Forestry *An International Journal of Forest Research*

Institute of Chartered Foresters

Forestry 2019; **93**, 163–177, doi:10.1093/forestry/cpz058
Advance Access publication 29 November 2019

Joining up optimisation of wood supply chains with forest management: a case study of North Karelia in Finland

Hyvönen Pekka[1,*], Lempinen Reetta[1], Lappi Juha[2], Laitila Juha[3] and Packalen Tuula[1]

[1] *Natural Resources Institute Finland (Luke), Bioeconomy and Environment, Yliopistokatu 6 B, 80100 Joensuu, Finland*
[2] *University of Eastern Finland, Faculty of Science and Forestry, School of Forest Sciences, PO Box 111, 80101 Joensuu, Finland*
[3] *Natural Resources Institute Finland (Luke), Production Systems, Yliopistokatu 6 B, 80100 Joensuu, Finland*

*Corresponding author. Tel: +358 29 532 5178; E-mail: pekka.hyvonen@luke.fi

Received 28 January 2019

This paper presents a spatially explicit methodology for integrated forest management and wood supply chain optimization over time in the context of a Finnish forest strategy anticipating new investments and renewal of business in the wood processing industry. The Finnish MELA simulator was used to generate multiple treatment schedules over time at the management unit level – each treatment schedule providing unique estimates of extracted wood volumes by different assortment categories for each time period. The J linear programming (LP) software was used to analyse different regional forest strategies in terms of wood supply and transportation costs to multiple market destinations. The analysis revealed clear differences both in wood flows and forest resources between strategies maximizing wood supply or optimizing wood supply to market destinations. In addition, the wood flows appeared responsive to new mill and increased demand. Further, the changes in factory price had a heavier impact on pulpwood supply than on sawlog supply. The same methodology can be applied for analysing the impact of new factories on wood flows from forest to factories and between factories or to support forest enterprises in planning their wood supply over multiple time periods and multiple destinations.

Introduction

Forestry plays an important role in climate change mitigation (Eriksson *et al.*, 2012; Packalen *et al.*, 2017). First, trees store carbon. Second, wood-based products are therefore carbon sinks. Third, wood-based products and energy can substitute for fossil-based products and energy. In this era of climate change mitigation, there is an obvious and increasing demand for wood both as a raw material and as an energy source.

From the long-term forest managerial perspective and subject to certain ecological, social and economic sustainability constraints, it is important to maximize the discounted flow of future net income based on multiple forest products and services. For the wood user, this means that not all standing timber in the area surrounding the factories will be available as wood supply in the short term. Consequently, when defining a regional forest strategy balancing the needs of the forest-based industry with other forest-related interests, there is a need for the integrated optimization of wood supply and forest management.

In recent years, numerous optimization models have been developed for wood supply chains and forest management (Weintraub and Romero, 2006; D'Amours *et al.*, 2008; Bettinger *et al.*, 2009; Gunn, 2009; Shahi and Pulkki, 2013; Marques *et al.*, 2014; Hoganson and Meyer, 2015; Rönnqvist *et al.*, 2015). Typically, supply chain optimization identifies the best possible transformation and transportation strategy, tactics and operations from the industry's point of view for a given forest resource, while forest management optimization tries to fulfil the objectives of the owner or manager of the resource. The focus of forest management optimization has mainly been on industrial or state forests supplying their own industry (e.g. Borges *et al.*, 2014a; Bouchard *et al.*, 2017). For the estimation of regional supply from owners with heterogeneous objectives, either forest sector models (for a review see Toppinen and Kuuluvainen, 2010; Sjølie *et al.*, 2015) or forest resource projection models (for a review see Barreiro *et al.*, 2016) have been applied. Actually, there are studies (e.g. Borges *et al.*, 2014b, 2017) concerning forest management planning problems involving forested landscapes with heterogeneous land tenures and/or stakeholders. However, these studies do not include transportation costs into factories as part of the optimization. In addition, there are models such as DTRAN (Hoganson and Kapple, 1991) that recognize explicit harvest timing and multiple product flows over time to different market locations (i.e. factories).

The Finnish JLP software (Lappi, 1992) uses linear programming (LP) to efficiently solve the problem where there are several treatment schedules over time for forest management units, and the goal is to select the optimal combination of schedules for a forestry unit, i.e. for an estate or a region. As a part of the Finnish MELA software, JLP has been used to analyse the regional or national impacts of different forest strategies in terms of wood supply (e.g. Nuutinen *et al*., 2000, 2006; Kärkkäinen *et al.*, 2008; MELA Summary Reports, 2017) or carbon sequestration (e.g. Matala *et al*., 2009; Kallio *et al.,* 2013). The MELA software has two components, a stand (later referred to as a management unit) simulator and a forestry unit (later referred to as a region) level optimizer, integrated under the same control mechanism and a report writer to allow the smooth transfer of decision variables from the simulator to the optimizer (Redsven *et al.*, 2012). The MELA/JLP summary results for regions also have been disaggregated and spread for analysing the impact of various ecological and technical constraints on the potential wood supply (Nivala *et al*., 2016). As far as we know, there have been only a limited number of studies that analyse the impacts of new development plans of the forest-based industry and energy use at the regional level. In fact, we know of only one (Jaakko Pöyry Consulting Inc, 1994).

Originating from JLP, the J software (Lappi and Lempinen, 2014a) has a new functionality that incorporates the wood supply chain into the forestry unit optimization problem. J is a generic tool adjustable for different types of optimization tasks but tailored for optimal efficiency in a specific type of problem typical in forest management planning (e.g. Bergseng *et al*., 2012). In J, the decision variables for transport (shipping) options to multiple markets (factories) are explicitly enumerated (Lappi and Lempinen, 2014a).

This paper presents a study on the optimization of forest management for wood supply in the context of Finnish forest strategy anticipating new investments and renewal of business in the wood-processing industry. The first objective was to compare different regional forest strategies in terms of harvested and transported volumes as well as treatments in forests. The second objective was to analyse the impacts of market changes on those volumes and treatments. The study is based on the combined use of the Finnish MELA stand simulator and the J software.

Materials and methods

Overview of the study area and framework

The study area, North Karelia, is located in Eastern Finland (Figure 1). The forestry land area comprised about 1.6 million ha of which forest land covered 1.5 million ha (MELA Summary Reports, 2017). Almost 60 per cent of the forest land and growing stock were owned by private forest owners (MELA Summary Reports, 2017). Finnish National Forest Inventory (NFI) sample plots and trees (Korhonen, 2016), measured in the field in the years 2009–2013, were used as initial data for the analysis (Figure 1). An overview of the data sources, main calculation steps and outputs of the study are shown in Figure 2.

The planning horizon was 50 years and treatment schedules for the management units were generated with the MELA simulator (Redsven *et al.*, 2012) for five 10-year sub-periods. For each treatment schedule, decision variables were calculated. The J software (Lappi and Lempinen, 2014a) was used to solve the optimization problems based on data describing the treatment schedules, factories and transportation costs. The solution defined both the transported volumes and optimal treatments for forest management of units over time.

Simulation of treatment schedules

There were 5130 sample plots, and each plot was considered to represent one management unit. The MELA stand simulator (Redsven *et al*., 2012) uses models for individual trees (e.g. Hynynen *et al*., 2002 Jutras *et al*., 2003) when simulating growth, mortality and yield including volumes of harvested trees in different assortment categories (Malinen *et al*., 2007; Nuutinen *et al*., 2009). Therefore, NFI tally tree data such as tree species and diameter at breast height were augmented using sub-model predictions to compensate for missing MELA sample-tree variables such as height and age, and MELA sample-plot variables were derived using the sample plot data. For the simulation, management units were constructed and classified into three management categories based on ecological and social objectives available as spatially referenced data: (1) no restrictions on wood production, (2) restrictions on wood production exist, but wood production is not totally forbidden and (3) no wood production is allowed. In the first category, all typical forest management measures such as thinning and regeneration cuttings were allowed, in the second category, clear cuttings were forbidden and in the third category, all forest management measures were forbidden. The first category covered about 83 per cent of the data and the second about 6 per cent, both spreading evenly throughout the study area. The third category covered about 11 per cent of the data, concentrating mainly on the eastern and northern part of the study area.

The MELA simulation is based on a user-defined set of rules for feasible options for treatments. The rules are based on management category, site and tree data (e.g. minimum age or mean diameter for final felling). Treatments were simulated at the midpoint of each sub-period for individual management units. The Finnish forest management recommendations (Äijälä *et al*., 2014) were used to control the simulations and feasible forest management actions and outputs. These included clearing and soil preparation of the regeneration area, seeding and artificial regeneration, tending of young stands, first thinning (based on the number of stems), thinning (based on basal area), final felling and seed tree and shelterwood cutting for natural regeneration. Each management action was carefully controlled during simulations. For example, first thinning can take place as several criteria are met: like minimum removal (stems per hectare), minimum mean diameter and maximum mean height before thinning. After first thinning, there must be enough remaining stems; e.g. with Scots pine (*Pinus sylvestris* L.) growing on mesic sites at least 1100 stems. In addition to the simulated management activities, there was always a no-treatment alternative for every management unit.

