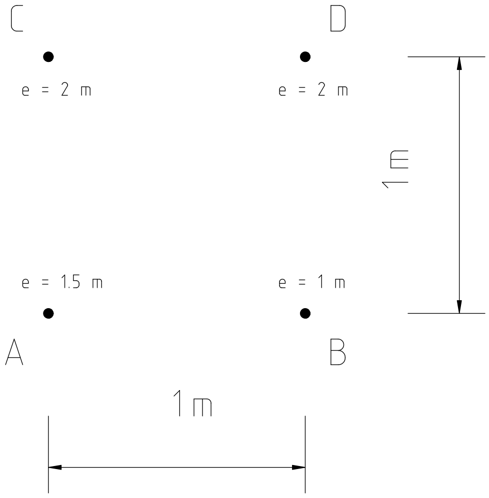


Figure 1: Illustration of the calculation of terrain dependent forwarding cost, e is the elevation.

this way because machine overturn angles and wheel slip angles vary with speed, steering angle and load (Frønsdal, 1985; Ringdahl et al., 2012). Roll is penalized more than pitch, as a forest machine can handle pitch better, and machine overturn is considered more severe than wheel slip. Also, the wheelbase of a forest machine is several times the grid spacing of $1m$, and the machine can handle very high inclination for shorter distances. The width of a forest machine is closer to the distance used in Equation (7).

2.2 Adding new trail segments with the greedy heuristic

The greedy, constructive heuristic (Heuristic 1) starts with an empty plan except for the existing roads. When considering which new trail segments to add, the number of possible trail segments is large. To reduce the computation time, we only consider front vertices consisting of the region beyond the set of vertices that are covered by existing roads or the already selected trails. For each of the vertices in the front, we use Dijkstra's shortest path algorithm (Dijkstra, 1959) to find the shortest path to an existing trail or road, and then we calculate the change in objective value. For the greedy, constructive heuristic, we select the front vertex that gives the largest increase in objective value.

Heuristic 1 The greedy constructive heuristic

```
Initialize the terrain, roads and other data.
Initialize the area covered by the road.
Initialize the front.
repeat
    Select best trail from road or trail to a front vertice, and calculate the change in objective value $\Delta f$.
    if $\Delta f > 0$ then
        Add trail segment
    end if
until $\Delta f \leq 0$
```

2.3 Adding new trail segments with the GRASP metaheuristic

The metaheuristic Greedy Randomized Adaptive Search Procedure (GRASP technique) is an efficient constructive metaheuristic, first presented by Feo and Resende (1989). Heuristic 1 was modified to a GRASP metaheuristic (Metaheuristic 1). When selecting a trail segment to add, instead of choosing the one that yields the best increase in objective value, we randomly select a segment from the best p percent segments that give positive increases in the objective value. This procedure is, as in the constructive heuristic, repeated until the selected segment yields a decrease in objective value, which means that adding more trail segments is not profitable. The resulting solution is saved, and the overall procedure is repeated. Each repetition is called a GRASP iteration.

Metaheuristic 1 The constructive metaheuristic using GRASP

```
Initialize the terrain, roads and other data.
Initialize the area covered by the road.
Initialize the front.
for $i = 1$ to number of iterations do
  Reset solution
  repeat
    Select one of the $p$ percent best trail segments, requiring that $\Delta f > 0$, from road or
    trail to a front vertice.
    if Trail found then
      Add trail segment
    end if
  until No trail with $\Delta f > 0$ found.
  Save solution
end for
return solution with best objective value
```

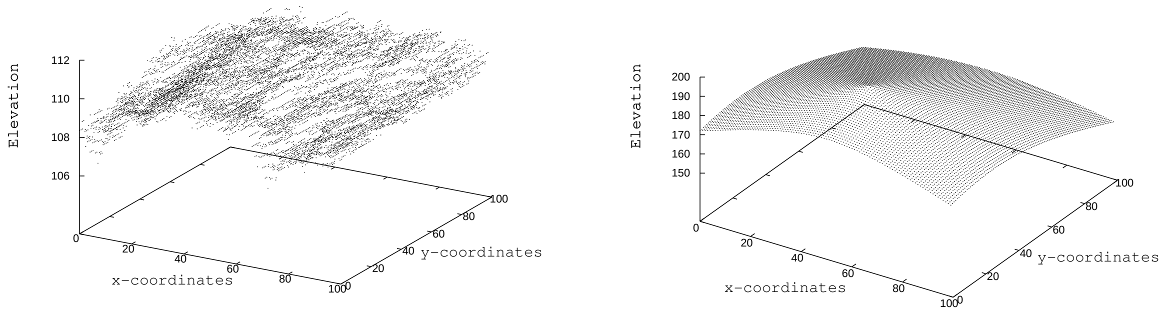
The greedy solution is often reasonably good, whereas the values from GRASP runs with a percentage p will have some better and some worse solutions. Typically, increasing p will improve the best solution up to a point, after which the best solutions will begin to degrade (Resende and Ribeiro, 2003).

2.4 Test cases

The two methods were tested using digital terrain models (DTM) for two different terrains. Each DTM data consists of 100×100 grid points with $1m$ distance between the points. Terrain 1, shown in Figure 2(a), is semi random. Each vertex was given a random elevation between $100m$ and $120m$. The elevation was then smoothed to have a maximum elevation difference of $0.5m$ between neighboring vertices.

Terrain 2, shown in Figure 2(b), is a smoothed cone with a peak at $200m$ and the lowest point at $155m$. The reason for using generated DTMs and not real world DTMs, was to ensure that the generated terrain was suitable for evaluating the influence of roll and pitch.

For each terrain, we generated a road by starting in the south-west and selecting the north, north-east or east vertex that gave the lowest inclination.



(a) The randomly generated DTM (Terrain 1). (b) The smoothed conical DTM (Terrain 2).

Figure 2: Plot of the DTMs used in the test cases.

The crane reach of the machines was set at $5m$ and the timber price on roadside was $\$54.55m^{-3}$ (exchange rate at 5.5NOK to $\$1$). The cost of felling, delimbing and cross cutting, C_h, was $\$7.27m^{-3}$ (hourly cost $\$181.8h^{-1}$, productivity $25m^3h^{-1}$) and the loading and unloading cost of forwarding, C_f was $\$1.82m^{-3}$ (hourly cost $\$94.5h^{-1}$, loading and unloading $13m^3$ in 15 minutes). The cost of driving in flat terrain, C_0, was $\$0.011m^{-4}$ (hourly cost $\$94.5h^{-1}$, productivity (less loading and unloading) $17m^3h^{-1}$ when driving $500m$ back and forth). The timber volume was generated randomly from a uniform distribution ranging from $100m^3$ to $300m^3$ per hectare.

For both terrains, the GRASP metaheuristic was run with 100 iterations for 10 GRASP percentage values between 5% and 50%. All the other parameters remained the same as those used in the greedy heuristic. The best GRASP percentage was 5% in both terrains, and this value was used for another 900 iterations, giving a total of 1000 GRASP iterations.

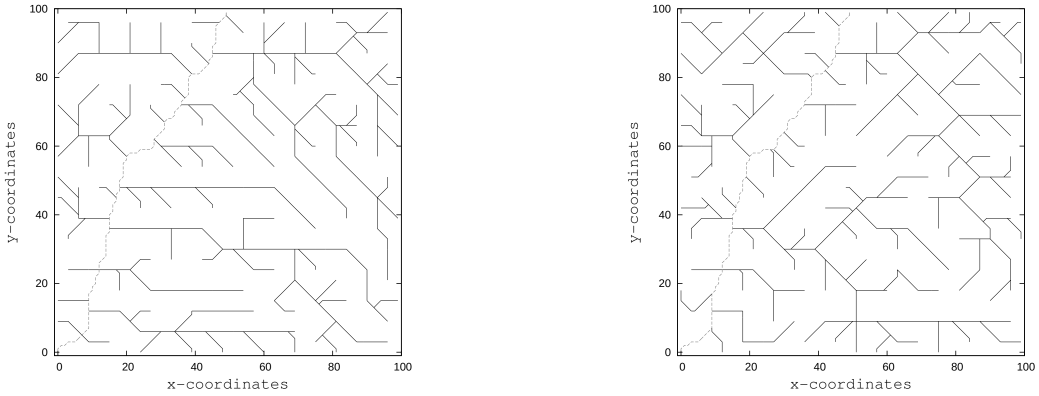
The method was implemented in C++. The computer and software used was a Dell Precision 6400 laptop, the GNU Compiler Collection and Opensuse 11.2.

3 Results

3.1 Solution for Terrain 1

The greedy heuristic found a solution for Terrain 1 in 251 seconds, with an objective value of $\$7,656$, a total extraction trail length of $1,313m$ and a total volume that could be harvested of $196.3m^3$. The weighted mean cost of forwarding (less loading and unloading) was $\$7.17m^{-3}$. The resulting trail layout is shown in Figure 3(a). We can see that the greedy heuristic gave relatively long and straight extraction trails, with shorter branches, compared to those of the GRASP metaheuristic.

The best solution found by the GRASP metaheuristic had an objective value of $\$8,085$, a total machine trail length of $1,327m$ and a total volume that could be harvested of $195.8m^3$. This solution is plotted in Figure 3(b). Compared to Figure 3(a), the trail lay-



(a) Trail solution for greedy heuristic.

(b) Trail solution for GRASP metaheuristic.

Figure 3: Trail solutions for Terrain 1. The winding curve represents the existing forest road.

out of the greedy solution, the machine trails now form a tree with more randomly sized branches.

For the best GRASP solution in Terrain 1, the variable cost of terrain transportation ranges from 0 to $\$22m^{-3}$. The weighted mean cost was $\$5.03m^{-3}$ (Figure 4).

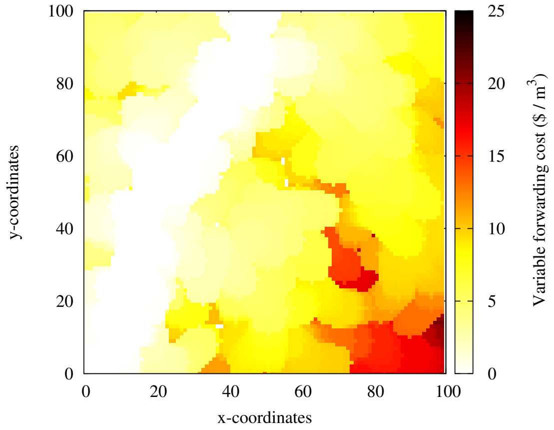
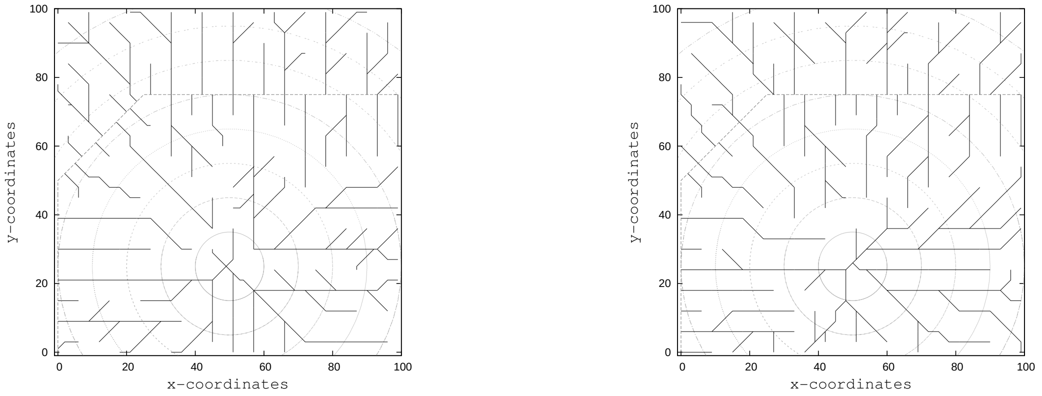


Figure 4: Variable cost of terrain transportation, Terrain 1.

3.2 Solution for Terrain 2

The solution obtained with the greedy heuristic for Terrain 2 was found in 262 seconds, with an objective value of $\$7,720$, a total extraction trail length of $1,346m$ and a total volume that could be harvested of $197.1m^3$. The weighted mean variable forwarding cost of the greedy solution was $\$6.90m^{-3}$. The resulting trail layout for Terrain 2 is shown in Figure 5(a). Also this time, we can see that the greedy heuristic gave relatively long and straight machine trails, with shorter branches, compared to those of the GRASP metaheuristic.

The best solution found by the GRASP metaheuristic had an objective value of $\$7,901$, a total machine trail length of $1,342m$ and a total harvesting volume of $196.7m^3$ (fig. 5(b)). Contrary to Terrain 1, there is no obvious difference between the GRASP solution and the greedy solution shown in Figure 5(a). However, the best solution consists of a large



(a) Trail solution for greedy heuristic.

(b) Trail solution for GRASP metaheuristic.

Figure 5: Trail solutions for Terrain 2. The forest road is represented by straight lines.

branch collecting timber around the hilltop, and shorter extraction trails covering the rest of the area.

We also plotted the corresponding variable terrain transportation cost, shown in Figure 6. The cost ranges from 0 to $\$45.45m^{-3}$. However, the weighted mean cost is $\$5.97m^{-3}$, as most of the terrain has a terrain transportation cost in the same range as Terrain 1, except for a small area with higher cost.

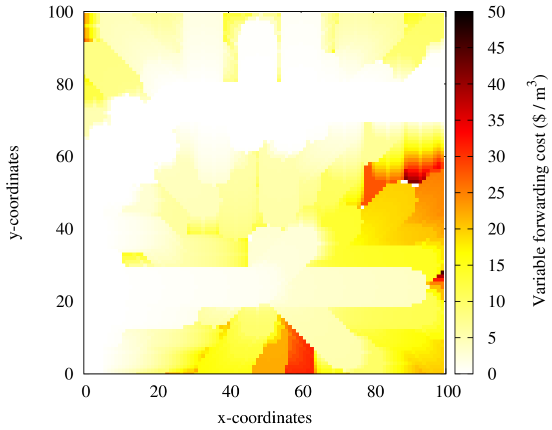


Figure 6: Variable cost of terrain transportation, Terrain 2.

4 Discussion

In this work, we applied a greedy heuristic and the GRASP metaheuristic to optimize the layout of extraction trails. The two methods were tested on two terrains. For Terrain 1, the solution found by the greedy heuristic gave a net profit of $\$7,656$. The GRASP metaheuristic improved the net profit by 5.6%, resulting in an objective value of $\$8,085$. If we consider the improvement of the variable forwarding cost, the improvement was from $\$7.17m^{-3}$ to $\$5.03m^{-3}$, a decrease of 30%. For Terrain 2, the improvement of the net profit was from $\$7,720$ to $\$7,901$, an improvement of 2.3%. The improvement of the variable forwarding cost was from $\$6.90m^{-3}$ to $\$5.97m^{-3}$, a 13% decrease. The lower improvement in Terrain 2 is to be expected, as the terrain is more regular.

Even though the net profit is maximized, keeping timber price, harvesting cost and forwarder loading and unloading cost constant make the optimization a minimization of the variable forwarding cost with a constraint that only economically viable timber is harvested.

Keeping timber price, harvesting cost and forwarder loading and unloading cost fixed is a simplification that reduces the impact of volume distribution. Trail segments into areas with higher timber volumes will have a higher possible increase in net profit, and higher probability of being selected by GRASP. However, as long as the trail segment can increase the net profit, the area will eventually be covered.

The greedy solution, shown in Figures 3(a) and 5(a), has relatively long and straight machine trails, whereas the GRASP solution, shown in Figures 3(b) and 5(b), consists of more dispersed and shorter trail segments. This difference is due to the implementation of the neighborhood for the greedy heuristic. When we evaluate a trail segment to add, the end of an existing trail will be where a new trail segment covers the most unreached vertices. As long as the terrain transportation cost of the existing trail is low compared to the alternatives, the new addition will improve the objective value the most. It is interesting to note that this may be close to how an operator of forest machines will try to make the harvest efficient, but it does not necessarily yield the optimal solution.