In Finland, industrial wood is harvested using the cut-to-length (CTL) method for final felling and thinning. In the CTL method, both delimbing and crosscutting into different assortments are carried out at the stump, and fractions of trees from a

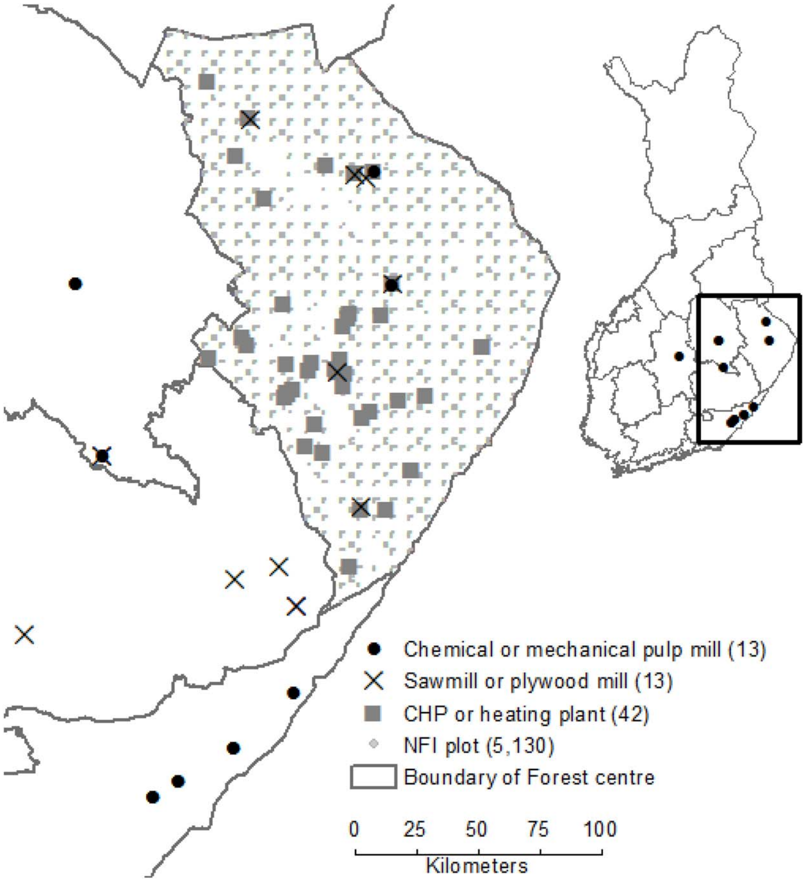

Figure 1 NFI sample plots and factories used in analysis.

specific unit can be transported to different mills. In this study, both options related to industrial wood harvesting as well as options for extracting or not extracting energy wood, either as a by- or main-product, were simulated. Energy wood removal could consist of stems, logging residues, stumps and roots. Altogether, there were 1 083 981 treatment schedules, with an average of 211 per management unit, for which the decision variables such as volumes of growing stock and removal, income as well as silvicultural, harvesting and off-road transportation costs were calculated.

Factories and transportation costs

In the study area, there are 50 factories of which five are sawlogs, one is a plywood mill, two are chemical or mechanical pulp mills and 42 are heat or combined heat and power (CHP) plants (see Figure 1). In addition, eleven chemical or mechanical pulp mills and seven saw or plywood mills located in neighbouring areas were included in the model. For each mill and plant (later referred to jointly as factories), the location (as coordinates in the Finnish reference system), the maximum technical capacity and the recipes were derived from public sources (Finnish Forest Industries Statistics, 2018).

The maximum technical capacity refers to how much raw material, such as pulpwood, a factory can utilize during a year. The recipe for tree species describes whether, and if so, how, a factory can combine different tree species with specific requirements for the dimensions and quality. Six of the chemical or mechanical pulp mills can use only one tree species (five of them use softwood and one hardwood), three chemical pulp mills can use a mixture of softwoods and four can use a mixture of both softwood and hardwood. Norway spruce (*Picea abies* (L.) H. Karst) pulpwood is primarily intended for mechanical pulping, but it can also be used for chemical pulping of softwood species. In Finland, the most common hardwood species is birch, either silver birch (*Betula pendula*, Roth) or downy birch (*Betula pubescens* Ehrh.), hereafter collectively referred to as birch. Both can be used as sawlogs by sawmills and plywood mills, as pulpwood by chemical pulp mills and in various forms for heating or combined heating and power production. In our study, only broadleaved (hardwood) species logs other than birch could be transported to chemical pulp mills. Further, other hardwood, pulpwood and logs than birch could be transported to heating or CHP plants, and not just energy wood. The total capacities of the factories are presented in Table 1.

For the modelling of wood supply chains, we used factory prices and road transportation costs. A factory price means the price for a timber assortment when at the factory gate. As the factory price for sawlogs we used 80€ per m^3 (softwood) and 70€ per m^3 (hardwood), and for pulpwood 47€ per m^3

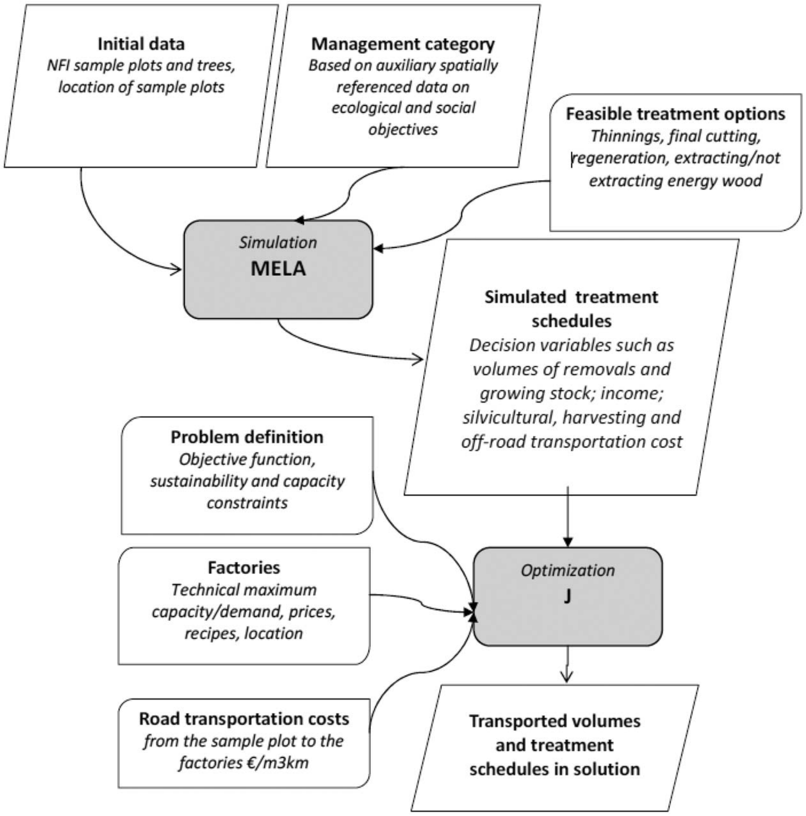

Figure 2 Overview of the simulation and optimization framework used in the study.

Table 1 The sum of the maximum technical capacities (1000 m^3 a^{-1}) of all factories in the model (capacity of factories located in North Karelia in brackets).

	Pine	Spruce	Softwood	Hardwood	Total
Sawmill or plywood mills	1074 (1045)	2407 (1260)	3481 (2305)	665 (165)	4146 (2470)
Chemical or mechanical pulp mills	18 850 (1560)	21 457 (1840)	21 457 (1840)	7661 (1040)	29 118 (2880)
Heating or combined heating and power (CHP) plants					473
Total	19 924 (2605)	23 864 (3100)	24 938 (4145)	8326 (1205)	33 264 (5350)

Because some of the industrial wood users can use a mixture of tree species collectively referred to as “Softwood”, “Softwood” is not a sum of “Pine” and “Spruce” and “Total” is not a sum of “Softwood” and “Hardwood”. Note: For privacy reasons, we do not document here the separate capacity of each factory even if these data were used in the modelling.

(softwood) and 49€ per m^3 (hardwood) as reported by the public sources (Suomen metsäteollisuuden kilpailukyky, 2012). For the energy wood factory price we used 36€ per m^3, which was based on the information on the statistical web-service that gathers information on the realized, two most recent months’ prices from both the “buyers and sellers” base (Metsäpohjaisen energian hinta käyttöpaikalla, 2018). The price of energy wood varies several Euros depending on the season. We found prices varying between about 32 and 40€ per m^3 (calculated from € per KWh), so we used 36€ per m^3 as an average price.

Road transportation costs for logs, pulpwood and energy wood (Strandström, 2018) were expressed as euros per transported cubic metre kilometre (€ per m^3km). For sawlogs, the transportation cost was 0.07€ per m^3km, for pulpwood it was 0.09 and for energy wood, 0.1. Because the coordinates for every sample plot and every factory were known, distances along roads from each sample plot to each factory and from each sawmill or plywood mill to each chemical and mechanical pulp mills were calculated using the DigiRoad data and Network Analyst in ArcGIS. For each sample plot, the nearest point of the road was solved, and calculation of the transportation distance to factories started from that point. There were 59 cases that Network Analyst couldn’t produce distance from sample plot to factories. The most common reason for this was that the nearest road to a sample plot was just a short piece without connection to the whole road network. For these sample plots, we used the closest sample plot's transportation distances to factories. Factory prices and transportation costs were kept at the same level for all periods.

According to Ylitalo (2018), about 9.8 million m^3 of sawmill wood chips and sawdust were utilized by the pulp and paper industries in secondary wood consumption in 2017. In our study, this secondary wood consumption was taken into account; 30 per cent of log volumes transported into sawmills and 31.5 per cent of log volumes transported into plywood mills were converted into sawlog chips (Metsätilastollinen vuosikirja, 2014), which were allowed to be transported to certain chemical and mechanical pulp mills.

Optimization

In our study, there were many treatment options for management units and many factory options for all harvested volumes. Our primary objective was to compare three different forest strategies in terms of harvested and transported volumes as well as treatments in forests. For the comparison, we selected strategies corresponding to: (1) the National Forest Strategy 2025 (2015), i.e. maximum sustainable harvest (SusSupply), (2) maximum wood supply (MaxSupply) and (3) demand-driven harvest (Demand). On all of these three strategies, the net present value with 4 per cent interest rate was maximized. The first strategy (SusSupply) means non-declining periodic total industrial wood and energy wood removals, sawlog removals and net income. In order to efficiently utilize the dynamics of forest structure, there are no sustainability constraints concerning tree species, cutting methods, age classes or the growth/drain ratio. The second strategy (MaxSupply) does not take into account any sustainability constraints or the demand of wood products. This means that all the cutting possibilities are utilized as soon as they are feasible for harvesting according to the silvicultural recommendations and which do not fulfil the economic prerequisite for further growing. On the third strategy (Demand) harvesting operations are done based on factories' demand for different timber assortments.

The secondary objective was to analyse the impacts of changes on the market of those volumes and treatments. First, we defined an optimization task Demand+ to study the impacts of a new chemical pulp mill planned to be built in Kuopio, which is considered to have an impact on the industrial wood market in North Karelia. For Demand+ analysis we also increased the capacity of one sawmill, which has announced new investments on enhancing production. In addition, we ran for MaxSupply and Demand a series of sensitivity analyses where we decreased (minus 5 per cent, MaxSupply_m5, Demand_m5) and increased (plus 5 and 10 per cent, MaxSupply_p5, MaxSupply_p10, Demand_p5, Demand_p10) factory prices. The above-mentioned "_m5" with the strategy name means that factory prices were decreased by 5 per cent; "_p5" and "_p10" means that factory prices were increased by 5 and 10 per cent, respectively.

For the optimization tool we selected the J software (Lappi and Lempinen, 2014a). In J, the special structure of the Model I type LP problem (Johnson and Scheurman, 1977; Dykstra, 1984) tracking individual management units throughout the length of time horizon is inherent. When using J, we assumed that the decision or policy maker wants to formulate the objective function and constraints using only total amounts for harvests and incomes and total amounts for different timber assortments transported to different factories. J automatically takes into account technical constraints specifying how the total amounts are computed summing schedule coefficients over management units and transportations over management unit-factory combinations. Therefore the user of J specifies only the objective function (see formula (A1) in Appendix A) and the utility constraints (see formula (A2) in Appendix A) and gives information about how the program can compute or access coefficients for the utilities. The software then automatically takes care of the technical constraints (formulae (A3)–(A7) in Appendix A). In J, the area constraints (formula (A4) in Appendix A) are taken into account using the Generalized Upper Bound (GUB) technique of Dantzig and Van Slyke (1967). The GUB technique was extended also for transportation constraints (formula (A7) in Appendix A) by Lappi and Lempinen (2014b). As the area and transportation constraints are taken into account using GUB techniques, the effective number of constraints, the dimension of the basis matrix in the LP, is very small compared with the original problem formulation. We present the general mathematical formulation which J is using in the computations in Appendix. Here we present the optimization problems in a form which corresponds to the way how the user of J can define our specific optimization problems.

Factories were not included in the first optimization (SusSupply), which was designed to correspond to the Finland's National Forest Strategy 2025 (2015). In SusSupply we maximized the net present value of forest management where the periodic costs of silviculture and harvesting were subtracted from the future income from harvesting and then discounted by a 4 per cent interest rate. The objective function was subject to non-declining periodic total industrial wood and energy wood removals, sawlog removals and net income. Because the Finland's National Forest Strategy 2025 (2015) covers forestry more widely than as a source of non-declining yield, following its definition we included an additional sustainability constraint where the net present value of the forest management at the end of the planning period (ending inventory) had to be at least as large as at the initial stage. The calculation of the income component of the value of ending inventory variable was based on roadside prices for which we used the statistical data available for various timber assortments (Metsätilastollinen vuosikirja, 2014).

In all subsequent optimizations (MaxSupply, Demand and their variants Demand+, MaxSupply_m5, MaxSupply_p5, MaxSupply_p10; Demand_m5, Demand_p5, Demand_p10), factories were included. In MaxSupply, the sum of the net present value of different value chains from forests to factories and costs of forest management at period t as well as the value of ending inventory of forest management after the planning period t at time T was maximized without constraints (formula (1)). In Demand and Demand+, the same objective function (formula (1)) was maximized subject to capacity constraints (formula (2)). In Demand, the capacity constraints (formula (2)) were defined by volume and tree species or a tree species mixture for each sawlog, plywood mill, mechanical pulp mill, chemical pulp mill and heating or combined heating and power (CHP) plant located in North Karelia and the mills existing nearby. This meant that each factory could only accept a certain quantity of wood per year and certain tree species or a mixture of tree species f. In Demand+, the capacity constraints were defined to include the new chemical pulp mill in Kuopio and the increased capacity of one sawmill. The objective function was in all factory optimization problems as follows:

$$
\begin{aligned}
\mathrm{Max}&\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{i=1}^{m}\left(-R_t * c_{si} + R_t u_s\right) RL_{tsi}\\
&+\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{i=1}^{m}\left(-R_t * d_{pi} + R_t v_p\right) RP_{tpi}\\
&+\sum_{t=1}^{T}\sum_{h=1}^{H}\sum_{i=1}^{m}\left(-R_t * e_{hi} + R_t x_h\right) RE_{thi}\\
&+\sum_{t=1}^{T}\sum_{h=1}^{H}\sum_{i=1}^{m}\left(-R_t * d_{hi} + R_t x_h\right) RP_{thi}\\
&+\sum_{t=1}^{T}\sum_{h=1}^{H}\sum_{i=1}^{m}\left(-R_t * c_{hi} + R_t x_h\right) RLO_{thi}\\
&+\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{p\in P'}\left(-R_t * g_{sp} + R_t v_p\right) SC_{tsp}\\
&-\sum_{t=1}^{T} R_t W_t + R_{T+} NPV_{T+},
\end{aligned}
\qquad (1)
$$

where T, S, P, H and m are the number of periods (5), sawmills (13), pulp mills (13), heating plants (42) and management units (5130), respectively,

P' is the set of chemical or mechanical pulp mills receiving sawmill wood chips and sawdust,

i is the management unit,

R_t is the discounting factor for period t,

c_{si} is the transportation cost for sawlogs from management unit i to sawmill or plywood mill s,

$u_s/v_p/x_h$ is the sawlog/pulpwood/energy wood price at sawmill or plywood mill s/chemical or mechanical pulp mill p/heating or combined heating and power (CHP) plant h,

RL_{tsi} is the transported sawlog volume in period t from management unit i to sawmill or plywood mill s,

d_{pi}/d_{hi} is the transportation cost for pulpwood from management unit i to chemical or mechanical pulp mill p/heating plant or combined heating and power (CHP) plant h,

RP_{tpi} is the transported pulpwood volume in period t from management unit i to chemical or mechanical pulp mill p,

e_{hi}/c_{hi} is the transportation cost for energy wood/hardwood (other than birch) logs from the management unit i to heating or CHP plant h (note: transportation cost for pulpwood from management unit i to heating or CHP plant h is d_{hi} see above),

$RE_{thi}/RP_{thi}/RLO_{thi}$ is transported energy wood/pulpwood/hardwood (other than birch) log volumes from the management unit i in period t to heating or CHP plant h,

g_{sp} is the transportation cost for sawmill wood chips and sawdust from sawmill or plywood mill s to chemical or mechanical pulp mill p,

SC_{tsp} is the transported sawmill wood chips and sawdust volume in period t from sawmill or plywood mill s to chemical or mechanical pulp mill p,

W_t is the total amount of expenditure (forest management's costs including, e.g. regeneration, silvicultural and harvesting costs) in period t,

R_{T+} is the discounting factor at the end of the planning horizon and

NPV_{T+} is the value of ending inventory, which is calculated as total net present value of forest management after the planning horizon. This is computed by simulating the development of each management unit to the end of rotation using standard management rules and average stumpage prices. In addition, the discounted land value at the end of the rotation is taken into account.