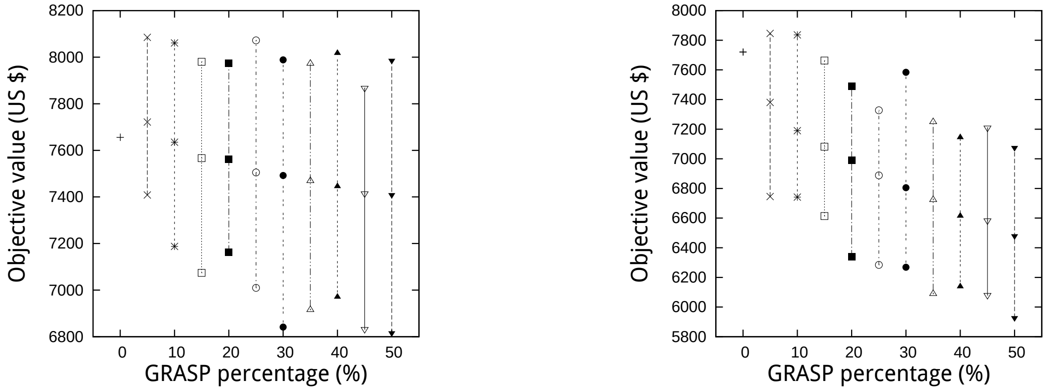
The GRASP metaheuristic, on the other hand, introduces more diversification in where the extraction trails grow, resulting in more balance between the different trail segments. The heuristics provide both a linear (trail) and surface (vertices covered) solution. As such it could be used to make an initial allocation of the area to ground based or aerial harvesting systems, which is a critical decision in road network planning (Heinimann, 1998).

In this work, we use a crane reach of only $5m$. This is a compromise between keeping the computing times low by using a small map, and reducing possible border problems (Peters and Nieuwenhuis, 1990). Swing to tree harvesters generally have a working swath radius in clearfelling of 7-8m and a maximum reach of $10m$. The shorter crane reach doubles the machine trail length. Compensating for that, our findings closely resemble those of Bettinger et al. (1994) who found that 23.5% of the site was occupied by logging trails.

One of the aims of this study was to investigate terrain accessibility constraints of forest machines. The trail layout for Terrain 2 (Figure 5) seem to be reasonable in terms of orientation to the slope, where the machine trails are close to perpendicular to the contour curves. This corresponds well with the fact that a forest machines overturning is more severe than wheels slipping.

A useful secondary result of our optimization is that our cost calculations yield a detailed estimate of the harvesting cost, which can be valuable for a contractor or forest owner when considering where to harvest. Although the parameters in the cost function have to be refined to reflect real forwarding operations, our parameter values gave a noteworthy difference even in our small map of $100m \times 100m$ (Figures 4 and 6).

The optimization with different values for the GRASP percentage gave results shown in Figure 7. The results are consistent with what we would expect from the literature, the greedy solution is adequate, but the GRASP heuristic yields some better solutions (Feo and Resende, 1989). The best GRASP value was found to be 5% for both terrains, and for Terrain 1, this GRASP percentage also gave an average objective value better than the greedy solver.



(a) Terrain 1.

(b) Terrain 2.

Figure 7: Identifying the best GRASP percentage (p) between 0 and 50%. Each vertical line represents mean, minimum and maximum values for 100 runs.

The time consumption of the solver is not excessive, although we would like to use larger maps and extend the model. There are faster computers available at budget prices, and the computer program can be parallelized and probably tuned for better performance.

4.1 Conclusion

We found that the GRASP metaheuristics found better solutions than the greedy heuristic, and should be preferred unless time constraints require faster solution times. The solutions constructed by our methods can be used as a starting point for Tabu search or other metaheuristics, for further improvement of the solutions found.

The advances and cost reduction of high accuracy maps (e.g. generated from LIDAR) and the advances in optimization techniques offer new opportunities to revise the planning of ground based harvesting. An accurate DTM can be utilized for evaluation of terrain accessibility for forest machines, and also for generating an extraction trail layout. However, studies linking forwarder production to detailed terrain topography are lacking in the literature.

The model could be further developed and refined by including more input data (e.g. soil and tree species) and by modifying the objective function. This could be done in numerous ways, e.g. the timber price is different for different tree species and tree sizes, while harvester productivity and forwarder loading time vary with the volume distribution.

4.2 Acknowledgement

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Paper 3

A scenario-based method for assessing the impact of retention patches on forest harvesting cost

A scenario-based method for assessing the impact of retention patches on forest harvesting costs

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Abstract

Variable retention harvesting is acknowledged as a cost-effective conservation measure, but previous studies have focused on the environmental value and planning cost. In this study, we present a model for optimizing harvesting cost using a high resolution map generated from airborne laser scanning data. We use the harvesting cost optimization model to calculate the objective value of different scenarios. By comparing the objective values, we find better estimates of the opportunity cost of retention patches or woodland key habitats. The model can be used by a forest manager when evaluating what silvicultural treatments to implement, or as an input for improving the nature reserve selection problem for retention patches. The model was tested on four real world cases and the results indicate that terrain transportation costs vary more than reported in the literature, and that it may be worthwhile to divide the opportunity cost into its direct and indirect components.

Keywords: green tree retention, reserve selection problem, optimization, opportunity cost, forest harvesting.

1 Introduction

The preservation of biodiversity in forests is one of the major environmental challenges of our time. Spatial conservation prioritization is one of several tools to address this challenge (e.g. Margules and Pressey, 2000; Moilanen et al., 2009). In this approach quantitative techniques are used to generate spatial information on which parts of the forest to prioritize for biodiversity. The early development of these methods included analysis to identify the set of reserves which maximized the total number of species included (e.g. Vane-Wright et al., 1991; Sætersdal et al., 1993; Pressey, 1994). Today, in addition to a range of

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methodological developments, these approaches typically integrate economy and socio-political analysis into the planning process to meet the real world prioritization challenges (e.g. Knight and Cowling, 2007; Wilson et al., 2007).

In the beginning of the 1990s, the focus of conservation planning was on nature reserves, but today, variable retention harvesting (Green Tree Retention, GTR) (Franklin et al., 1997) is becoming the dominant biodiversity management practice in boreal forests of North-America and Europe (Gustafsson and Perhans, 2010). Retention forestry is a good example of a conservation approach that integrates biodiversity conservation with economic and socio-political realities (Gustafsson et al., 2012). Another conservation measure, introduced in Fennoscandia, is Woodland Key Habitats (WKHs) (e.g. Gustafsson, 2000). These three conservation measures can be compared as follows:

1. A nature reserve is typically many times larger than a forest stand, whereas a WKH is typically smaller than a stand, and a retention patch, a small part of a stand.

2. Retention patches are selected by the forest owner, the forest manager or the machine operator, whereas reserves and WKHs are identified by experts. As a result, WKHs generally have higher environmental values.

3. A nature reserve is typically left unmanaged, whereas WKHs and retention patches may require various silvicultural treatments to increase biodiversity.

4. In countries with private ownership, nature reserves usually have to be bought or compensated by e.g. the public. Retention patches, on the other hand, are required by most forest standards, and thus they are a cost that the seller of timber has implicitly agreed upon. WKHs may sometimes be eligible for compensation (like reserves), and sometimes not (like retention patches).

This comparison indicates that WKHs and retention patches should be modeled differently than nature reserves.

Although the benefits of GTR may be varying and sometimes uncertain, cost-benefit analysis may provide a better measure when evaluating a conservation measure. Wikberg et al. (2009) estimated the cost of nature reserves, WKHs and GTR patches, and compared the cost with the presence of large trees, deciduous trees and dead wood, as well as beetles, bryophytes and lichens. They found that reserves and WKHs have more biodiversity than retention patches, but also higher cost.

A promising approach for improving the cost-benefit ratio of GTR is to apply optimization techniques. Several variants of the Reserve Selection Problem (RSP) have been formulated for nature reserves (e.g. Williams et al., 2004), either as maximization of some environmental value with budget constraints, or minimization of cost with environmental constraints. Such an approach was used by Perhans et al. (2011), who found that cost-benefit ratios varied in six different types of retention patches. Juutinen et al. (2004) used exact and heuristic solution methods for different RSP formulations to select stands for retention. They found that exact methods in general yielded better cost-benefit ratios, and that the marginal species coverage was diminishing with increasing total cost. While these attempts to use RSP formulations for retention patches are encouraging, we have concerns regarding the approach. Nature reserves typically have unmanaged forests, whereas WKHs or retention patches may benefit from various silvicultural treatments (e.g. Fries et al., 1997; Götmark et al., 2005; Lõhmus, 2006; Franc and Götmark, 2008). To our knowledge, the RSP has not been modified in the literature to address this, although there are some studies of the cost-benefit of different silvicultural treatments. Howard and Temesgen (1997) studied the estimated net profit of nine silvicultural prescriptions. Both the prescriptions and the harvesting cost calculations were on stand level, and thus not adapted to retention patches. Jonsson et al. (2006) did a cost-benefit simulation of how six types of Coarse Woody Debris (CWD) varied with seven management options. One of the management options were retention of small parts of the area, but their focus was the environmental values. Also, their cost estimates were at stand level.

The harvesting cost is a major influence on the forest revenues, and hence on the calculations of the lost forest revenues from imposing restrictions such as retention patches (opportunity cost). A forest is typically modeled as a set of spatial units (e.g. parcels, stands or a grid), and the harvesting cost (as well as other parameters and variables) is associated with the spatial units. The harvesting cost can be divided in the work done by a harvester (felling, cross cutting and limbing) and by a forwarder (loading, unloading and terrain transportation). Of these work tasks, the terrain transportation cost is the task that is most dependent on the spatial layout, and the main focus in our study. As remote sensing techniques and computational power have evolved, the size of the spatial units have decreased, and the cost calculations have changed somewhat. Traditionally, the harvesting cost has been calculated using a road density function or an average distance to the road (Matthews, 1942; Peters, 1978), possibly using adjustments for difficult terrain or non-regular trail and road layout (von Segebaden, 1964). When the grid size decreases, instead of calculating the cost of harvesting a spatial unit as a function of the spatial unit's distance to the road, we can calculate the cost as a sum of costs going through neighbors (a path) to the roadside. This path calculation method was used by Tan (1992), who calculated the cost as a function of distance and terrain class. Contreras and Chung (2007) used a skidding cost derived from the regression model by Han and Renzie (2005), including distance and slope gradient uphill or downhill. In a more recent paper, Contreras and Chung (2011) refined the skidding model to also include a maximum roll limit. Chung et al. (2008) used a cost based on distance.

We believe that the path calculation method should be used when calculating the opportunity cost of retention patches. A WKH or a retention patch can be a very small part of a stand, and using a stand for the calculations may be too coarse. However, the method may be refined. Early forest machine stability studies reported that forest machines are more sensitive to roll than pitch (Frønsdal, 1985; Hunter, 1993), but studies of how driving speed vary with micro topography is missing in the literature (Contreras and Chung, 2011). We try to fill parts of this gap by introducing a novel way of calculating terrain transportation cost from airborne laser scanning (ALS) terrain data, including both roll and pitch estimated from micro topography.

The aim of this study is to use a scenario based multi-objective optimization model to find the opportunity cost of different silvicultural treatments of WKHs and retention patches. This is a method using *A posteriori articulation of preference* (Hwang and Masud, 1979), today sometimes refered to as a *Generate First – Choose Later* approach (Marler and Arora, 2004). Such approaches are suitable for solving multi-objective problems if the generated solutions can be easily assessed by a decision maker. The terrain transportation cost is calculated as a function of micro topography and together with a dense raster grid of the solutions. The solutions are more detailed than reported in the cited literature. The optimal solution to each scenario is found using dynamic programming.

2 Material and methods

In this work we present a novel model for terrain transport cost and net profit. By comparing the optimal solutions of the model for different scenarios, we find the opportunity cost of the scenarios. We assume that the scenarios have different environmental values. This is scenario based multi-objective optimization, and decision makers can use the results to support their decision making.

The basic idea is that a digital terrain model generated from airborne laser scanning (ALS) is accurate enough to find the resulting roll and pitch of a forest machine driving in the terrain. We assume that higher roll and pitch at a grid point increase the cost of driving the machine at that particular point.

2.1 Analytical model

We assume that the terrain is given by a weighted graph $G = (V, E)$, where each vertex $v_i \in V$ represents a point in the terrain with coordinates and elevation, and has a timber volume U_i from the nearby area. We assume that the edges E link each vertex with its neighbors, and that the weight of each edge is the terrain transport cost $C_{ij} = C(v_i, v_j)$. A path from vertex v_0 to vertex v_k is given by $p = \langle v_0, v_1, \ldots, v_k \rangle$, and the cost of transporting timber on this path is the sum of its constituent edges, given by Equation (1).

$$C(p) = \sum_{i=1}^{k} C(v_{i-1}, v_i) \tag{1}$$

The first part of our optimization is to find the shortest/cheapest path from any vertex v_i to a vertex v_r that is an existing road. The cost C_i of using the shortest path is given by minimizing Equation (2).

$$C_i = \begin{cases} \min \left\{ C(p) : v_i \overset{p}{\rightsquigarrow} v_r \right\} & \text{if there is a path from } v_i \text{ to } v_r \\ \infty & \text{otherwise} \end{cases} \tag{2}$$

The net profit of a vertex v_i is given by Equation (3), and is the timber volume U_i at the vertex, multiplied with timber revenue at roadside, Π, minus harvesting costs. In the model, C_i, given by Equation (2), is variable with respect to transport distance (unit [$\$m^{-3} \cdot m^{-1}$]), whereas C_h and C_f are fixed (unit [$\$m^{-3}$]). C_h is the cost of felling, cross cutting and limbing, whereas C_f, is the cost of loading and unloading the forwarder.

$$f_i = U_i \left(\Pi - (C_h + C_f + C_i) \right) \tag{3}$$

Finally, the net profit is the sum of net profit from all vertices with positive net profit, given by Equation (4)

$$\text{Net profit} = \sum_{f_i > 0} f_i \tag{4}$$

In addition to the net profit, we introduce scenarios representing different silvicultural treatments, which we assume have varying environmental values. One advantage of this approach is that we can do multi-objective optimization without specifying a second objective function for environmental values. Non-monetary objective functions can be hard to define, and sometimes the evaluation of non-monetary values can be easier to assess by a decision maker after the calculations. We assume that the scenarios have rules that affect the calculations of the net profit.

2.2 Cases

The model was tested using four real world cases, all located at Mathiesen Eidsvold Værk (MEV) (lat. 60.44, long. 11.07), a large forest property in Norway (Table 1). Each case had one or more WKHs, but retention patches were not included. This choice was made to keep the cases simple and easier to analyze. Also, WKHs and retention patches would be treated in the same way in the model.

Table 1: Cases

Case	Total area (ha)	WKH area (ha)	WKH area (%)
1	111	13.6	12.2
2	94	6.5	6.9
3	203	18.8	9.3
4	345	24.2	7.0

Within each case, we use five scenarios. In Scenario 1, vertices v_i inside the WKHs were not harvested ($U_i = 0$) and driving was not allowed ($C(v_i, v_j) = \infty$). For Scenarios 2 – 5, driving in WKHs was allowed, but the harvest was limited to 0%, 30%, 70% and 100%, respectively.

As we could not find studies of how driving speed or forwarding costs are affected by micro topography, we invented a simple model penalizing roll and pitch. The variable forwarding cost of transporting timber from vertex v_i to a neighboring vertex v_j in uneven terrain is given by Equation (5), where C_0 is the cost of driving 1 meter (back and forth) in flat terrain and d_{ij} is the distance from v_i to v_j. P_r is the penalty for roll, given by Equation (6), and P_p is the penalty for pitch, given by Equation (7).

$$C_{ij} = C_0 d_{ij} P_r P_p \tag{5}$$

$$P_r = \begin{cases} 1 + 2r & \text{if } r \leq r_{\text{max}} \\ \infty & \text{if } r > r_{\text{max}} \end{cases} \tag{6}$$

$$P_p = \begin{cases} 1 + p & \text{if } p \leq p_{\text{max}} \\ \infty & \text{if } p > p_{\text{max}} \end{cases} \tag{7}$$

The roll r in Equation (6) and pitch p in Equation (7) are calculated using the difference in the elevation at some vertices in the vicinity of the wheels of a forest machine, and are given by Equations (8) and (9).

$$\begin{aligned} r &= \max\left(r_f, r_b\right) \\ &= \max\left(\frac{|e_{lf}-e_{rf}|}{d_f}, \frac{|e_{lb}-e_{rb}|}{d_b}\right) \end{aligned} \tag{8}$$

$$p = \frac{\left|\frac{e_{lf}+e_{rf}}{2} - \frac{e_{lb}+e_{rb}}{2}\right|}{d_p} \tag{9}$$

r_f is the roll at the front axle, and r_b is the roll at the back axle, i.e. the percentage of inclination between the wheels on the axle. e_{lf}, e_{rf}, e_{lb} and e_{rb} are the mean elevation at each wheel or bogie, and d_f, d_b and d_p are the mean distances between the coordinates of the vertices (Figure 1). Note that in flat terrain, r and p are zero, and hence, $P_r = 1$ and $P_p = 1$. Here, $C_{ij} = C_0 d_{ij}$. If the terrain is steep in the driving direction (pitch) or perpendicular to the driving direction (roll), either penalty factor will be larger than one, and positive. This will increase the estimated cost of driving at that location.

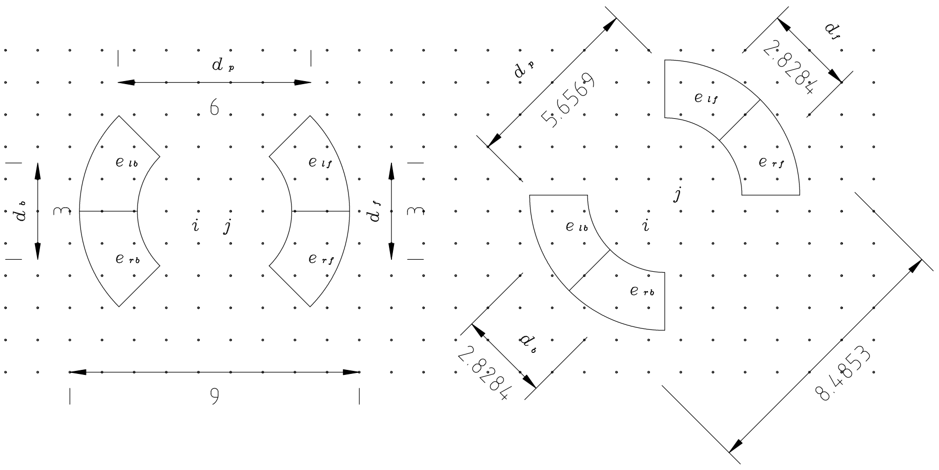


Figure 1: Sectors used for calculating forwarding cost (distances in meters).

To find an estimate of C_0, we used observations by Nurminen et al. (2006). We assumed that their observed maximum speeds while driving loaded and unloaded was in the flattest terrain, and the average of the two was $73m \cdot \min^{-1}$. A forwarder hourly cost of $\$175h^{-1}$ and delay factor of 1.33 give $C_0 = \$7.57 \cdot 10^{-3} m^{-3} \cdot m^{-1}$.

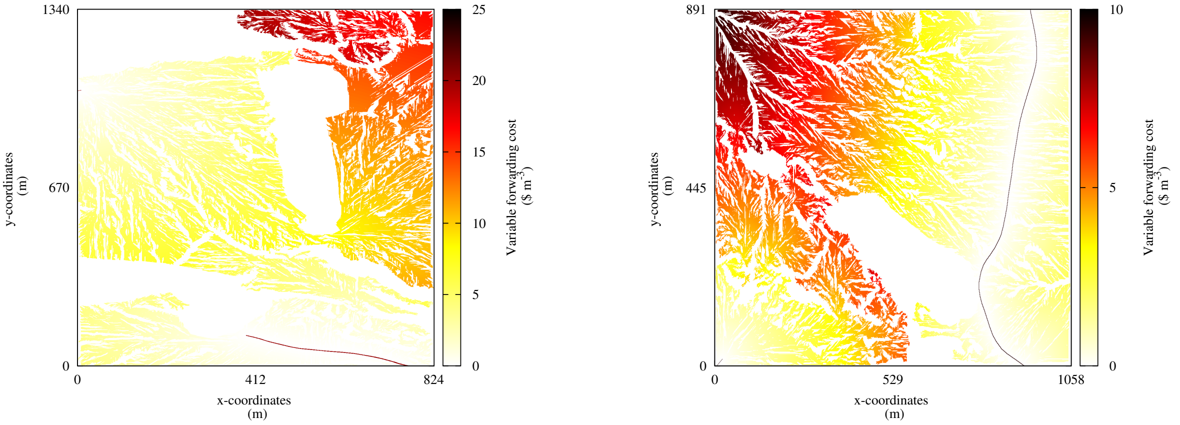
We used $r_{\text{max}} = 0.23$ and $p_{\text{max}} = 0.35$ in the calculations, as a conservative estimate based on static stability studies (Frønsdal, 1985; Hunter, 1993).

The average timber price used was $\Pi = \$50m^{-3}$. The other parameters of the model were calculated from an hourly harvester cost of $\$200h^{-1}$, an hourly forwarder cost of $\$175h^{-1}$ and average values of Nurminen et al. (2006), and found to be $C_h = \$7.4m^{-3}$ and $C_f = \$5.0m^{-3}$.

The terrain was represented by a raster grid with a resolution of $1m \times 1m$, generated from a high accuracy ALS dataset. Each grid point was linked with the eight neighbors, and the timber volume at each grid point was $U_i = 2.37 \cdot 10^{-2} m^3$ (i.e. $237m^3$ per hectare).

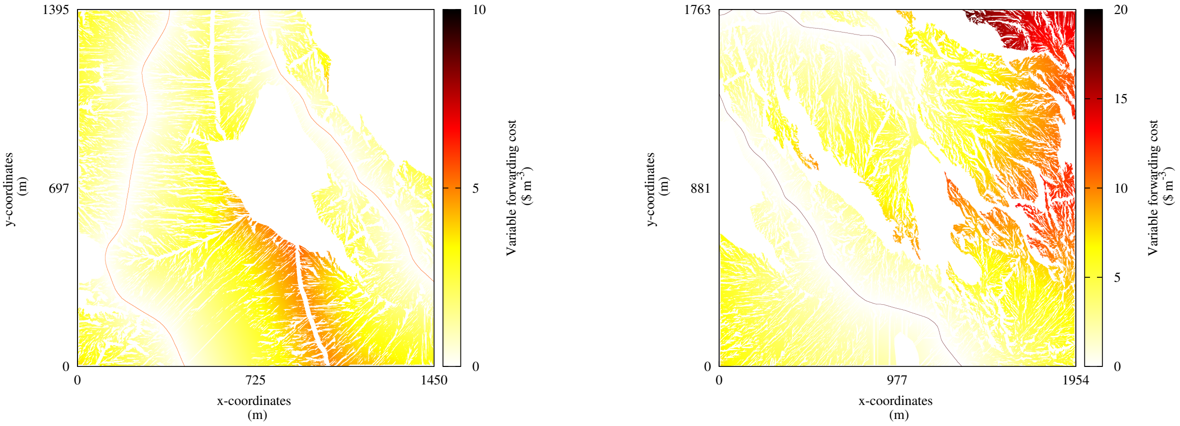
3 Results

The shortest path optimization returned the variable cost of forwarding, and the maximum cost was found in Case 1, Scenario 1 at $\$20m^{-3}$. A heat map of variable forwarding cost for Scenario 1 for all cases is given in Figure 2.



(a) Case 1.

(b) Case 2.



(c) Case 3.

(d) Case 4.

Figure 2: Heat maps of the variable forwarding cost.

The calculated net profit for each scenario and case is given in Table 2. By comparing Scenarios 1-4 with Scenario 5, we can find the opportunity cost of imposing the environmental restrictions associated with each scenario (Table 3). Furthermore, by a stepwise comparison, we can differentiate the opportunity cost, e.g. the difference between Scenario 2 (no harvesting, driving allowed inside the WKHs) and Scenario 1 (no harvesting and no driving inside the WKHs) as the opportunity cost of being allowed to drive through the WKHs in each case (indirect opportunity cost), and the difference between Scenario 5 and Scenario 2 as the lost net profit from not harvesting inside the WKHs (direct opportunity cost).

The indirect opportunity cost was found to be negligible in Cases 2-4, but $\$25\,091$ in Case 1. This increase in net profit was partly due to a $0.6ha$ increase in harvested area, i.e. the area that was not reachable without driving through the WKHs. This resulted in an increase in harvested volume of $147m^3$. The mean net profit per volume for Case 1, Scenario 2 was $\$32.3$, and the value of the increased harvested volume is thus $\$4\,746$.

Table 2: Objective values for scenarios and cases.

Scenario	Description	Case 1 ($\$$)	Case 2 ($\$$)	Case 3 ($\$$)	Case 4 ($\$$)
1	No trails, no harvest	637 339	700 233	1 360 604	2 286 526
2	Trails, no harvest	662 430	700 438	1 360 642	2 288 134
3	Trails, 30% harvest	686 301	712 867	1 404 178	2 340 318
4	Trails, 70% harvest	718 129	729 440	1 462 227	2 409 897
5	Trails, 100% harvest	742 001	741 869	1 505 763	2 462 082

Table 3: Opportunity costs.

	Case 1	Case 2	Case 3	Case 4
WKH area (ha)	13.6	6.5	18.8	24.2
Reachable WKH area (ha)	10.5	5.0	17.7	22.7
Total opportunity cost ($\$$)	104 662	41 636	145 159	175 556
Marginal total opportunity cost ($\$ha^{-1}$)	9 989	8 325	8 218	7 724
Direct opportunity cost ($\$$)	79 571	41 431	145 121	173 948
Marginal direct opportunity cost ($\$ha^{-1}$)	7 594	8 284	8 215	7 653
Indirect opportunity cost ($\$$)	25 091	204	38	1 608
Marginal indirect opportunity cost ($\$ha^{-1}$)	2 395	41	2	71

The rest of the increased net profit is due to reduced terrain transportation cost found at $31ha$ (Figure 3).

The main extraction trails for Case 1 are shown in Figure 4. The main extraction trails are trails with a minimum transit volume of $40m^3$.

To investigate the sensitivity of the model, we tried different maximum values of roll between 0.21 and 0.33, and different values of maximum pitch between 0.33 and 0.43 for Case 1, Scenarios 1-2. The relative values obtained are given in Table 4.

Table 4: Net profit for Scenario 1 divided by net profit of Scenario 2 for different roll and pitch limits (Case 1). Ratios close to one means that there are small differences between the net profit of Scanario 1 and Scenario 2 (i.e. low indirect opportunity cost).

	Max roll						
Max pitch	0.21	0.23	0.25	0.27	0.29	0.31	0.33
0.33	0.968	0.972	0.959	0.959	0.985	0.985	0.984
0.35	0.958	0.962	0.959	0.986	0.987	0.988	0.988
0.37	0.958	0.983	0.983	0.987	0.987	0.992	0.992
0.39	0.964	0.984	0.986	0.988	0.993	0.994	0.995
0.41	0.985	0.989	0.988	0.992	0.995	0.996	0.997
0.43	0.988	0.992	0.995	0.996	0.996	0.996	0.997

4 Discussion

In our cases, we have used a novel model for terrain transportation costs using micro topography and penalty functions for roll and pitch. The resulting variable terrain transportation costs (Figure 2) are in general increasing with the distance to road, as would be

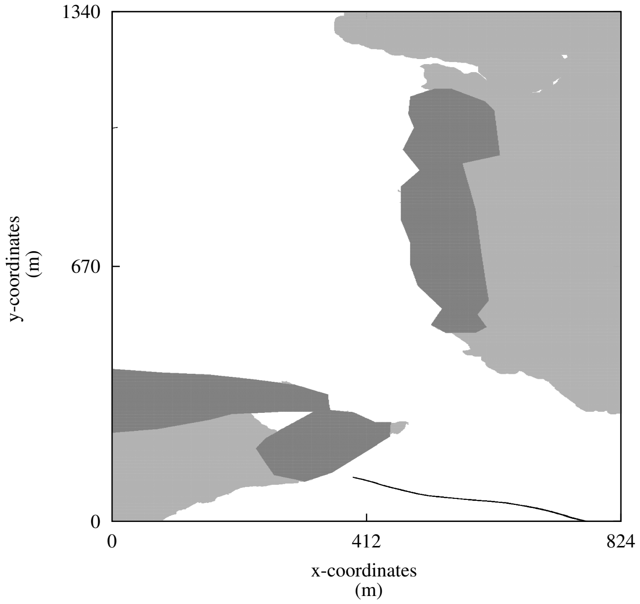


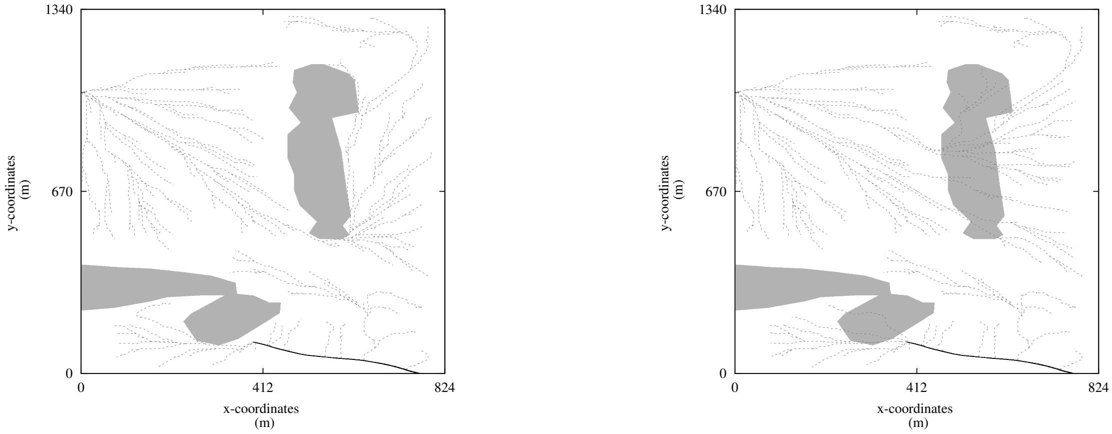
Figure 3: Woodland key habitats (dark gray) and areas with reduced terrain transportation cost from driving through the WKH area (light gray), Case 1.

expected from traditional cost calculations. However, in all cases there are areas where the costs are significantly higher than in areas nearby, indicating that the micro topography is causing detours.

The scenarios have different environmental restrictions, and also different silvicultural treatments. By comparing the objective values (Table 2) of different scenarios, we can find the opportunity cost of each scenario. In Table 3, the total opportunity cost is the difference in objective value of Scenario 5 and Scenario 1. The direct opportunity cost is the part of the total opportunity cost that can be located to areas inside the retention patch, i.e. the difference in objective value of Scenario 5 and Scenario 2. The indirect opportunity cost is the part of the total opportunity cost that can be located to areas outside of the retention patch, i.e. the difference in objective value of Scenario 2 and Scenario 1. Although the latter difference was negligible in Cases 2-4, it was $\$$25 091 in Case 1.

4.1 Model evaluation and some limitations

When building an optimization model, the model will be a simplification of the real world, and the input data will have measurement errors. In addition, some model formulations are intractable for computers (Garey and Johnson, 1979), i.e. at some problem size, the time or memory needed to find the optimal solution exceed physical limits. One such class of problems is the class of NP-hard optimization problems, which have no known exact solution method for large problem instances. For large problem instances, we can either formulate a simplified model and solve it to optimality, or we can use non exact methods (e.g. heuristics or metaheuristics) for solving large problems. In the latter case, solutions found may not be optimal ones. Our model is a two-step model where the first step solves using Dijkstra's shortest path algorithm, and the second step compares different scenarios. This is a simplified model that can be solved to optimality very fast, a crucial feature when optimizing large problem instances. The computational complexity of Dijkstras' shortest path algorithm is $\mathcal{O}(n\log(n))$ (Fredman and Tarjan, 1987), i.e. the time



(a) Driving in WKHs not allowed, no harvest in WKHs (Scenario 1).

(b) Driving in WKHs allowed, no harvest in WKHs (Scenario 2). The trails inside the WKHs are for transportation of timber harvested outside the WKH.

Figure 4: Main extraction trails for Case 1 (transit volumes $> 40m^3$*).*

needed to find the solution is bound by a constant multiplied by $n\log(n)$ where n is the problem size.

4.1.1 Cost model evaluation

In our model, we assume that timber at a vertex is picked up and transported to the roadside through the shortest path. Figure 5 shows that our shortest path model gives a dense path network. In reality, only some of the trails will be used when the area is harvested, as a forwarder (and the harvester) would use trails, collecting what is reachable from the trails. However, the estimated forwarding cost will be quite good, because the cost of transportation in parallel trails is almost equal, otherwise there would be more merging of trails. In fact, our estimate will be a lower bound compared to a less dense solution, giving a sound estimate of the cost. On the other hand, the layout of main extraction trails found by our method seems acceptable. In Figure 4, we plot trails with more than $40m^3$ transit volume. A forwarder operator will collect timber until the machine is fully loaded, and then use the shortest paths to the roadside (i.e. the main extraction trails).