The following capacity constraints were used with Demand and Demand+:

$$
\begin{aligned}
&RL_{tsf} \le CA_{tsf}\\
&RP_{tpf} \le CA_{tpf}, p \notin P'\\
&RP_{tpf} + SC_{tpf} \le CA_{tpf}, p \in P'\\
&SC_{tsf} \le q_f * RL_{tsf}\\
&RE_{th} + RP_{th} + RLO_{th} \le CA_{th}
\end{aligned}
\qquad (2)
$$

where f is a tree species or a mixture of tree species, CA is the maximum technical capacity and symbols t, s, p, h and P as in formula (1),

RL_{tsf} is the transported sawlogs of tree species f or a mixture of tree species f to sawmill or plywood mill s in period t,

RP_{tpf} is the transported pulpwood of tree species f or a mixture of tree species f to chemical pulp mill or mechanical pulp mill p in period t,

SC_{tsf} is the transported sawmill wood chips and sawdust of tree species f or a mixture of tree species f from sawmill or plywood mill s in period t,

q_f is the proportion of the log volume of tree species f or a mixture of tree species f converted into sawmill wood chips and sawdust,

SC_{tpf} is the transported sawmill wood chips and sawdust of tree species f or a mixture of tree species f to chemical or mechanical pulp mill p in period t,

RE_{th} is the transported energy wood to heating or combined heating and power plant h in period t,

RP_{th} is the transported pulpwood to heating or combined heating and power plant h in period t and

RLO_{th} is the transported hardwood (other than birch) log volumes to heating or combined heating and power plant h in period t.

Results

In the first 10-year sub-period, the use of MaxSupply led to a greater removal of sawlogs, pulpwood and energy wood than SusSupply (Figure 3). Later, the sustained removal of sawlogs and energy wood (in SusSupply) was greater than those removed in MaxSupply. The area of clear cutting was larger in MaxSupply than in SusSupply, except in the fourth sub-period (Figure 4). Both strategies normalized the age class distribution (Figure 5). In SusSupply, both the area of thinning and the area of clear cutting remained almost the same for all five decades. For pulpwood, industrial wood in MaxSupply exceeded SusSupply in all other 10-year sub-periods than fourth, and for energy wood, MaxSupply exceeded SusSupply only on first 10-year sub-period.

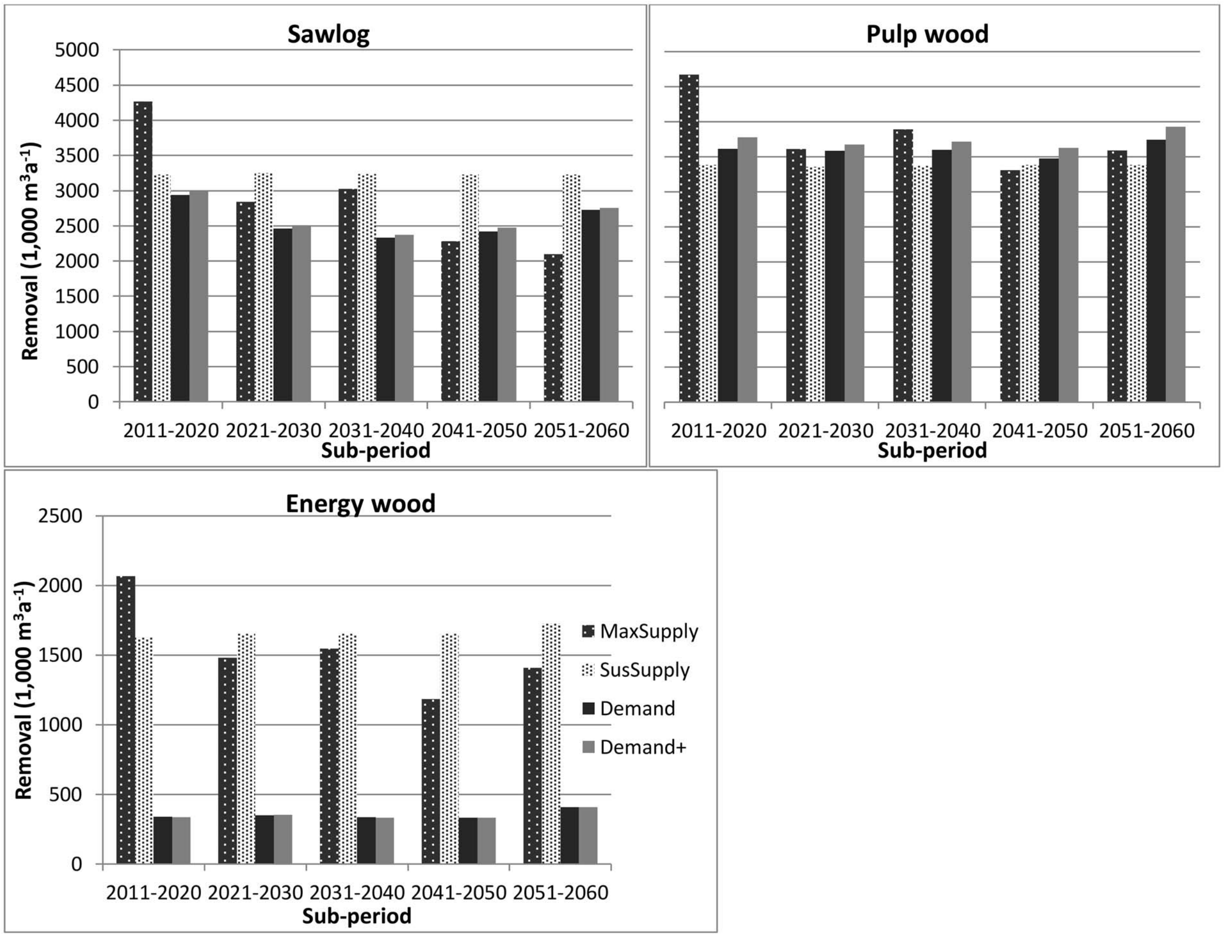

Figure 3 Sawlog, pulpwood and energy wood removals (1000 m^3 a^{-1}) for five sub-periods (2011–2020, 2021–2030, 2031–2040, 2041–2050 and 2051–2060) in strategies corresponding to the maximum sustainable harvest of Finland’s National Forest Strategy (2015) (SusSupply), maximum wood supply (MaxSupply) and demand-driven harvest for existing (Demand) or for existing and planned (Demand+) factories.

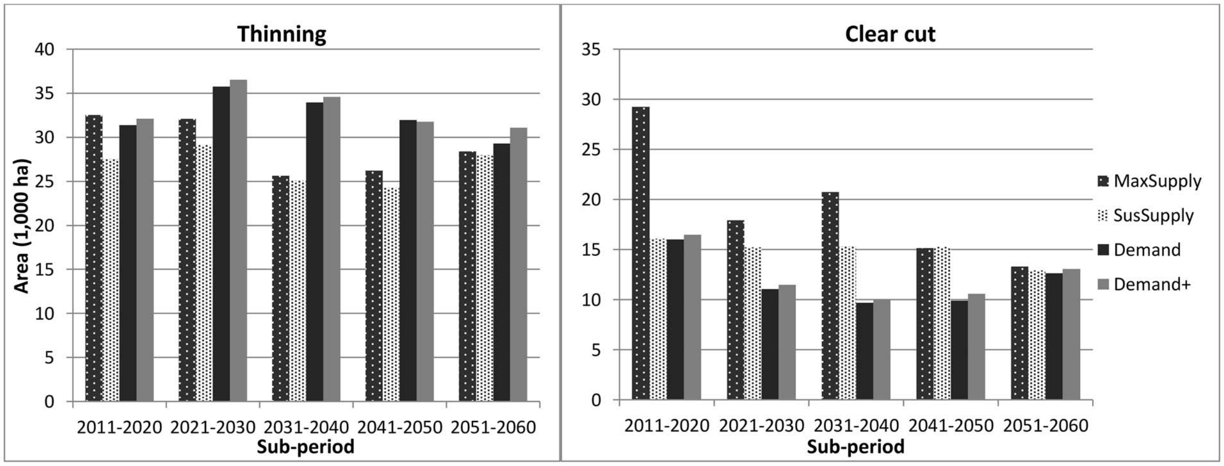

Figure 4 Areas (1000 ha) of thinning and clear cutting for five sub-periods (2011–2020, 2021–2030, 2031–2040, 2041–5200 and 2051–2060) in four strategies. For the definition of SusSupply, MaxSupply, Demand and Demand+, see Figure 3 caption.