Another simplification of the model is the cost of felling, cross cutting and limbing, C_h, as well as the fixed cost of forwarding, C_f. In our model, these costs are independent of the harvest percentage inside the WKHs. In general, both C_h and C_f will increase when the harvested volumes per area decrease (e.g. Nurminen et al., 2006). Although a tabular correction of these costs, as a function of volume per area, can be implemented without affecting the computational complexity much, a more detailed formulation of the loading phase was suggested by Flisberg et al. (2007). By describing the phase as a vehicle routing problem (VRP), they found significant improvements. However, the VRP is known to be NP-hard, and thus not suitable for our model.

4.1.2 Model sensitivity

Any change in the parameters of the model will change the net profit, but not necessarily the shortest path solution. The maximum terrain transportation cost in all the cases was found to be $\$20m^{-3}$ (in Case 1, Scenario 1), resulting in a minimum marginal profit of

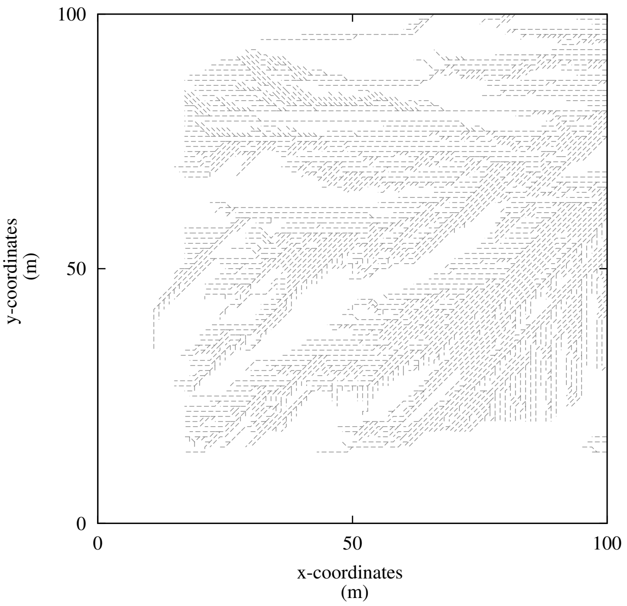


Figure 5: Part of the solution of Case 1, showing the density of the trails.

$\$17.6m^{-3}$. As Equation (4) requires that only economically viable timber is harvested, the price of timber can decrease by $\$17.6m^{-3}$ without changing the shortest paths. Likewise, the cost of felling, cross cutting and limbing, and the fixed cost of forwarding could each increase by the same amount without changing the shortest paths. Furthermore, if the marginal net profit decreases below $\$0$ at a vertex v_i, the shortest paths would remain unchanged up to that vertex. The model's sensitivity to C_0 is similar, but the penalty factors make it difficult to predict the limits of C_0 where changes in the paths occur.

To evaluate the model's sensitivity to the limits for roll and pitch in the penalty factors, we calculated the net profit of Scenario 1 and 2 for different limits. From Table 4, we see that the ratio of net profit of Scenario 1 to net profit of Scenario 2 seems to be stable. However, the indirect opportunity cost is decreasing as maximum roll and/or maximum pitch increase, and a roll limit of 0.29 and a pitch limit of 0.39 give a ratio that is higher than 99%.

4.1.3 Other machines and places

Our model can be described as a three-part model consisting of a scenario part, a shortest path part and a micro topography terrain part. For the latter one, we assumed that driving speed is dependent on the micro topography, and that this this dependency could be modeled with penalty factors for roll and pitch. These assumptions were due to what we believe is a gap in the literature, and we predict that studies describing the relationship between driving speed and micro topography will soon appear in the literature. When such studies are published, the model can be verified for forwarders, and easily adjusted for different wheel and ground based extraction systems, e.g. skidders, farm tractors or horses.

Cable yarding systems, on the other hand, has not been modeled as a shortest path problem in the literature, but rather as a facility location problem (e.g. Dykstra and Riggs, 1977). Scenario based optimization of opportunity costs could still be implemented, but the shortest path part would have to be replaced with a cableway facility location routine. This would not be straightforward, as facility location problems are generally NP-hard.

4.2 Cost comparison with the literature

We used a cost of terrain transportation in flat terrain of $C_0 = \$7.57 \cdot 10^{-3} m^{-3} \cdot m^{-1}$. The maximum possible penalty is $P_r \cdot P_p = 1.97$, and hence, the maximum possible terrain transportation cost is $C_{ij} = \$0.0149 m^{-3} \cdot m^{-1}$. Contreras and Chung (2007) used a variable skidding cost of $\$0.0203 m^{-3} \cdot m^{-1}$ (flat and downhill) and $\$0.0244 m^{-3} \cdot m^{-1}$ (uphill). Chung et al. (2008) used a variable skidding cost of $\$0.05 m^{-3} \cdot m^{-1}$, but also $\$0.025 - -0.1 m^{-3} \cdot m^{-1}$ in the sensitivity analysis. This may indicate that either the value used for C_0 or the penalty factors are too low, or that forwarding is cheaper than skidding. However, further discussion of this issue is of little value in the absence of studies that specifically address how micro topography affects the driving speed.

The opportunity costs found by our method are given in Table 3. Our results are in the same range as in the literature, but direct comparison is difficult because net present value is frequently used. Wikberg et al. (2009) found that WKHs had an opportunity cost of €5 277ha^{-1}, and that retention patches were significantly cheaper. The latter was also found by Perhans et al. (2011). Jonsson et al. (2006) simulated different silvicultural treatments in southern, middle and northern Sweden, and the opportunity cost of setting aside stands as reserves in middle Sweden was SEK43 424ha^{-1}, which is of the same magnitude as the opportunity cost given by Wikberg et al. (2009).

4.3 Implications

The RSP for nature reserves is a problem that is inherently strategic. For retention patches, however, the task of selecting what silvicultural treatment to apply to which patches can also be tactical or operational. It can be that forest managers are free to manage within some guidelines or standards, or that they can negotiate with a political body (or a public office).

4.3.1 Implications for forest managers

Our two step model may be directly applicable for a forest owner or a forest manager. From a presentation of the opportunity costs, a silvicultural treatment can be chosen according to the environmental values found in the WKH and the operational guidelines. Our model may also be used by the public when designing the guidelines for the forest managers. A scenario based presentation is easy to understand, and shows a trade-off between environmental impact and net profit. This can be useful when considering which policy to implement, or when compensation may be given. Such a presentation may also be an asset if the forest manager can negotiate with the public what silvicultural treatments to implement. An example of this is could be our Case 1 (Figure 4), where not being allowed to drive in the WKHs increased the harvesting cost. Maybe a negotiation could result in a single extraction trail through the WKH, greatly reducing the cost of harvesting, but leaving most of the WKH unharmed.

4.3.2 Implications for RSP

Our scenario based optimization model can be utilized to generate input for the RSP for WKHs or retention patches (GTR-RSP). A GTR-RSP formulation requires some environmental value in the objective function or in the constraints, and this will vary according to the silvicultural treatments in our scenarios. The corresponding opportunity cost can be found in Table 3. In our test cases, we used a uniform timber volume of $237m^3ha^{-1}$, and assumed that all the areas were mature forest. In reality, different stands in the forest would be of different age and have varying timber volume. The net present value of a future opportunity cost (or profit) can be easily found, but we have not implemented stands in our model.

The presented *Generate First – Choose Later* approach is applicable as long as the number of possible treatments and the resulting environmental values are easily assessed by a decision maker. These assumptions will in general not be met for a GTR-RSP formulation. Selecting different treatments for a large number of WKHs and retention patches while assessing numerous environmental values is not an easy task. Formulating and solving a GTR-RSP will require high quality input data. Some of the costs could be estimated as presented in this work, and the silvicultural prescriptions of Howard and Temesgen (1997) could be included.

5 Conclusions and future work

Our model can be utilized for detailed calculations of the cost of forest operations, and thus getting better estimates of the cost of conservation of retention patches. This can in turn be utilized for conservation prioritization. We have shown that both the variable forwarding cost and the opportunity cost of retention patches vary significantly given our input data and assumptions. However, these assumptions should be studied further, in particular how the driving speed is affected by the micro topography.

We introduced a separation of the opportunity cost into direct and indirect opportunity cost, and found that in three of four cases the indirect opportunity cost was negligible. In one of the cases, we found that retention of a WKH may affect the cost of forest operations in surrounding areas.

The model should be applied to an RSP case for retention patches. This would require it to be adapted to the environmental values and silvicultural options found in the specific RSP case.

6 Acknowledgement

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Paper 4

A semi-greedy metaheuristic for the European cableway location problem

A semi-greedy metaheuristic for the European cableway location problem

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Abstract

The Cableway Location Problem (CLP) is a facility location problem usually studied as a part of hierarchical problems or for large cable yarding systems outside of Europe. Small adaptable cable yarding systems are used in Europe. This increases the number of possible landing sites and makes the layout problem hard to solve to optimality. Here, two approaches are presented that solve the novel European Cableway Location Problem (E-CLP). The methods are tested on several generated cases and one real world case. Here, the lateral yarding distance is introduced in the cost calculations to improve the quality of the solutions.

Keywords: semi-greedy, optimization, facility location, harvesting, cable yarding.

1 Introduction

Forestry is an important sector in many countries. Wood production constitutes a major part of forest revenues. There are few costs incurred while trees grow, but the cost of the harvesting operation may be high. In steep or difficult terrain, harvesting relies principally on cableways, i.e. an elevated cable from a landing into the area to be harvested. Different cable yarding systems are used throughout the world, but common features are a yarder or tower located at the landing, a cable with carriage and a tail spar fixing the end of the cable.

A harvesting operation starts with the rigging of the system, continuing with the actual yarding of the trees or logs. When the yarding is finished, the cableway is taken down and

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the equipment is moved a small distance to another landing and the process is repeated until the entire area is harvested.

The rigging time (up and down) is dependent on several factors (e.g. terrain and cableway length), but not on the harvested volume. The yarding time, however, is dependent on volume as well as other factors. As each tree can be yarded from numerous possible cableways, the cableway location problem (CLP) is the problem of picking the set of cableways that maximizes the total net profit. This problem can be formulated as a generalized simple plant location problem, known to be NP-hard (Krarup and Pruzan, 1983).

In the literature, the CLP has usually been formulated as a part of hierarchical optimization problems. Dykstra (1976) included rigging and yarding cost, landing construction cost and different machine characteristics, and solved the problem with a heuristic. The heuristic first constructed a feasible solution, then iterated through a drop phase based on the drop-routine of Feldman et al. (1966) and an add phase based on the add-routine of Kuehn and Hamburger (1963) until the solution did not improve. Later research has included road construction cost and road transportation cost. Chung (2002) based the optimization on the method of Cooper and Drebes (1967), iteratively calculating the shortest path flows and modifying the variable costs. Inclusion of road location options has shifted the focus from the CLP to the Steiner tree problem of connecting selected landings to an existing forest road network.

Epstein et al. (2006) described the PLANEX software developed for several Chilean forest companies. The software optimizes access road layout and harvesting with skidders and cable yarders using heuristics. They used a greedy, constructive heuristic to include landings sequentially. After using a heuristic for solving the Steiner tree problem (the road network), the solution was evaluated by forest engineers and the optimization repeated with other parameters if necessary. The PLANEX software has also been used as a basis for other solution approaches. Vera et al. (2003) proposed two methods for solving the problem and obtaining a bound of the objective: strengthening of the original linear programming formulation and a Lagrangian Relaxation algorithm. The methods solved small and medium sized problems but not larger problems. Diaz et al. (2007) modified the greedy heuristic for the machine location sub-problem in PLANEX and solved it using tabu search. They reported “better solutions than those provided by state-of-the-art integer programming codes in limited computation times, with solution times significantly smaller”.

Bont et al. (2012) compared a mixed integer linear programming formulation with the PLANEX software and solved the formulation to optimality. In addition to the exact solver, Bont et al. (2012) addresses the fact that European yarders can operate from any location on a forest road, unlike other yarders dependent on landing construction. One practical implication of the European systems is that the resulting cableway layout tends to be parallel (Bont et al., 2012), whereas the cableway layout of systems requiring construction of landings tends to be fan-shaped (Chung, 2002).

The technological development from the 1970s to the present is evident when reviewing the literature of the CLP. Computational power has increased, as has the quality of the input data. Advances in remote sensing give more accurate digital terrain models with the possibility of locating tail spars (Kato and Schiess, 2007) and to plan harvesting utilizing locations of individual trees (Heinimann and Breschan, 2012). Another field of technology with significant improvements is the field of metaheuristics, where faster methods and/or larger problem sizes are reported. A recent review by Mladenović et al. (2007) found that metaheuristics find better solutions than classic heuristics to the p-median problem, a problem similar to the simple plant location problem and the CLP. Thus, it is worthwhile to apply metaheuristics to the CLP, like TABU search (Diaz et al., 2007).

The focus of this study is the CLP for European yarding systems, i.e. yarding systems that do not need constructed landings. This flexibility increases the number of possible landings and possible cableways considerably, making the problem harder to solve using exact solution techniques. By introducing the lateral yarding distances in the yarding cost calculations, the accuracy of the costs and the quality of the solutions are improved. This requires a higher resolution than reported in the literature and thus it may be impossible to solve the problem to optimality.

The aim is to formulate a yarding model including lateral yarding and the flexibility of European yarding systems. Furthermore, a greedy heuristic that utilizes the structure of the European CLP (E-CLP) is modified to a semi-greedy metaheuristic. Both methods are tested on generated terrain examples and on a real world terrain.

2 Material and methods

There are numerous types of cable yarding systems operating around the world, but this approach is on a commonly used system in Europe (yarders mounted on trucks). The truck is equipped with a tower and an elevated cable between the tower and the tail spar (Figure 1). Along the cable, a carriage with a drop line can yard timber to the tower. Trees are felled and choked manually and then yarded to the tower where they are limbed and bucked typically with a crane and processor. This system is flexible in the sense that the tower can be rigged at any point on the road as long as the cableway is feasible.

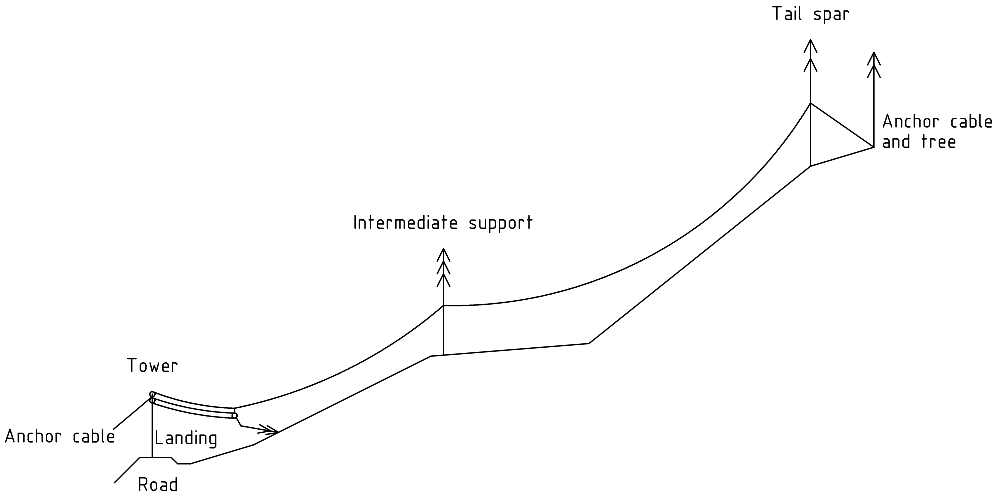


Figure 1: An example of a cableway.

A mathematical model for European yarding systems is defined here as the European CLP (E-CLP). The sets and parameters of the formulation are defined in Table 1. The costs are rigging and yarding costs and the revenues are the harvested volumes multiplied by the timber price. The objective function used maximizes profit, i.e. revenues less costs, given by Equation (3).

Table 1: Sets and parameters

Set or parameter	Description
$\Gamma_j, \quad (k,l) \mapsto j$	Corridor using tower at a vertex v_k and tail at a vertex v_l is feasible.
Γ^i	The subset of Γ that can harvest or reach vertex i.
C_{Γ_j}	The cost of rigging corridor Γ_j.
$c_{i\Gamma_j}$	The cost of transportation of timber from vertex i to corridor Γ_j, and further to the landing of corridor Γ_j.
$d_{i\Gamma_j}$	The longitudinal distance along corridor from vertex i to the landing of corridor Γ_j.
$l_{i\Gamma_j}$	The lateral distance from vertex i to corridor Γ_j.
Π	The timber price.
U_i	The timber volume at vertex i.
g_{Γ_j}	The gradient of corridor Γ_j.

The basic problem involves locating cableways and assigning parcels (represented by vertices i) to be harvested by a specific located cableway. To formulate this, we need to introduce to decision variables:

$$x_{i\Gamma_j} = \begin{cases} 1 & \text{if timber at vertex } i \text{ is transported through corridor } \Gamma_j \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$y_{\Gamma_j} = \begin{cases} 1 & \text{if corridor } \Gamma_j \text{ is used} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The constraints are that timber has to be harvested only once (Equation (4)), and if timber at vertex i is harvested using corridor Γ_j , the corridor must be used (Equation (5)).

$$\max \left(\sum_i \Pi U_i \sum_{\Gamma_j \in \Gamma^i} x_{i\Gamma_j} - \sum_i \sum_{\Gamma_j \in \Gamma^i} c_{i\Gamma_j} x_{i\Gamma_j} - \sum_{\Gamma_j \in \Gamma} C_{\Gamma_j} y_{\Gamma_j} \right) \tag{3}$$

$$\text{s.t.} \sum_{\Gamma_j \in \Gamma^i} x_{i\Gamma_j} \leq 1, \qquad \forall i \tag{4}$$

$$x_{i\Gamma_j} \leq y_{\Gamma_j}, \qquad \forall i, \Gamma_j \tag{5}$$

$$x_{i\Gamma_j} = \{0,1\} \tag{6}$$

$$y_{\Gamma_j} = \{0,1\} \tag{7}$$

This formulation for the E-CLP is a facility location problem, where the rigging of the cableways corresponds to the set-up of the facilities and the yarding is the service provided by the facilities. A practical difference from traditional facility location problems is that the CLP is two-dimensional in the sense that the location of the cableway is defined by the two end points. This fact makes it difficult to design efficient neighborhoods for local search as small changes may cause a ripple effect through the solution. Adding or dropping a cableway may require numerous small moves or adjustments of many other cableways in order to realize any net improvement in the objective. For this reason, a constructive metaheuristic is designed for the E-CLP.

2.1 Metaheuristic 1 (StructuralSemiGreedy)

Hart and Shogan (1987) proposed a semi-greedy constructive metaheuristic where solutions are constructed by interatively adding parts of the solution. For each iteration, a candidate list is found and evaluated according to a greedy evaluation function. Whereas a greedy heuristic would select the candidate yielding the best value, the semi-greedy solver creates a restricted candidate list (RCL) of the best candidates and selects randomly from the RCL. Such a semi-greedy metaheuristic is the basis of Metaheuristic 1 . It is structural in the sense that good solutions to the E-CLP are assumed to have parallel cableways and the candidate list is created with this in mind.

The candidate list for a semi-greedy solver should be created with care. Even though possible landings are limited to grid points along the existing road curve, the number of cableways that can be rigged from a landing is large (i.e. to any grid point within the reach limit of the system, barring ifeasibility of the cableway). For this reason, possible tail spars are assumed to be predefined as a tail spar curve, and some rules for pairing landings and tails should be applied. A yarding operation is confined to an area defined by property borders, terrain topography, technical limits of the equipment, and forest maturity. The layout of the yarding area limits the quality of specific cableway layouts. In order to guide the search towards good solutions, a basic cableway at each possible landing is introduced. This basic cableway could be choosen from different criteria (e.g. perpendicular to the road tangent line or the tail tangent line), but should indicate the locally optimal cableway at the possible landing.

Metaheuristic 1 StructuralSemiGreedy

```
 1: Initialize the terrain, roads, possible cableways $\Gamma$ and other data;
 2: for $i = 1$ to number of iterations do
 3:     Solution $\leftarrow \emptyset$;
 4:     Select first cableway $\Gamma_{\text{start}}$, and divide the yarding area in Area 1 and Area 2 by this;
 5:     Solution $\leftarrow \Gamma_{\text{start}}$;
 6:     for Area 1 and Area 2 do
 7:         $\Gamma_{\text{last}} = \Gamma_{\text{start}}$;
 8:         repeat
 9:             Create the candidate list;
10:             Evaluate the candidate list and create the RCL;
11:             if the size of the RCL is satisfactory large then
12:                 Select a cableway $\Gamma_j$ from the RCL at random;
13:                 Solution $\leftarrow$ Solution $\cup \Gamma_j$;
14:             end if
15:             $\Gamma_{\text{last}} = \Gamma_{\text{next}}$;
16:         until No cableway added
17:     end for
18:     Save Solution if it is the best found so far;
19: end for
```

After initialization, the first step of Metaheuristic 1 is to choose the starting cableway (line 4), and this step divides the problem into two parts. This first selection is based on the maximum average profit of a single cableway, i.e. if a timber volume U_j is harvested using cableway Γ_j, the average profit $\bar{f}_j = \Pi - (C_j + \sum_i c_{i\Gamma_j})/U_j$. However, as the yarding cost $c_{i\Gamma_j}$ is increasing with both the distance to the landing $d_{i\Gamma_j}$ and the lateral distance $d_{i\Gamma_j}$, the area yielding the maximum average profit of a cableway may be wedge shaped. For this reason, and the assumed parallel layout of European cableways, the area evaluated in the function $\bar{f}_j$ is assumed to be rectangular. This locally optimal area covered by a cableway is defined by the cableway length and the optimal lateral yarding distance, l^*. To ensure that the first cableway selected is a good one, it is chosen from among the basic cableways.

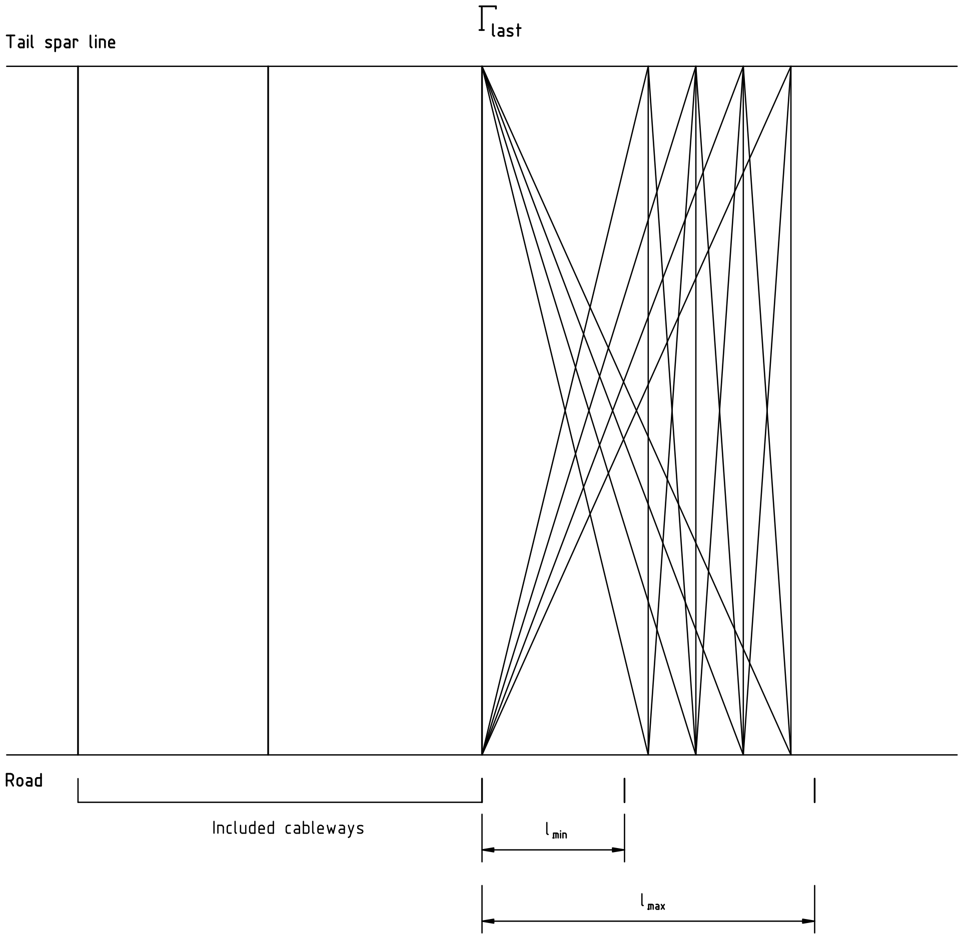


Figure 2: Illustration of the candidate cableways.

The creation of the candidate list and the RCL are the key features of Metaheuristic 1. The candidate list (line 9) is all feasible cableways with landings and tails within a minimum distance l_{min} and a maximum distance l_{max} from the landing and tail of the previously added cableway Γ_{last}, as well as fanning cableways (Figure 2). The creation of the candidate list focuses the search on better parts of the solution space. However, the creation of the RCL (line 10) is not straightforward. The greedy evaluation function is an estimate of the marginal profit of adding a possible cableway. A local choice providing a high marginal profit may limit the benefit of subsequent cableway additions. For this reason, three assumptions are made. First, the fixed rigging cost included in the function is only the rigging cost of the candidate cableway. Second, timber can only be yarded by the candidate cableway and the last added cableway. Third, only timber from an assessment area is included. This assessment area is the area from the last added cableway Γ_{last} and some distance ahead. This is illustrated with two cases in Figure 3. For a candidate cableway Γ_j, the optimal lateral yarding distance $l^*_{\Gamma_i}$ is found, and the basic cableway Γ_{border} at the landing this distance further ahead is the second border of the assessment area. In Figure 3, at the right hand side, the road and the tail spar line is almost parallel, and the assessment area is close to a rectangle. On the left hand side, however, the road curves, and the assessment area is wedge shaped. The greedy evaluation function used for the creation of the

RCL is the maximum average profit that can be achieved by considering the yarding costs $c_{i\Gamma_j}$ and $c_{i\Gamma_{\text{last}}}$, but only the rigging cost C_{Γ_i} of cableway Γ_j, given by Equation (8).

$$\bar{h}_j = \Pi - \frac{C_j + \sum_i \min\left(c_{i\Gamma_j}, c_{i\Gamma_{\text{last}}}\right)}{U_j} \tag{8}$$

The RCL was created using a combination of the *percentage based* and *cardinality based* criteria of Hart and Shogan (1987). If p is the selection percentage, the RCL was the p percent best candidate cableways of the candidate list (i.e. if the size of the candidate list is n and the size of the RCL is m, then $m = pn$).

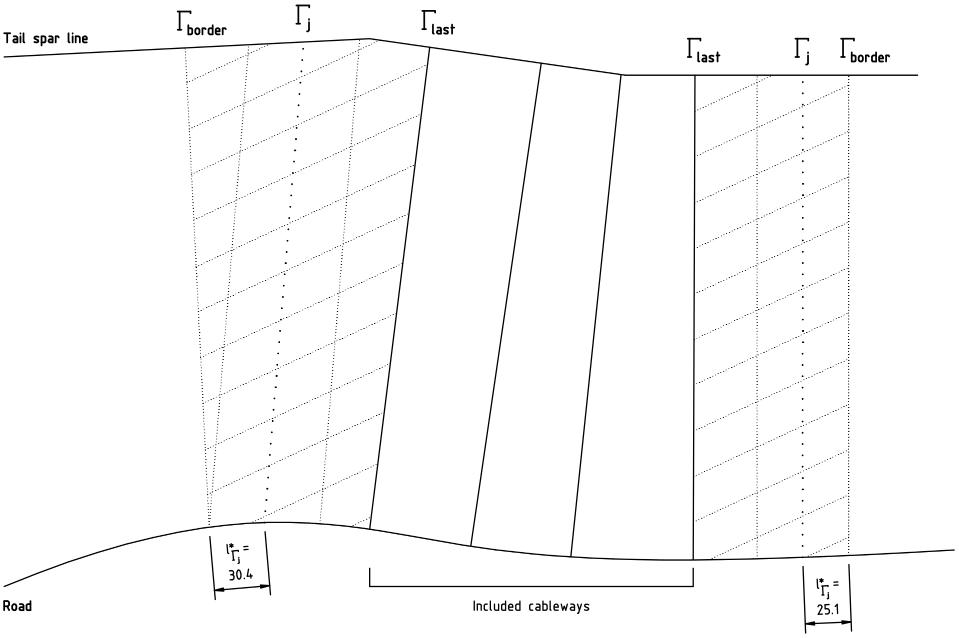


Figure 3: An example of adding cableways.

2.1.1 Cost calculations and model parameters

Stampfer et al. (2006) studied rigging times for European yarders, and we use a simplified version of their findings. The rigging time of cableway Γ_j, without intermediate supports, is given by Equation (9), where d_{Γ_j} is the length of cableway Γ_j. t'_{Γ_j} is the number of hours (man hours) needed to set up cableway Γ_j.

$$t'_{\Gamma_j} = \exp\left(1.42 + 2.29 \cdot 10^{-3} d_{\Gamma_j}\right) + \exp\left(0.96 + 2.33 \cdot 10^{-3} d_{\Gamma_j}\right) \tag{9}$$

There are no detailed studies of rigging times for intermediate supports in the literature (Bont and Heinimann, 2012), but Stampfer et al. (2006) did report some observations. The findings of Stampfer et al. (2006) were modified to have an estimate given by Equation (10), where h_k is the height of the support and $d_{k\Gamma_j}$ is the distance from the support to the landing of cableway Γ_j. The rigging times for supports are also given in effective hours (man hours).

$$t_k = 0.4 h_k + 10^{-3} d_{k\Gamma_j} \tag{10}$$

The total rigging time of cableway Γ_j is given by Equation (11) and the rigging cost is given by Equation (12). The rigging is assumed to be done by a crew of n workers. C_w is the hourly cost of a worker and C_m is the hourly cost of the yarder.

$$t_{\Gamma_j} = t'_{\Gamma_j} + \sum_k t_k \tag{11}$$

$$C_{\Gamma_j} = t_{\Gamma_j} \left(C_w + \frac{C_m}{n} \right) \tag{12}$$

Possible cableways at each landing were evaluated for cableway feasibility. Ground clearances were calculated according to Samset (1985) (often refered to as the Pestal approach (Pestal, 1961)). The locations of intermediate supports were found by the method of Leitner et al. (1994). For each landing, the closest tail was found from the predefined tail curve and if the cableway was feasible, it became the basic cableway of that landing. Tails within $75m$ of the closest feasible tail were located and feasible cableways were included in the set of possible cableways.

The results of Omnes (1980) were adapted for calculation of the yarding cost. The yarding time $t_{i\Gamma_j}$ is given by Equation (13) and the yarding cost by Equation (14). Note that the yarding time was reported in total time, not man hours.

$$\begin{aligned} t_{i\Gamma_j} = U_i\Big(&5.65 \cdot 10^{-2} + 2.42 \cdot 10^{-4} d_{i\gamma_j} - 1.67 \cdot 10^{-8} d^2_{i\Gamma_j} + \\ &5.67 \cdot 10^{-4} l_{i\Gamma_j} + 10^{-5} l^2_{i\Gamma_j} + 2.17 \cdot 10^{-2} g_{\Gamma_j}\Big) \end{aligned} \tag{13}$$

$$c_{i\Gamma_j} = t_{i\Gamma_j} \left(nC_w + C_m \right) \tag{14}$$

The average timber price was $\$60m^{-3}$ and the timber volume was $200m^3$ per hectare. The hourly machine cost, C_m, was $\$150h^{-1}$ and the hourly worker cost, C_w, was $\$40h^{-1}$. The number of workers, n, was 3.

2.2 Test cases

A digital terrain model (DTM) was used as input data. DTMs can be implemented in numerous ways, but a simple model can be a grid of vertices with x- y- and z-coordinates. In addition, a vertex has a timber volume, and can have other features, such as being a road or a tail. To test the metaheuristic in a controlled fashion, a DTM of a simplified hillside was generated. This DTM was modified by including obstacles at the hillside. The obstacles were a small hillock, a medium sized hillock, a big hillock and a ridge along the hillside. The hillside and the medium sized hillock is shown in Figure 4.

A real world unit was also evaluated. It is located in Gudbrandsdalen, Norway (lat. 61.658, long. 9.755), and was harvested in 2010. For this case, three variations were tested. The first variation was with parameters as described above. For the second variation, the harvested area was divided into three parts, as this area consists of three properties, with different owners. For the last variation, the timber price was set to $\$40m^{-3}$, the other parameters remained as described above.