Optimization under the capacity constraints (Demand) caused greater pulpwood removal but lower sawlog and energy wood removal than SusSupply. The majority of pulpwood from North Karelia was processed in North Karelia with some flow to

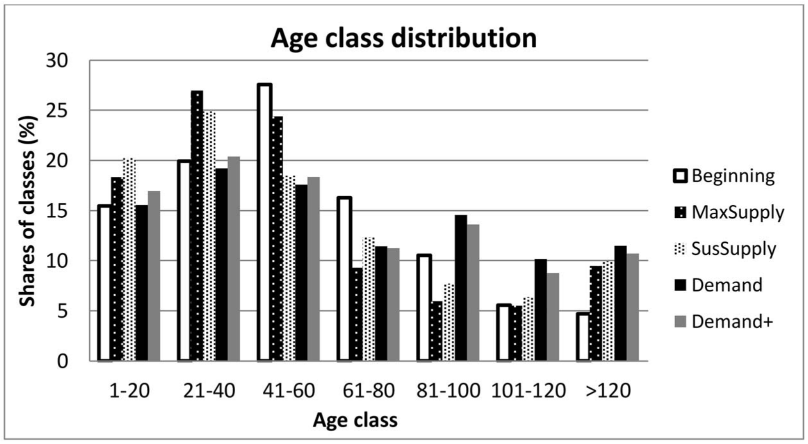

Figure 5 Age class distribution (as a percentage of forest and scrub land area) in the initial state in 2011 (Beginning) and in 2060 in four strategies. For the definition of SusSupply, MaxSupply, Demand and Demand+, see Figure 3 caption.

neighbouring regions, for example to a mechanical pulp mill using Norway spruce and to the chemical pulp mills using birch or a mixture of birch and softwood. When considering the raw materials, all sawmills and the plywood mill located in North Karelia fulfilled their capacity 100 per cent until the second 10-year period. In addition, sawlogs were transported from North Karelia to five factories located in the south-west from North Karelia. In North Karelia, from the second 10-year period to fourth, the capacity of the mill using hardwood logs was fulfilled but it was not for two sawmills using Norway spruce softwood logs. In addition, transportation of hardwood sawlogs to the south-west from North Karelia increased on the second, third and fourth 10-year periods compared with first 10-year period.

The felling potential (MaxSupply) of energy wood is much greater than the capacity (Demand) of the heating plants. In Demand, the objective function leads to a solution and energy wood flows (Figure 6) where the capacity constraints are fulfilled in the order of economic profitability, mainly with energy wood based on harvesting residues.

Adding one chemical pulp mill outside of North Karelia (Demand+) and increasing the capacity of one sawmill in North Karelia increased the cutting removals during the first period by 3.5 per cent and on the next periods by 2.3–3.5 per cent. The new chemical pulp mill received, depending on the 10-year period, 344 000–484 000 of Scots pine softwood and 120 000–225 000 of Norway spruce softwood. As a result of the new chemical pulp mill (to the west of North Karelia), the increased competition for wood changed the profitable flow of Scots pine and Norway spruce pulpwood considerably (Figure 7). For the one pulp mill, the rate of capacity utilization decreased from 60 to 21 per cent. However, the share of the Scots pine or Norway spruce pulpwood of the total capacity of the two pulp mills at North Karelia stayed at the same level or even increased a little.

On the first 10-year period, 947 000 m^3 (Demand) and 899 000 m^3 (Demand+) of sawmill wood chips per year were transported to pulp mills. Especially with two pulp mills, sawmill wood chips made up a remarkable share of the total capacity (Figure 8). In both, Demand and Demand+, sawmill wood chips of Norway spruce logs were transported to pulp mills situated at long distances. The longest transportation of sawmill wood chips from sawmill to pulp mill was 143 km (Demand) and 125 km (Demand+).

Changes in factory prices affected the profitability of the wood supply chain, and consequently the share of thinning and clear cutting operations. The logging costs for industrial wood (sawlogs and pulpwood) were higher with the capacity constraints than without (Figure 9). The costs varied on different 10-year periods between 11.7 and 12.1€ per m^3 (MaxSupply) and between 11.7 and 12.7€ per m^3 (Demand). On average, the logging costs in Demand were 5.4 per cent higher than in MaxSupply. The main reason for the higher logging costs is the higher share of thinning operations.

In contrast, the logging costs for energy wood were the other way round, varying between 13.8 and 16.4€ per m^3 (MaxSupply) and between 8.9 and 10.9€ per m^3 (Demand), i.e. logging costs for energy wood were 35 per cent lower in Demand than in MaxSupply. The main reason for this is that the contribution of harvesting residues as the source of the energy wood is higher in Demand than in MaxSupply. The costs of the extraction and transport of harvesting residues are lower than the same costs for small-size trees from silvicultural operations.

The changes in factory prices had only minor effects on the average logging costs during the first three 10-year periods. Increasing factory prices resulted in slightly higher logging costs for industrial wood. Thinning operations were more sensitive to changes in factory prices than clear cuttings. Therefore, changes in factory prices had bigger effects on both the pulpwood potential (MaxSupply) and the removals to match the capacity of the factories (Demand) than on the respective potentials or removals of sawlogs. Also, the energy wood potential (MaxSupply) from thinning operations in young stands was sensitive to changes in factory prices.

Discussion

This study illustrates the combined use of the Finnish MELA simulator and the J software in the context of a Finnish forest strategy anticipating new investments and renewal of business in

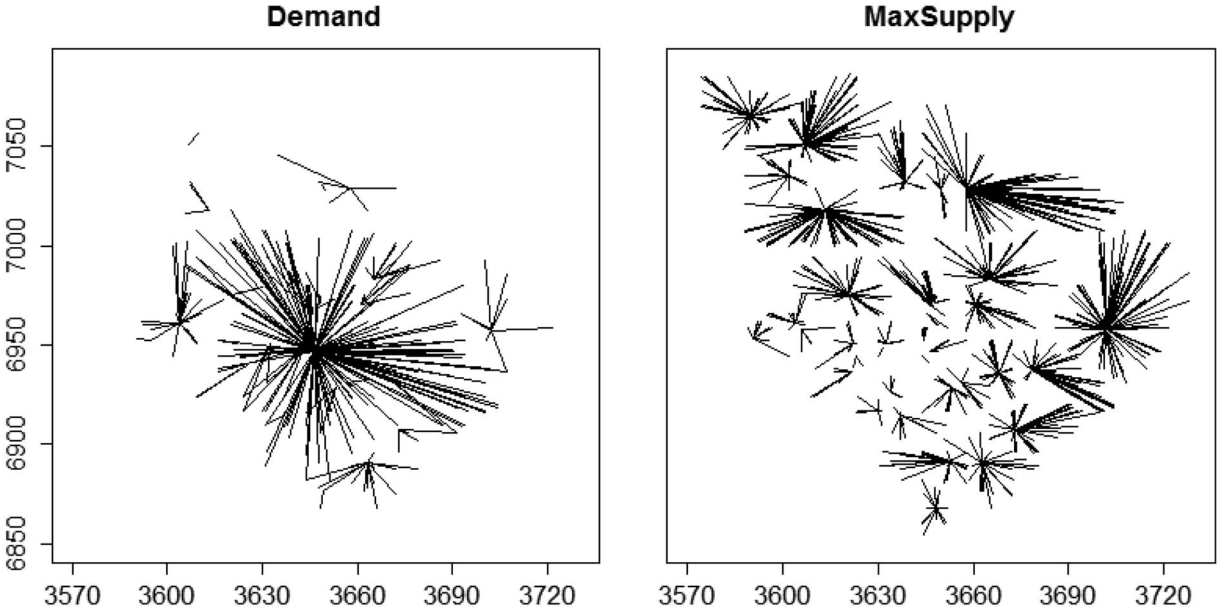

Figure 6 Energy wood flows in the Finnish map coordinate system from forest to heat and power (CHP) plants in the sub-period 2011–2020. On the left, the flows in response to the demand of each plant (see the definition for Demand in Figure 3 caption). On the right, the flows based on supply (see the definition for MaxSupply in Figure 3 caption).

the wood-processing industry. Our aim was to analyse different regional forest strategies in terms of wood flows and treatments. In addition, we wanted to study the impacts of market changes on those flows and treatments.

Our study compared long-term forest management strategies such as maximum (MaxSupply) and sustainable (SusSupply) wood supply potentials with demand-driven strategies (Demand, Demand+). The results show a clear difference in harvested volumes and in the share of thinning and clear cutting operations between different strategies.

Our model was spatially explicit for wood-processing factories and energy producers, forest resources and reporting the flows between them. Until now, it has not been possible to analyse spatially how the wood supply for multiple market destinations will react to a new factory or a new product line with a certain capacity, or how wood flows to other factories may change with implications for forest management. In preceding studies, results are presented only at a regional level (Nuutinen *et al.,* 2000, 2006; Kärkkäinen *et al.*, 2008), or procurement zones are used to model forest resources (e.g. Nivala *et al.*, 2016). Our study revealed a clear difference in wood flows between strategies maximizing wood supply or optimizing wood supply to market destinations. We also found that wood flows are responsive to new factories and the changes in factory price had a heavier impact on pulpwood supply than on sawlog supply.

We did not use any restrictions for wood flows other than the maximum capacity of factories in optimization. This means that wood flows can vary between different 10-year periods and, in addition, all factories' demand might not be fulfilled. However, all pulp mills' demand located in North-Carelia was fulfilled on all five 10-year periods. That was also the situation for four of six sawmills in North-Carelia. The other two sawmills fulfilled their demand on the first 10-year period and 58–97 per cent of the demand on the following periods. We gathered the information of capacities and realized outputs from public sources. As we didn't have exact figures for capacities, we didn't want to force even wood flows to factories. It is also reality that factory demand and output can vary between years, due to, e.g. market environment. However, it would be quite simple to make such adjustments to the model used in this study.

In our study area, forest age class structure was slightly skewed (Nuutinen *et al.*, 2006, 2009), with the majority of the forests being mature enough for thinning. Therefore, the National Forest Strategy 2025 (2015) constraint for the value of ending inventory in SusSupply was not binding. From a strictly wood production point of view, the constraint for the value of ending inventory is meaningful neither for regions with a majority of young forests nor regions with a majority of old-growth forests. In the future, attention should be paid to selecting optimization criteria case by case to reflect the utilities of decision makers or policy makers in question. Specifically, the domain concept in J facilitates the inclusion of site-specific constraints or strata-based objectives to address the ecological or social constraints typical for integrated management (Nalli *et al.*, 1996). In addition, domains could be utilized for addressing owner-specific strategies and the distribution of utilities (wealth) between them.

In Finland, average logging costs are the cheapest for final felling (less than 9€ per m^3 in 2014), than for thinning (15€ per m^3 in 2014), further for first thinning (more than 17€ per m^3) and most expensive for harvesting of energy wood (between 20 and 30€ per m^3 depending on the harvesting system). Our results show that fulfilling the demand of factories causes higher average logging costs. In addition, the results indicate that the

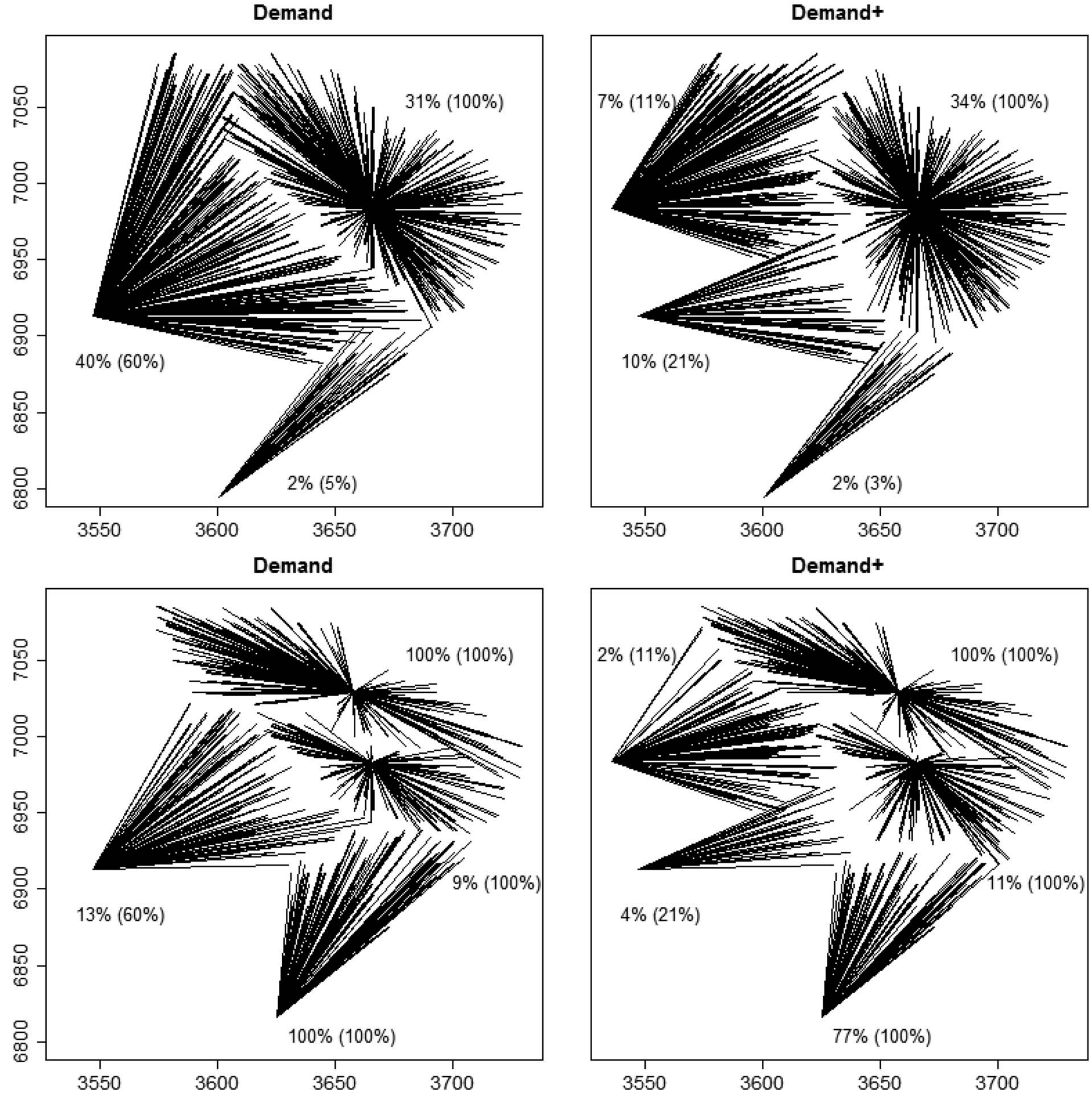

Figure 7 Scots pine and Norway spruce pulpwood flows in the Finnish map coordinate system from forest to factories in the sub-period of 2011–2020. On the left, the flows in response to the demand of each existing factory (see the definition for Demand in Figure 3 caption). On the right, the flows when a new chemical pulp mill is added (see the definition for Demand+ in Figure 3 caption). On the upper pictures, flows of Scots pine pulpwood and below flows of Norway spruce pulpwood. Shares of the Scots pine and Norway spruce pulpwood of the total capacity in percentages, and capacity utilization as a percentage of productive capacity in brackets.

market-based solution of energy extraction from wood is dependent on the industrial use of wood because the most profitable source of energy wood is harvesting residues from final fellings or forest industry by-products such as bark and sawdust. The mobilization of energy wood from young forests through thinning operations obviously requires either a technological jump or a considerable increase in the factory price to make the operation more profitable.

Although the major improvement in the modelling capacity is based on the capability of J to include transportation costs and the capacity of factories into the optimization, MELA still plays an important role in our study. In almost all other wood supply optimization models, the available forest resources are fixed. In our study, forest management, including rotation times for each management unit, was solved endogenously while prices were fixed. The latter was specific for this study, not inherent for J. Traditionally, competition of the industrial and energy wood market has had only a minor influence on prices. For example, peat or bi-products can be used instead of wood in energy and power plants or industrial wood imported. However, the competition