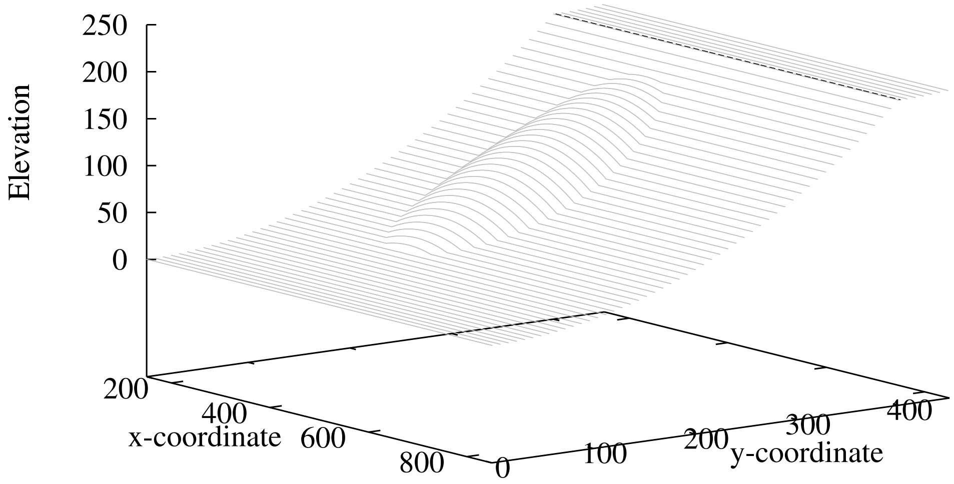


Figure 4: The generated hillside with a medium sized hillock.

The DTMs used had a grid size of $5m \times 5m$. The real world case was generated from airborne laser scanning data.

3 Results

For each case, Metaheuristic 1 was first tested with 1,000 repetitions with different selection percentages ranging from 0 to 40%, or if neccessary, 60%. A selection percentage of 0 cooresponds to a strict greedy heuristic, as it would then consist of selecting the best possible cableway locally at each step. From these results, we selected the selection percentage that seemed to give the best objective values, and did 10,000 more repetitions of the heuristic. For the real world case, Metaheuristic 1 seemed to yield the best overall objective values using a selection value of 15%, and the best overall objective value from 10 000 iterations was 101,558. However, optimization of the case was repeated with 20,000 additional runs for selection percentages 10%, 15%, and 20%, for a total of 71,000 iterations for that case. The best overall objective value found was 101,780, using a selection value of 10%. The results are given in Table 2.

The actual cableway layout used when the area was harvested was identified from aerial photographs. The calculated objective value was $\$100,453$ for the unit, which is slightly lower than the results generated by the heuristic.

4 Discussion

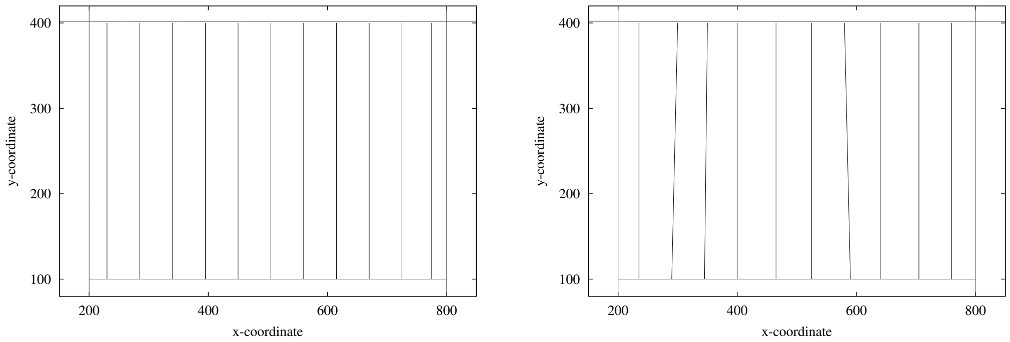
4.1 The simplified terrains

For the simplified terrain, without obstacles, the best solution was found both by the greedy heuristic and the semi-greedy metaheuristic by only considering the basic cableways. The net profit was $\$87,725$ (Table 2). For the full set of cableways, the solution found by the greedy heuristic had an objective value of $\$86,992$, whereas the semi-greedy heuristic improved the objective value to $\$87,432$ (Table 2). The solution for the basic cableways

Table 2: Results

Case	Best selection percentage (**selected**)	Objective value greedy heuristic ($)	% of best solution found	Objective value selection ($)	% of best solution found
Simplified hillside	**5**	86,992	99.2	87,432	99.7
only basic cableways	0, 5, **10**, 15	**87,725**		**87,725**	
Small hillock	**5**	86,486	98.7	87,376	99.7
only basic cableways	15, **20**, 30	86,742	99.0	**87,647**	
Medium hillock	**5**	86,796	99.2	87,105	99.6
only basic cableways	0, 5, **10**, 15	**87,496**		**87,496**	
Big hillock	**5**	85,528	99.0	85,887	99.4
only basic cableways	**15**	85,910	99.4	**86,391**	
Ridge obstacle	**15**	83,949	98.3	84,666	99.2
only basic cableways	10, 15, **20**, 25, 30	85,224	99.8	**85,361**	
Kvam	**15**	100,795	99.2	**101,780**	
Kvam, divided					
North property	**50**, 55, 60	13,978	97.2	**14,381**	
Middle property	**45**	53,399	97.8	**54,612**	
South property	**25**	31,380	98.7	**31,804**	
Sum		98,757	98.0	**100,797**	
Kvam, timber price $\$40m^{-3}$	**40**	19,723	95.8	**20,577**	

is plotted in Figure 5(a), where the cableways are parallel. The best cableway layout for the full set of cableways is plotted in Figure 5(b), and for this solution the cableways are not completely parallel. This is due to the choosen greedy evaluation function. The cableway added at each iteration will usually be slightly off parallel as a result of varying yarding cost (Figure 8) and the choice of area to evaluate in the greedy evaluation function (Figure 3).

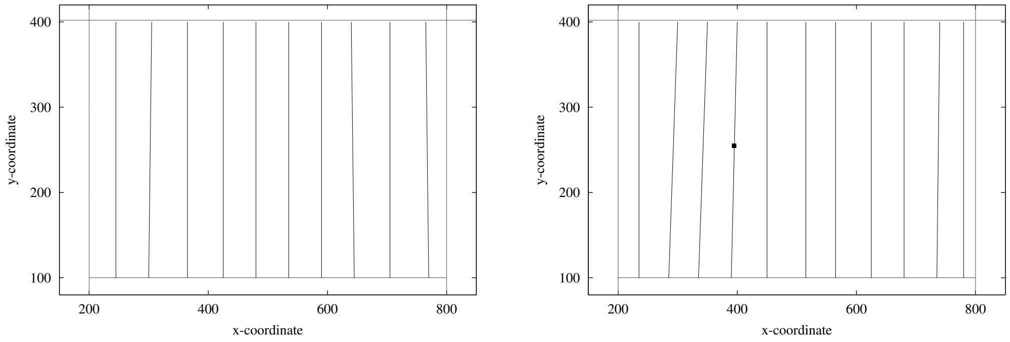


(a) Best solution found from basic cableways for the simplified hillside.

(b) Best solution found from the full set of cableways for the simplified hillside.

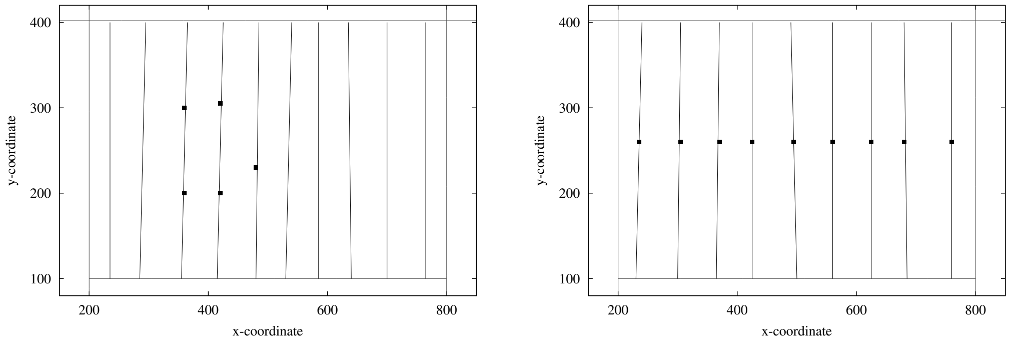
Figure 5: Best solutions for the simplified hillside without obstacles. The road is located at $y = 400$, the tail spar line at $y = 100$ and the other borders at $x = 200$ and $x = 800$.

When obstacles were included in the simplified case, the net profit decreased. The hillocks were centered at (400, 250), and for the small hillock in Figure 6(a), the best solution found for the full set of cableways were without intermediate supports. This was expected, as the hillock could be harvested from cableways at each side. For the medium sized hillock and the big hillock, however, this was not the case. The best solutions for the medium sized hillock and the big sized hillock required between one and five intermediate supports, as shown in Figure 6(b) and 6(c).



(a) Solution for the small hillock at (400, 250).

(b) Solution for the medium hillock at (400, 250).



(c) Solution for the big hillock at (400, 250).

(d) Solution for the ridge at ($y = 250$).

Figure 6: Best solutions from the full set of cableways. The dots are intermediate supports. The road is located at $y = 400$, the tail spar line at $y = 100$ and the other borders at $x = 200$ and $x = 800$.

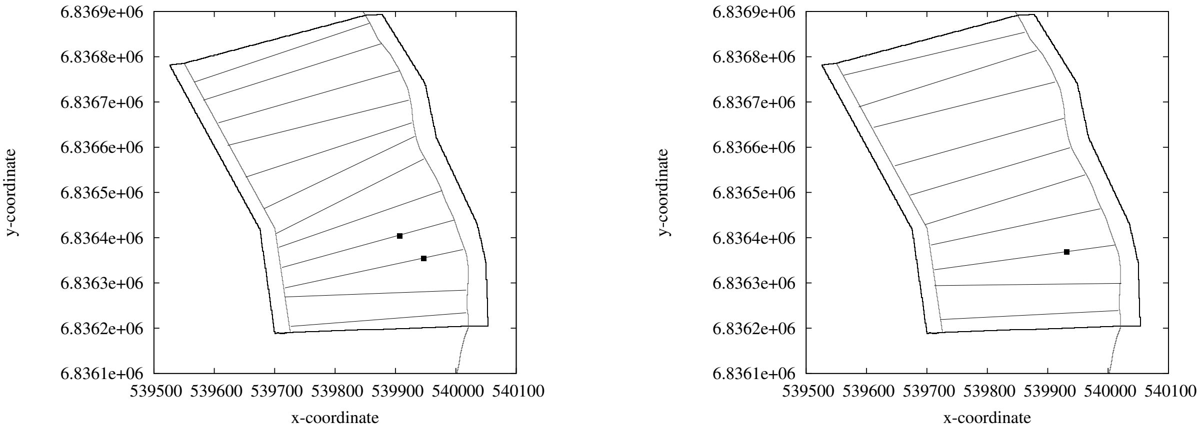
For the ridge along the hillside, the required intermediate supports increase the rigging cost, and one would expect that the maximum lateral yarding would increase compared to the hillside without the ridge. This was also the case in Figure 6(d).

In the generated cases, one would expect that more and larger obstacles will tend to increase the need for diversification of the search, but this was only partly so. For the full set of cableways, the best selection percentage was 5% for all the generated cases except for the ridge. For the ridge case, the best solution was found using a selection percentage of 15%. On the other hand, the differences in best objective value found between the full set of cableways and the basic set increase with obstacle size.

4.2 The real world cases

For the real world case, the best solution found is plotted in Figure 7(a), and yielded an objective value of $\$101{,}558$, with $4,103m^3$ timber harvested. The best solution used 12 cableways and three intermediate supports. For the case which involved a lower timber price, the harvested area decreased and the number of cableways also decreased (Figure 7(b)). For this case the harvested volume was $3,628m^3$ and the best solution used 10 cableways and one intermediate support.

The impact of the timber price to the solutions is due to the fact that the model disregards timber where the yarding cost exceeds the timber price. Figure 8 illustrates the yarding

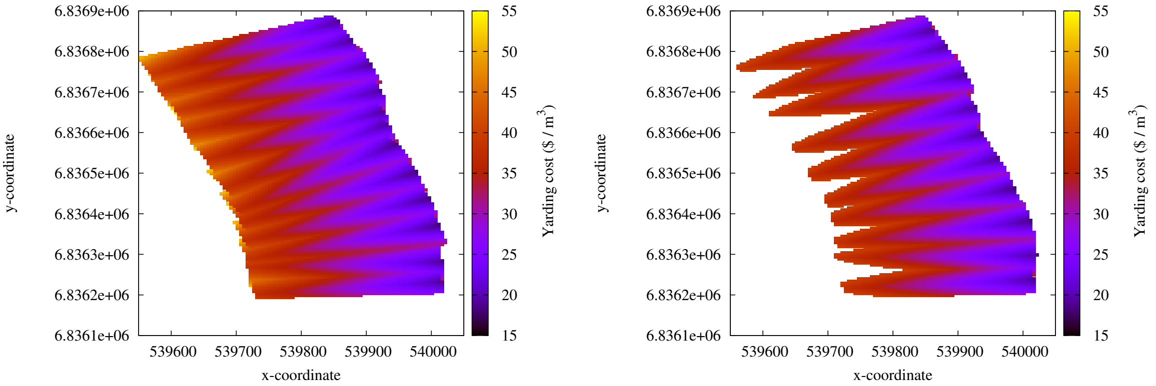


(a) Timber price $\$60m^{-3}$.

(b) Timber price $\$40m^{-3}$.

Figure 7: Best solutions found for the real world case.

cost, and also the area that was harvested. The increased lateral yarding for the case with a reduced timber price is expected, as the rigging cost is in a way assigned to the total volume harvested through a cableway, and a smaller harvested volume in the longitudinal direction is compensated with more volume havested in the lateral direction. However, the solution to the case with a reduced timber price has a practical and a computational issue. A harvesting layout which leaves some of the forest not harvested due to high harvesting cost is not popular among forest practioners. Although there are some reasons for harvesting the whole area (e.g. bark beetle attacks), the focus on retention patches (Franklin et al., 1997) and the fact that the forest owner in the end will have to pay the increased harvesting cost are reasons for leaving trees with high harvesting costs in the forest. The computational issue is that choosing not to harvest the areas with high yarding costs may reduce the required cableway length. Although this was not the case here (Figure 8), a reduction of the cableway length will also reduce the rigging cost. This was not included in the model.



(a) Timber price $\$60m^{-3}$.

(b) Timber price $\$40m^{-3}$.

Figure 8: Heat map of yarding cost, best solutions found.

The calculated objective value for the actual cableway layout used when the area was harvested was $\$100,453$. This is 98.9% of the best solution found. However, the layout used when harvesting the area may have been designed with other concerns, e.g. the area consists of three properties. For this reason, Metaheuristic 1 was tested for each property, with solutions yielding a total net profit of $\$100,797$ (Table 2, layout shown in Figure 9).

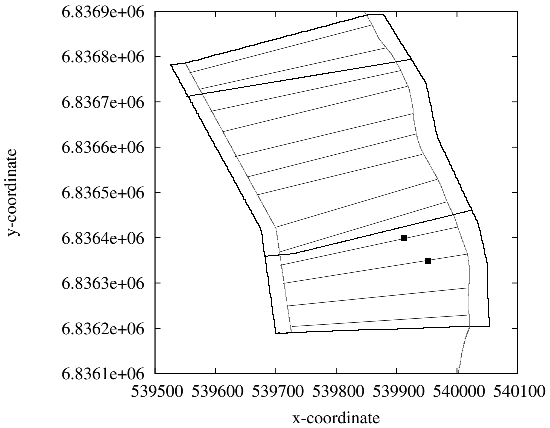


Figure 9: Best solution, the real world case solved for each property separately.

4.3 The model

The design and solution of a mathematical model consists of several steps which may result in a loss of information, and hence this may lead to a suboptimal solution for a real world case. Some simplifications are inevitable, such as the discretization of the terrain or which terms to include in the objective function. It may be possible to improve the accuracy of specific model terms. In this work, the possible tail spars were given as input of line segments approximately $300m$ from the forest road, and this disregards the fact that cableway options may include shorter lengths if the area's layout or the terrain dictates it. In the cited literature, possible cableways are found by evaluating the feasibility of cableways radiating from each landing and keeping the longest feasible ones. That approach is more applicable for yarding systems that require large (and hence few) landings than for the E-CLP in general and Metaheuristic 1 in particular. Metaheuristic 1 searches in two directions from a starting point, and is designed for systems that have nicely ordered tail spars (and landings).

Another simplification used here that may reduce the quality of solutions is how the possible cableways are found when matching landings with tail spars at the tail spar line. The method used first selects a basic cableway at each landing and then searches for cableways that fan out away form that landing. If too few possible cableways alignments are defined, solution times will decrease, but so too the quality of the solutions. Another issue is that the possible cableways will surround the basic cableway, increasing the probability of needing to add cableways close to the basic cableway. The basic cableway was the cableway to the tail spar closest to the particular landing. In Figure 9, the borders of the three properties are shown together with the best solution found for each property. The south and middle properties have a reasonable cableway layout, but the border between the middle and north property is not parallel to the cableway layout. This may indicate that property borders and other features of the yarding area should be included when choosing the basic cableways.

The design of metaheuristics is a compromise between guiding the search towards good solutions and diversifying the search to explore more of the solution space. In Metaheuristic 1, the diversification varies with the number of possible cableways defined at each landing and with the selection percentage (the number of alternatives under which the random selection is made in GRASP). For the rectangular and simplified map, the best solutions were found with only the basic cableways at each landing and with a short list of alternatives (corresponding to a percentages away from the greedy defined best move). For the real world case, the best solution was found with a selection percentage of 15%, but for the case with a reduced timber price, a selection percentage of 40% gave the best solutions. It is unclear why the case with reduced timber price needs more diversification than the case with a timber price of $\$60m^{-3}$, but Figure 10 shows small differences for the varying selection percentages. The mean objective value tends to decrease as the selection percentage increases.

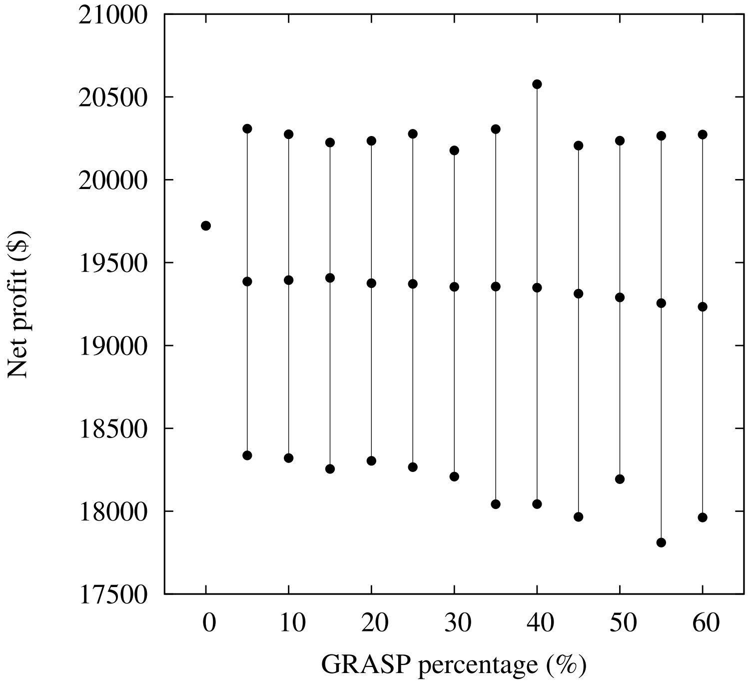


Figure 10: Objective values for different selection percentages. Kvam, timber price $\$40m^{-3}$.

5 Conclusions and future research

In this work a formulation for the E-CLP including lateral yarding is presented and solved with a greedy heuristic and a semi-greedy metaheuristic. In the real world case, the best solutions found by the two methods are only slightly better than the harvesting layout that was used. The greedy heuristic was almost as good as the semi-greedy metaheuristic, and has the advantage of being faster.

The CLP and the E-CLP are optimization problems that have received little attention in the literature, and the results indicate that further studies may be worthwhile.

5.1 Implications for operational planning

This work could be used by a forest manager or a contractor to create better harvesting plans. Although the improvement found by the metaheuristic was only 1.1% better than the layout used when the area was harvested manually, the improvement is expected to be larger in more difficult terrain. In addition, if a contractor can analyze the harvesting area before going there in person, their planning may be more efficient, reducing delays and problems.

The methods can also be used to find rules of thumb, e.g. an optimal lateral yarding distance. For the simplified terrain without obstacles, the best solution had a corridor width of $55m$, whereas the best solution for the simplified terrain with a ridge obstacle this value was $60m$. These values are a result of the cost functions used and perhaps functions from time studies of modern machines will result in different values.

5.2 Implications for strategic planning

Strategic forest planning involves a long planning horizon, and the cost of harvesting is an important issue. For the forest road location problem, this is especially so, as new forest roads have a high impact on the cost of harvesting. The forest road location problem is usually modeled hierarchically, and thus difficult to solve. Our study shows that the greedy heuristic is quite good (within 95.8% of the metaheuristic) and fast, and can be used as an estimate of the harvesting profit.

5.3 Future research

The quality of any optimization relies on good input data. The cited yarding cost function was adapted from older studies. Machines used today may have different levels of productivity. Although the rigging cost functions were modified based upon more recent studies, important aspects of rigging are not well described in the literature(e.g. the cost of intermediate supports).

A key element of Metaheuristic 1 is that the search is guided by the structure of presumeably good solutions (i.e. parallel cableways). The metaheuristic relies on good input data, in particular the possible cableway alignments. The question of how to select and include possible cableways in general, and the basic cableway in particular, is not thoroughly studied in this work. This task is not straightforward, and includes the delineation of the forest into yarding areas, identifying landings, tails and other borders. If the aim of such a task is input data for a Metaheuristic 1, the basic cableways should be designed from such an analysis. Another factor that may influence the solution quality but which is not thoroughly studied is the greedy evaluation function (line 10 in Metaheuristic 1). In facility location problems, adding locally good subsolutions to a solution sequentially is no guarantee for achieving a good solution overall. A future possibility for improving solutions might be to test other semi-greedy evaluation functions.

6 Acknowledgement

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Paper 5

Algorithms for estimating the suitability of potential landing sites

Algorithms for estimating the suitability of potential landing sites

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Abstract

Cable yarding systems are commonly used in steep or difficult terrain and require suitable landing sites. This work describes two algorithms that calculate the suitability of roads and areas for landing site use. The algorithms were tested against real world data. The results show that simple algorithms are sufficient to make stable, useful estimates that are comparable with human site placements. These techniques can be used to guide forest road network planning or reuse of existing roads.

Keywords: forest planning, forest operations, harvesting, cable yarding.

1 Introduction

Cableway harvesting is an important part of forest operations, as it is the primary method of harvesting steep and difficult terrain. In this method, a forest is harvested by a layout of cableways covering the area of the forest. Cableways collect timber from a large area and transport it to a landing site for temporary storage. They are time-consuming to set up, which affects production and profitability, and so landing sites are used as temporary storage areas to support cableways. The landing sites must be situated along the forest roads in appropriate positions.

The choice of position for a landing site has a significant impact upon the ease and profitability of operations. Large landing sites can store more timber, and are easier for timber trucks to access for loading. The gradient of a site is also important. Cable yarding is primarily used in steep terrain, and sites with locally shallower inclines are easier to operate and can store more timber.

A landing is essentially a temporary storage area for timber passing from cableway to truck transport or skidding. It is useful to classify two types of landings. A *landing by*

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convention is any part of a road where a tower yarder is set up. A *landing by construction*[1] is a built area typically used for larger cable yarders. In this paper a *possible landing* is any area around a point on a forest road or in the terrain evaluated for landing suitability. A *candidate landing* is a possible landing which has been selected as promising by an expert or mathematical model.

When planning operations, potential landing sites can be identified by an expert forester visiting the operations area. This requires an extensive site evaluation in person and a suitable skillset, which introduces costs and delays.

Forest operations could be made more efficient by systematically identifying potential sites with computers and remote sensing. Currently, industrial systems exist to support decision making about sites and cableways (e.g. RoadEng[2]), but these assist manual site surveying rather than replacing it.

This paper therefore identifies an unaddressed need for increased automation of site placement processes, and an opportunity to reduce manual surveying requirements and costs. The specific problem addressed here is: ‘For a given map, what is the suitability of each point as a landing site, based on a digital terrain model?’. The question, in this formulation, has not been studied before. Here, suitability is defined in terms of the storage capacity and truck access potential.

Two algorithms will be introduced that compute indicators of landing site suitability across a map, using only a digital terrain model derived from remote sensing data. These algorithms simplify the process of decision making, and if implemented in industry they will reduce or remove the need for an extensive manual site survey. This is the main contribution of this article.

After describing the algorithms, this paper analyses their behaviour and performance in several ways.

- A qualitative visual comparison of the output of the two algorithms.
- A comparison against real sites that were chosen in the area as part of a previous harvesting.

The findings are that both algorithms quickly produce similar results, which are comparable with previous site placement, without the need for further input data. Although there are opportunities for further study, the work appears to be suitable for practical use.

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[1] These two classifications are not found in the literature, but may be helpful to think about.

[2] url: www.softtree.com

2 Research problem context

2.1 Planning and optimization

Planning and optimization techniques have numerous applications in forestry, in operational, tactical and strategic planning (Church et al., 1998; Martell et al., 1998). Sometimes the objective is to enhance environmental values or public goods, but a more common goal is to maximize profits. The largest contribution to forest revenues comes from the sale of timber. The two major costs associated with this are the cost of harvesting and the cost of road construction. The latter cost is inherently strategic, as a forest road will be useful for decades or centuries, whereas harvest planning is an operational planning problem.

Currently, these problems are addressed at different levels of detail and calculation resolution, but developments in computers and remote sensing may allow detailed strategic planning models to be solved efficiently. This would bridge the gap between operational and strategic planning.

2.2 Methods of harvesting and yarding

Different harvesting systems are used throughout the world, and a large part of the harvested timber is produced using ground based systems. In steep or difficult terrain, cable yarding systems are commonly used (e.g. Bont, 2012). Cable yarding systems generally have a higher cost than ground based systems, because of the increased need for manual labor, and consequently there is more opportunity to reduce total costs through improved planning.

A commonly used yarding system in Europe is based on trucks equipped with a tower and a crane for processing and moving of timber. The trees are felled manually and yarded to the landing as whole trees. The trees are processed at the landing, and stacked for later transportation directly to the mill. European yarding systems operate largely in a parallel pattern along roads (Bont, 2012). With the assumption that existing roads are used, and with landings having the form of road areas used near the tower, this is a problem with only rigging costs and yarding costs. While the tower can be rigged at almost any location on the road, the terrain at a location will affect the productivity. The timber has to be released, processed and stored at the landing, and if the landing is too small, the operations are restricted. Truck loading costs may also increase at small or poorly positioned landings.

In contrast, American cable yarding systems are in general larger than the European systems, and tree length harvesting requires more space for log storage. To meet these requirements, landings have to be constructed. Assuming that existing roads are used, this is a problem consisting of landing construction cost, rigging cost and yarding cost. The construction cost of a landing site is dependent on the terrain before construction, and use of a landing may incur extra costs if the resulting landing is too small. For this case, manual landing evaluations may be time consuming, and automated landing evaluations may improve the cost estimates.

2.3 Operational analysis in forest operations

An early example of operational analysis of cable yarding systems and road location is Dykstra and Riggs (1977), who formulated a facility location model for the American cable yarding problem including yarding cost, cableway rigging cost, landing construction cost and road construction cost. This formulation is a hierarchical problem, as the roads, landings, cableways and yarding are at different levels. A solution for one level depends on and affects the solutions at all other levels. Hierarchical problems are inherently difficult to solve to optimality. At some problem size, storage resources or computational resources prohibit exact solutions. Their work is not directly applicable to the European problem, as experienced in Norway.

The problem complexity is highly influenced by the number of variables, and for spatial planning, the variables are commonly linked to a grid or some representation of the terrain. The number of variables can be reduced by changing the grid resolution or by restricting which grid points that can be selected (e.g. as landing or road). The selection of candidate landings for cableway planning and road location problems is usually manually performed by human experts (Dykstra and Riggs, 1977; Chung, 2002; Epstein et al., 2006; Bont et al., 2012).

However, for solutions utilizing high resolution digital terrain models, the number of grid points evaluated as possible landings can be large, and thus it is neither straightforward or trivial to obtain manual landing site evaluations for all possible landings. Computer systems may be used to assist human analysis, but these systems do not independently select candidate landing sites and there is little discussion of approaches to this problem in existing literature.

The idea behind this paper is therefore to replace the role of the expert with a suitability estimation algorithm. This would improve the speed of analysis, reduce costs and delays, and has the potential to improve the quality of the evaluation relative to manual analysis.

Furthermore, in terms of productivity studies (as opposed to site selection), presently there are no examples in forestry literature describing how to estimate landing site usage costs from digital terrain models as part of overall forest operational analysis. The technique of this paper might provide the basis of a cost model.

In Chung (2002), possible landings were analyzed by numerically calculating the feasibility of 36 cableways radiating from the possible landing in a star-shaped pattern, and the landing was graded by the size of the area that could be harvested by the cableways. This method was also used by Stückelberger (2008), who used the results for guiding the optimization of new forest road locations. Although the forest area covered by a landing is an important feature of a good landing, their method disregards the importance of the terrain close to the tower.

2.4 Specific problems addressed in this paper

The aim of this study was to design algorithms to predict the quality of possible landings on a local scale, and compare the algorithms. Such algorithms can link productivity studies aimed at finding cost parameters in forestry, and forest planning research. Whereas forest planning research has been utilizing high resolution spatial data for some time (a recent review is Akay et al., 2009), there are few reports of productivity studies linked to spatial location in general, and landings in particular.

The first algorithm calculates the amount of timber that can be stored at a road location. The second algorithm returns a mean absolute elevation difference of a point in the terrain or at a road location, and is thus easier to calculate and can be used off-road. The two algorithms were tested with a real world forest site, and the results compared. The results were compared with the landings used when the area was harvested previously. These were manually identified from aerial photographs. Finally, some rules of thumb for landing assessment are briefly discussed.

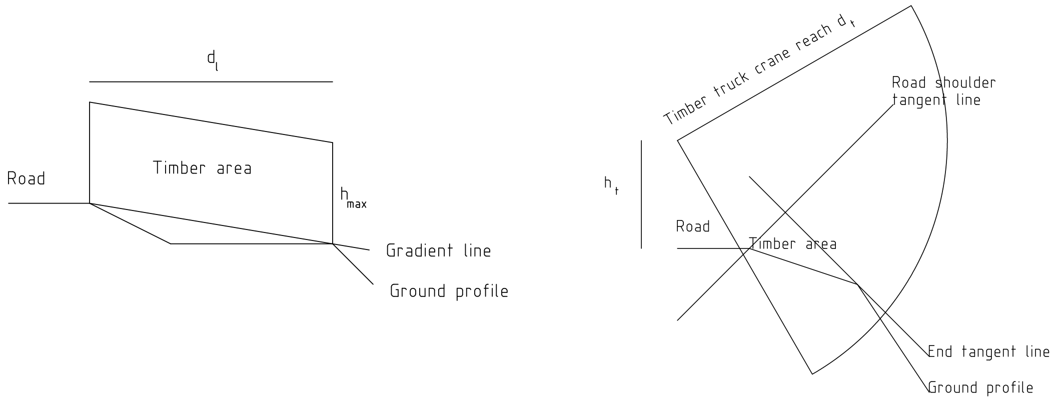
3 Method

3.1 Problem definition

The specific problem addressed here is: ‘For a given map, what is the suitability of each point as a landing site, based on a digital terrain model?’. Here, suitability is defined in terms of the storage capacity and truck access potential.

A key characteristic of a good landing is the possibility to stack logs, while still being able to process more trees. The timber volumes that can be stored at a road location depend on the road profile extended some meters into the terrain, depending on the reach of the crane of the equipment subsequently handling the wood.