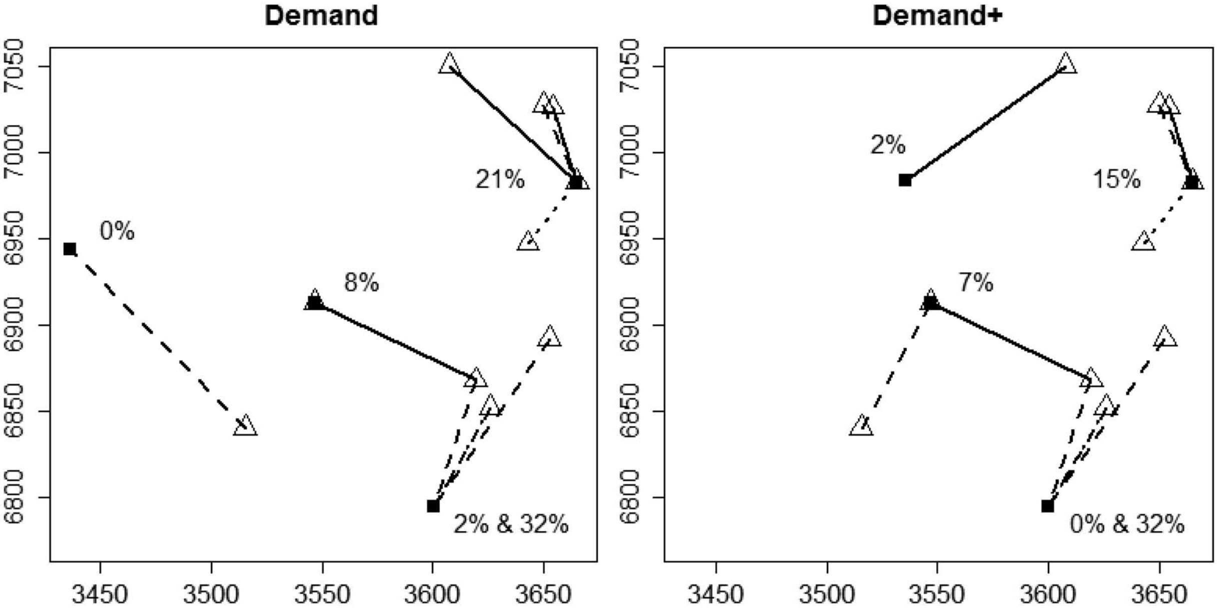

Figure 8 Transportation of sawmill chips from sawmills to pulp mills on period 1. Black squares denote pulp mills, and triangles denote sawmills. Solid line: sawmill chips of Scots pine logs, dashed line: sawmill chips of Norway spruce logs and dotted line: sawmill chips of birch logs. Percentages indicate how much of the pulp mills' total capacity is fulfilled with sawmill chips. On the lower right corner are two different pulp mills close to each other. For the definition of Demand and Demand+, see Figure 3 caption.

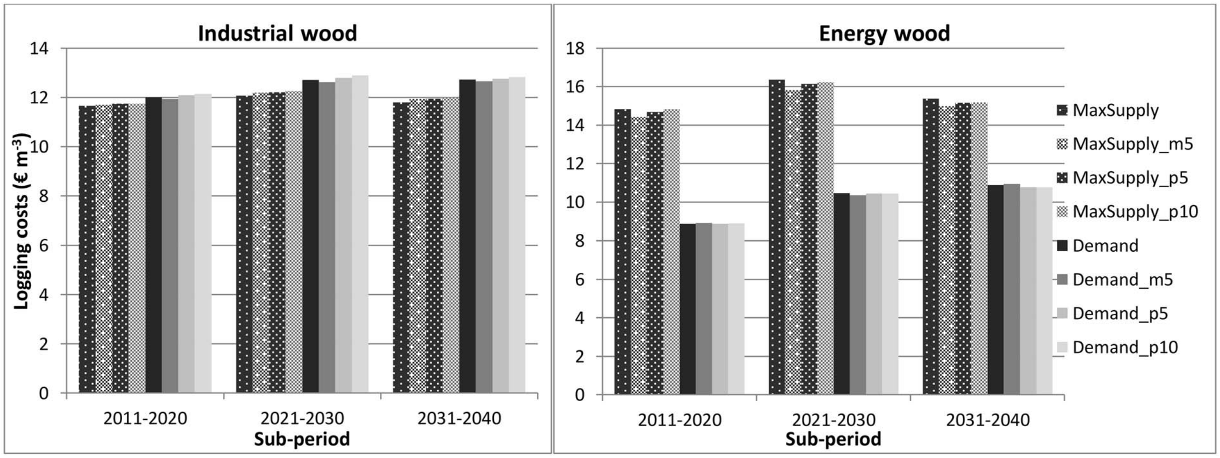

Figure 9 Logging costs of industrial and energy wood (€ m^{-3}) in MaxSupply and in Demand when factory prices were decreased (minus 5%, MaxSupply_m5, Demand_m5) and increased (plus 5% and 10%, MaxSupply_p5, MaxSupply_p10, Demand_p5, Demand_p10).

may change in the future. The use of shadow prices as a measure of competition would be an interesting topic for future studies.

MELA uses individual trees when calculating the value of decision variables such as volumes by tree assortment and the logging costs related to each treatment schedule and time period. For example, the cost of thinning operations is higher than that of clear felling because of the smaller tree size causing a higher processing time and therefore cost per m^3, while the smaller amount of harvested wood causes greater fixed costs per m^3. For each optimal solution, the average costs are therefore based on forest management solved endogenously. In the future, we need to consider also the uncertainties related to the values of decision variables. In this study, we restricted the planning horizon to 50 years, which in Finland is considered as a period for which the growth and yield estimates are sufficiently reliable.

In our model, there was no transport of wood into North Karelia from other regions, and transport from North Karelia to other regions was limited to the mills located nearby. Even if a simplification of the perfect market competition, the model corresponds to the current practice where the high transportation costs have the effect that especially pulpwood is often transported to the closest factory. This is facilitated by the exchange of wood between companies. However, the Finland's National Forest Strategy (2015) aims at a considerable increase in wood use by 2025. New factories are being planned for several sites in addition to those addressed by our study. Obviously, there is a need to carry out the same type of analysis for the whole of Finland to see how forest management and wood supply flows would reflect the new demand.

It is not only demand for wood which has effects on forest management. Forest owners, of course, have an important influence on how much wood is available for the market. About 60 per cent of forests in the study area are owned by private forest owners. This group is very heterogeneous, and they have different kinds of targets and goals for their property and how they want to manage forests. There are a lot of studies concerning Finnish forest owners' goals and their behaviour (e.g. Karppinen, 1998 Favada *et al*., 2009 Pynnönen *et al*., 2018). To include forest owners' goals into our study would have been a big challenge but could be an interesting topic for future work.

Our study shows a considerable increase in the solution times when the amount of utility constraints increases. Currently J keeps all the data in memory. When solving considerably larger problems, it will be necessary to develop the software so that only dynamically changing part of the data is in the memory. One option to make the algorithm faster is to define different partially overlapping timber assortment-specific factory groups and transport only to "legal" factory groups. Currently all sawmills, pulp mills and energy plants are treated as possible factories for all sawlogs, pulp wood or energy wood, respectively. The performance comparisons between J and some commercial software such as CPLEX would be interesting.

In our model, all harvested wood is transported to factories. The model should also be enhanced to cover storage facilities, terminals and flows between factories. In principle, these additions can be treated using the so-called z-variables of J (see Lappi, 1992 Lappi and Lempinen, 2014a). It will require a further study to see if this would work also in practice. In this study, the transportation of sawmill wood chips was solved by using z-variables. In 2017, Finnish forest industries consumed 69.7 million m^3 of roundwood (Ylitalo, 2018). Moreover, 9.8 million m^3 of sawmill wood chips and sawdust, were utilized by the pulp and paper industries in secondary wood consumption (Ylitalo, 2018). In our study, 6.4 million m^3 of roundwood and 0.95 million m^3 of sawmill wood chips were consumed per year on the first 10-year period.

Two years ago, 75 per cent of the industrial roundwood transported was brought to the mills directly by road (Strandström, 2018). Railway transportation accounted only for 22 per cent of the industrial roundwood volume, and waterway transportation (by floating and barge combined) accounted for 2 per cent (Strandström, 2018). The road network in Finland is so dense (Viitala *et al*., 2004) that the actual shortest distance between the management unit and the mill is very close to the distance of a line directly linking the two locations. We also calculated the results using this method and there were in practice no differences in summary results compared with the results shown here. However, there is a big variation in road conditions between regions in Finland. In the future, we need more detailed spatially referenced data on site conditions that affect the selection of season of operations and transportation routes that may depend on the seasons.

Conclusion

This study illustrates a spatially explicit methodology for integrated forest management and wood supply chain optimization over time. Considering the Finnish strategy to increase wood utilization by 2025, there is a need to carry out the same type of analysis for the whole of Finland using an improved model that includes also long-distance transport in addition to flow of sawmill wood chips and sawdust between factories. In addition to the planning of regional forest strategies or analysing the impacts of changes in market destinations, a combined simulation and optimization framework could support forest enterprises planning their own wood supply over multiple time periods and multiple destinations.

Acknowledgements

We would like to acknowledge Dr. Perttu Anttila, M.Sc. Olli Salminen and GIS Analyst Vesa Nivala, both from Natural Resources Institute Finland (Luke), for their support in the parameterization of the model. We would also like to thank the anonymous reviewers for their valuable comments.

Conflicts of interest

None declared.

Funding

This work was supported by the National Resources Institute Finland.

References

Äijälä, O., Koistinen, A., Sved, J., Vanhatalo, K. and Väisänen, P. (eds.) 2014 *Metsänhoidon suositukset (Forest Management Recommendations)*. Metsätalouden kehittämiskeskus Tapion julkaisuja. http://www.metsanhoitosuositukset.fi/wpcontent/uploads/2016/08/Metsanhoidon_suositukset_Tapio_2014.pdf 180 p (in Finnish).

Barreiro, S., Schelhaas, M-J., Kändler, G., Anton-Fernandez, C., Colin, A,, Bontemps, J-D. *et al.* 2016 Overview of methods and tools for evaluating future woody biomass availability in European countries. *Ann. For. Sci.,* **73**, 823–837.