Algorithm 1 was designed to estimate the amount of timber that can be stored at a possible landing. The inputs to the algorithm are a Digital Terrain Model (DTM) and the road location. The principle of the method is shown in Figure 1. From the possible landing, the centerlines of the road some distance d_c in front and behind are located, and ground profiles perpendicular to the centerlines are found at regular intervals. If the gradient between the road shoulder and the point some distance d_l (i.e. the maximum log length) from the road shoulder is not too steep, the logs can be piled perpendicular to the road, and the maximum timber pile area at that ground profile line is $d_l \times h_{\text{max}}$, where h_{max} is the maximum timber pile height (Figure 1(a)). If the profile is steeper, the timber has to be stacked parallel to the road (Figure 1(b)). In this case, the reach of a timber truck is considered first, and the timber is assumed to be stacked 45° up from the road shoulder and from the farthest profile point that could be reached.



(a) Area for perpendicular stacking.

(b) Area for a steep profile with parallel stacking.

Figure 1: Calculated pile area.

Algorithm 1 MAXLANDINGVOLUME

```
Find road centerlines $c_a$ ahead and $c_b$ behind the possible landing (of length $d_c$).
$V \leftarrow 0$
for $c_a$ and $c_b$ do
    Find average spacing $L$ between grid points of the centerline.
    for grid points $x_j$ in centerline do
        Find left and right ground profile lines ($p_l$ and $p_r$) perpendicular to $x_j$ (of length ($d_p$)).
        for $p_l$ and $p_r$ do
            Find the gradient $g$ from the road shoulder to the ground point one timber length ($d_l$) distance off the road.
            if $|g| \leq g_{\text{max}}$ then
                $A \leftarrow d_l \times h_{\text{max}}$
            else
                Find point on ground profile line within reach of a timber truck.
                Find the line $45°$ up from the road shoulder.
                Find the line $45°$ down that tangents the ground profile.
                Find the line at road elevation $z_r + h_{\text{max}}$.
                $A \leftarrow$ the minimum area above the ground profile and below the three lines.
            end if
            $V \leftarrow V + A \times L$
        end for
    end for
end for
return $V$
```

A simpler algorithm for landing evaluation is presented as Algorithm 2. In this algorithm, a measure of the landing suitability f is found as the sum of the mean absolute values of the elevation differences for grid points within a radius d_r of the possible landing. If the terrain is flat, f will be close to zero, but f will increase with steeper terrain. f is essentially measuring the steepness of the terrain.

Algorithm 2 SUMOFABSOLUTEDIFFERENCES

```
$z_i \leftarrow$ the elevation at grid point $x_i$.
$f \leftarrow 0$
$n \leftarrow 0$
for grid points $x_j$ within radius $d_r$ of $x_i$ do
    $f \leftarrow f + |z_j - z_i|$
    $n \leftarrow n + 1$
end for
return $f/n$
```

Both algorithms were tested for a real world terrain near Kvam in Gudbrandsdalen in Norway (lat. 61.658, long. 9.755), shown in Figure 2. The DTM was generated from airborne laser scanned data, and a $1m \times 1m$ grid was used. For Algorithm 1, the centerlines in front and behind were of length $d_c = 10m$, the perpendicular ground profile length was $d_p = 7.5m$ and the maximum gradient was $g_{\text{max}} = 0.25$. The maximum timber length was $d_l = 5.5m$ and the maximum pile height was $h_{\text{max}} = 2.5m$. The cranes of timber trucks were assumed to be attached to the truck at a height of $h_t = 3m$, and the maximum crane reach $d_t = 7.5m$. For Algorithm 2 the radius was set to $d_r = 10m$.

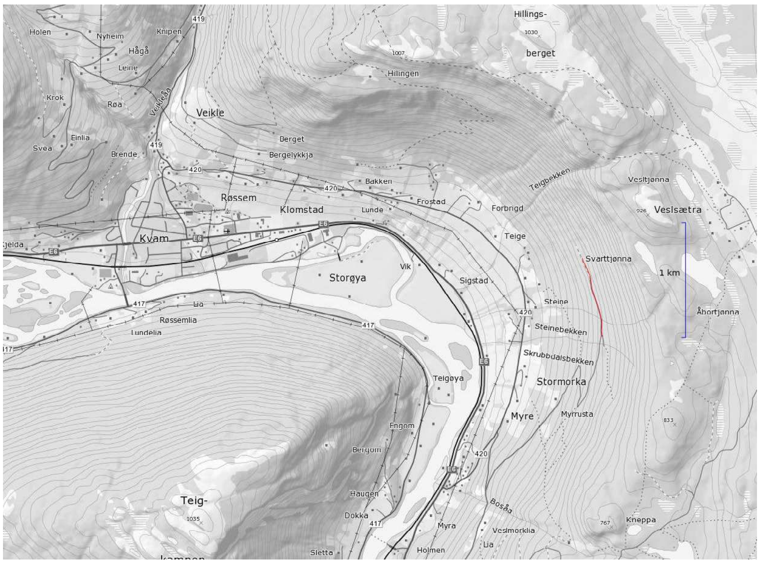


Figure 2: A map of the area where the forest road is located (red curve).

To compare the algorithms, the values returned by the algorithms were normalized. The normalized volume was $\hat{V} = (V - V_{\text{min}})/(V_{\text{max}} - V_{\text{min}})$, and the transformed normalized landing value was $\hat{f} = 1 - (f - f_{\text{min}})/(f_{\text{max}} - f_{\text{min}})$. Although the original units are different, it is the relative score that is important, and so they can be compared usefully.

4 Results

Algorithm 1 returned values for maximum timber storage that ranged from $146.3m^3$ to $612.5m^3$. The values along the road are plotted in Figure 3.

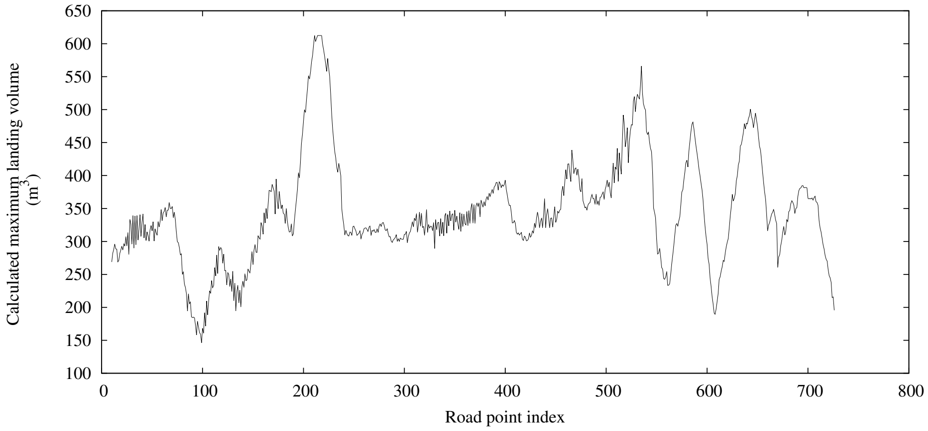


Figure 3: Maximum landing timber volumes along the road.

Algorithm 2 returned landing values that ranged from $0.24m$ to $2.46m$. The values along the road are plotted in Figure 4.

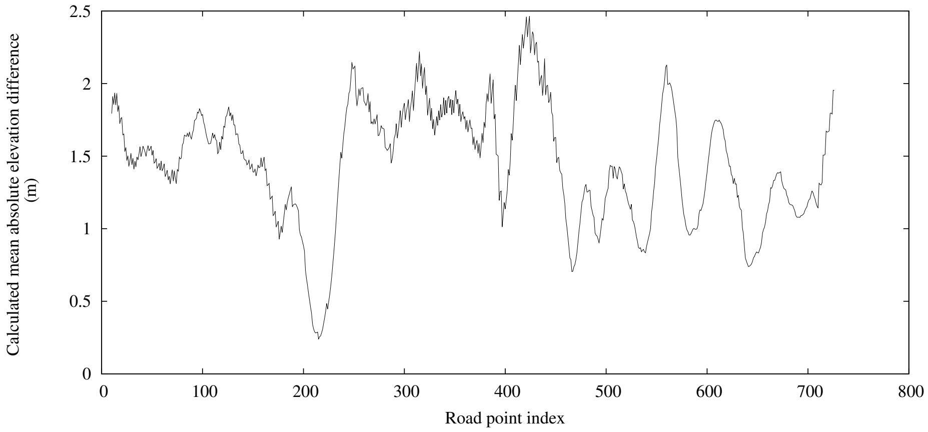


Figure 4: Sum of absolute differences along the road.

The normalized values returned by the two algorithms are plotted in Figure 5, together with vertical lines representing the landings manually identified from aerial photographs by the author.

Algorithm 2 was also tested with the entire area of the terrain, and returned landing values between $0.22m$ and $6.22m$. A heat map of the results is given by figure 6. To improve contrast, the scale was limited to 0 – $4m$ (i.e. black represent values $4m$ – $6.22m$).

5 Discussion

Qualitatively, the results returned by Algorithm 2 were compared with the results of Algorithm 1 in Figure 5. The results from the two algorithms diverge at some parts of the road,

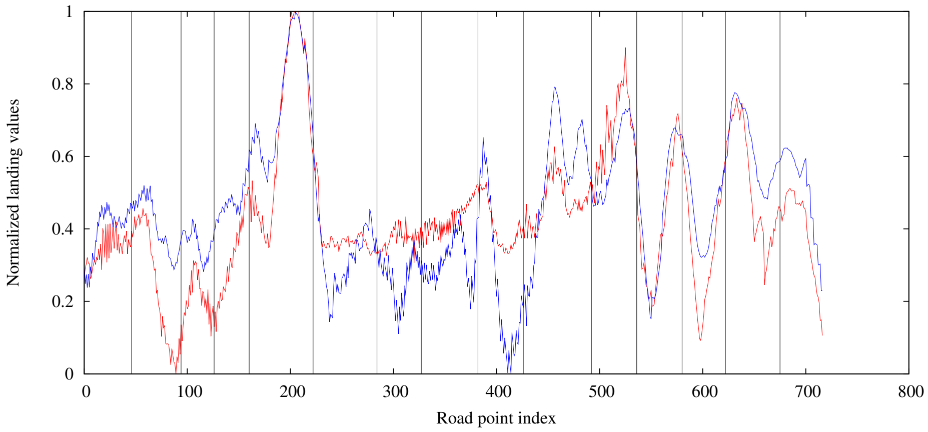


Figure 5: Normalized volumes (red) and transformed normalized landing values (blue) along the road. The vertical lines show the location of landings identified from aerial photographs.

but the derivatives of normalized landing score along the road are more consistent. When the landing score of one algorithm increases, the landing score of the other increases too.

Figure 5 also shows that the landing scores relate quite well with the landings used by the yarding contractor historically. The exit of the forest road is to the right in Figure 5, and the harvesting system processed the trees on this side of the truck. Landings (numbered from the left) 1, 2, 3, 4, 8, 9, 10, 13 and 14 all have increasing landing scores to the right of the vertical line. Landings 5, 6, 11 and 12 have decreasing landing scores, but the landing scores are in general above average.

For Landing 2 and 3 both algorithms returned low landing scores, and the landings are close to each other. This may be due to the fact that Landing 1 and 2 were located at a different property than Landing 3. Keeping the harvesting of each property separate may have lead to suboptimal landing selection by the human contractor. We do not know if this was a constraint on their work.

Both Algorithm 1 and Algorithm 2 ran quickly - a few seconds of CPU-time for the road and the area calculations. The algorithms are summing a finite set of values, and the computational complexity is $\mathcal{O}(n)$, where n is the number of evaluated points.

These landing suitability indicators can be used as input for several planning problems, including cableway and tower location planning, for limiting the number of candidate landings in such problems, and for estimating landing and road construction costs.

5.1 Using landing scores to improve cableway location planning for small tower yarders

In the European system, small tower yarders do not use constructed landings. Instead, they use any suitable location on existing roads. Such operations could be modeled as a facility location problem including rigging as a facility building cost and yarding as a facility usage cost. However, the quality of the landings may also affect the profitability of the operation.

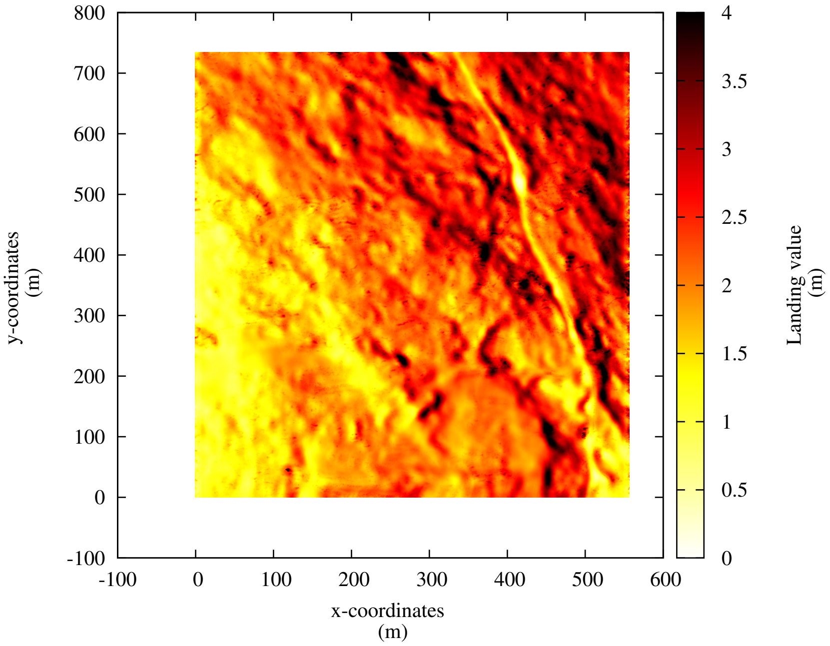


Figure 6: Heat map of the sums of absolute differences.

One approach could be to add a landing use cost in the objective function. This is not straightforward, as the landing use cost is highly stochastic and a result of interaction between the yarder and the truck removing timber. The yarder may experience reduced productivity due to delays, inefficiency or timber handling, and the loading of the truck may be inefficient if timber has to be short hauled to temporary storage or to the truck trailer. Also, the truck routing may be inefficient if the truck has to rush to the landing to relieve the yarder. There are no published studies of landing use costs, and defining a cost function is presently guesswork. One possible approach might be to estimate the total timber volume to be harvested at the landing, as well as the landing score, and define a two-dimensional table or function returning estimated costs.

If there are very many candidate landings, heuristic or metaheuristic solvers may be required depending on the problem instance size and complexity instead of algorithmic approaches. If the number of candidate landings has to be reduced, the landing score can be used as a cut-off.

5.2 Selecting candidate landings from all possible landings

Selecting candidate landings from all possible landings may be necessary both for constructed landings and road landings used by smaller tower yarders. The problem of selecting candidate landings was briefly discussed by Chung (2002) but is not formally defined in the literature. Which qualities should a good candidate landing set possess? Some possible criteria are:

1. All or most of the candidate landings should have a high landing score.
2. The set of candidate landings should be dispersed along the forest road to cover the area, at least for small yarders operating in parallel.

3. The set should be small enough to meet the requirements of the solver of the cableway location problem.

Unfortunately, criteria 1 and 2 can conflict, as the landing score may vary along a forest road.

The problem of how to reliably select the best candidate landings from all possible landings is beyond the scope of this paper. The landing scores from these two algorithms may be a useful tool.

5.3 Estimating landing construction cost and road construction cost

Landing construction costs are seldom discussed in the literature. Road construction costs are more studied, and Heinimann (1998) included a cut area contribution as well as a drainage contribution and a pavement surface contribution in the cost calculations. It is reasonable to assume that a similar cost function could be used for landing construction costs.

Algorithm 2 calculates the mean absolute elevation difference within a circle of a given radius. Flat terrain will result in low landing scores, whereas steep terrain yield high landing scores. Thus, the landing score will be correlated with cut volumes, and can be used for estimating the cut volume contribution to both landings and roads.

5.4 Landing scores for road planning

One advantage of Algorithm 2 over Algorithm 1, is that it can be used for any point in the landscape, not only roads. This feature can be useful for choosing the location of forest roads. The landing score shown in Figure 6 can be used in the same manner as in Stückelberger (2008), though these measures are looking at different problems in site placement.

6 Conclusions and future research

Two algorithms were developed for landing detection and evaluation, and tested against data from a real world site. The results show that the two algorithms have a similar ability to locate potentially good landings, and that volume storage capacities vary along the road. Furthermore, Algorithm 2 can be used for evaluating areas of terrain, a necessary feature when planning new forest roads.

It might be interesting to investigate how the micro topography in the vicinity of landings affects the cost of yarding operations.

Landing suitability has an impact on forest planning, and should be incorporated in industrial optimization models.

6.1 Acknowledgment

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