Bergseng, E., Ask, J.A., Gobakken, T., Framstad, E., Hoen, H.F. and Solberg, B. 2012 Balancing biodiversity protection and economics in long-term boreal forest management: combining quantitative modelling and subjective opinions. *Forest Policy Econ.* **15**, 12–21.

Bettinger, P., Boston, K., Siry, J. and Grebner, D. 2009 *Forest Management and Planning*. Elsevier Academic Press, Burlington 331 p.

Borges, J.G., Diaz-Balteiro, L., McDill, M.E. and Rodriguez, L.C.E. (eds.) 2014a *The Management of Industrial Forest Plantations*. Springer.

Borges, J.G., Garcia-Conzalo, J., Bushenkov, V., McDill, M.E., Marques, S. and Oliveira, M.M. 2014b Addressing multicriteria forest management with Pareto methods: an application in Portugal. *For. Sci.* **60**, 63–72.

Borges, J.G., Marques, S., Garcia-Conzalo, J., Ur Rahman, A., Bushenkov, V., Sottomayor, M. *et al.* 2017 A multiple criteria approach for negotiating ecosystem services supply targets and Forest owners' programs. *For. Sci.* **63**: 49–61.

Bouchard, M., D'Amours, S., Rönnqvist, M., Azouzi, R. and Gunn, E. 2017 Integrated optimization of strategic and tactical planning decisions in forestry. *Eur. J. Oper. Res.* **259**, 1132–1143.

D'Amours, S., Rönnqvist, M. and Weintraub, A. 2008 Using operational research for supply chain planning in the forest products industry. *Inform. Sys. Oper. Res.,* **46**, 265–281.

Dantzig, G.P. and Van Slyke, R.M. 1967 Generalized upper bounding techniques. *J. Comput. Syst. Sci.* **1**, 213–226.

Dykstra, D.P. 1984 *Mathematical Programming for Natural Resource Management*. McGraw-Hill, New York, p. 318.

Eriksson, L.O., Gustavsson, L., Hänninen, R., Kallio, M., Lyhykäinen, H., Pingoud, K. *et al.* 2012 Climate change mitigation through increased wood use in the European construction sector—towards an integrated modelling framework. *Eur. J. For. Res.* **131**, 131–144.

Favada, I.M., Karppinen, H., Kuuluvainen, J., Mikkola, J. and Stavness, C. 2009 Effects of timber prices, ownership objectives, and owner characteristics on timber supply. *For. Sci.*, **55**: 512–523.

Finnish Forest Industries Statistics, 2018 https://www.forestindustries.fi/statistics/industry/15-Pulp%20and%20Paper%20Industry/ accessed on 5 November, 2018)

Gunn, E. 2009 Some perspectives on strategic forest management models and the forest products supply chain. *Information Systems and Operational Research* **47**, 261–272.

Hoganson, H. and Kapple, D. 1991 *DTRAN version 1.0: A Multi-market Timber Supply Model, College of Natural Resources and Agricultural Exp. Sta., Dept. of Forest Resources Staff Paper Series Report No. 81*. University of Minnesota, St Paul, MN, p. 64.

Hoganson, H. and Meyer, G. 2015 Constrained optimization for addressing forest-wide timber production. *Curr. For. Rep.*, 1, 33–43.

Hynynen, J., Ojansuu, R., Hökkä, H., Salminen, H., Siipilehto, J. and Haapala, P. 2002 Models for predicting the stand development—description of biological processes in MELA system. *Metsäntutkimuslaitoksen tiedonantoja* **835**, 116 (in Finnish).

Jaakko Pöyry Consulting Inc 1994 *Final Generic Environmental Impact Statement Study on Timber Harvesting and Forest Management in Minnesota*. Minnesota Environmental Quality Board, St. Paul, Minnesota, p. 816.

Johnson, K.N. and Scheurman, H.L. 1977 Techniques for prescribing optimal timber harvest and investment under different objectives—discussion and synthesis. *For. Sci. Monogr.* **18**, 31.

Jutras, S., Hökkä, H., Alenius, V. and Salminen, H. 2003 Modeling mortality of individual trees in drained peatland sites in Finland. *Silva Fenn.* **37**, 235–251.

Kallio, A., Sievänen, R. and Salminen, O. 2013 Sequester or substitute—consequences of increased production of wood-based energy on the carbon balance in Finland. *J. For. Econ.,* **19**, 402–415.

Kärkkäinen, L., Matala, J., Härkönen, K., Kellomäki, S. and Nuutinen, T. 2008 Potential recovery of industrial wood and energy wood raw material in different cutting and climate scenarios for Finland. *Biomass Bioenerg*, **32**, 934–943.

Karppinen, H. 1998 Values and objectives of non-industrial private forest owners in Finland. *Silva Fenn.*, **32**, 43–59.

Korhonen, K.T. 2016 Finland. In: Vidal, C., Alberdi, I., Hernandez, L. and Redmond, J. (ed.) *National Forest Inventories. Assessment of Wood Availability and Use*. Gewerbestrasse 11, 6330 Cham, Switzerland: Springer International Publishing Switzerland. ISBN 978-3-319-44014-9. pp. 369–384.

Lappi, J. 1992 JLP—a linear programming package for management planning. *Finn. For. Res. Inst. Res. Paper* **414**, 134.

Lappi, J. and Lempinen, R. 2014a *J—Users' Guide 2.1*. Finnish Forest Research Institute, p. 130.

Lappi, J. and Lempinen R. 2014b A linear programming algorithm and software for forest-level planning problems including factories. *Scan. J. For. Res.*, **29**, 178–184.

Malinen, J., Kilpeläinen, H., Piira, T., Redsven, V., Wall, T. and Nuutinen, T. 2007 Comparing model-based approaches with bucking simulation-based approach in the prediction of timber assortment recovery. *Forestry*, **80**, 309–321.

Marques, A., de Sousa, J., Rönnqvist, M. and Jafe, R. 2014 Combining optimization and simulation tools for short-term planning of forest operations. *Scand. J. For. Res.,* **29**, 166–177.

Matala, J., Kärkkäinen, L., Härkönen, K., Kellomäki, S. and Nuutinen, T. 2009 Carbon sequestration in the growing stock of trees in Finland under different cutting and climate scenarios. *Eur. J. For. Res.*, **128**, 493–504.

MELA Summary Reports 2017 http://mela2.metla.fi/mela/tupa/index-en.php accessed on 15 May, 2017)

Metsäpohjaisen energian hinta käyttöpaikalla, 2018 *€/MWh* http://www.metsalehti.com/Metsaenergia/Kayttopaikkahinnat/ n Finnishaccessed on 10 April and 8 October 2018)

Metsätilastollinen vuosikirja 2014. http://urn.fi/URN:ISBN:978-951-40-2506-8428 p (in Finnish)

Nalli, A., Nuutinen, T. and Päivinen, R. 1996 Site-specific constrains in integrated forest planning. *Scand. J. For. Res.*, **11**, 85–96.

National Forest Strategy 2025, 2015. Ministry of Agriculture and Forestry 6b/2015. http://mmm.fi/documents/1410837/1504826/National+Forest+Strategy+2025/197e0aa4-2b6c-426c-b0d0-f8b0f277f332 accessed on 22 March, 2016)

Nivala, M., Anttila, P., Laitila, J., Salminen, O. and Flyktman, M. 2016 A GIS-based methodology to estimate the regional balance of potential and demand of forest chips. *J. Geogr. Inf. Syst.* **8**, 633–662.

Nuutinen, T., Hirvelä, H., Hynynen, J., Härkönen, K., Hökkä, H., Korhonen, K.T.. 2000 The role of peatlands in Finnish wood production – An analysis based on large-scale forest scenario modelling. *Silva Fenn.*, **34**, 131–153.

Nuutinen, T., Matala, J., Hirvelä, H., Härkönen, K., Peltola, H., Väisänen, H. 2006 Regionally optimized forest management under changing climate. *Clim. Chang.*, **79**, 315–333.

Nuutinen, T., Kilpeläinen, A., Hirvelä, H., Härkönen, K., Ikonen, V.-P., Lempinen, R. *et al.* 2009 Future wood and fibre sources – Case North Karelia in eastern Finland. *Silva Fenn.*, **43**, 489–505.

Packalen, T., Kärkkäinen, L. and Toppinen, A. 2017 The future operating environment of the Finnish sawmill industry in an era of climate change mitigation policies. *Forest Policy Econ.* **82**, 30–40. doi: 10.1016/j.forpol.2016.09.017.

Pynnönen, S., Paloniemi, R. and Hujala, T. 2018 Recognizing the interest of Forest owners to combine nature-oriented and economic uses of forests. *Small-Scale For.*, **17**, 443–470.

Redsven, V., Hirvelä, H., Harkönen, K., Salminen, O. and Siitonen, M. 2012 *MELA 2012 Reference Manual*. 2nd edn. The Finnish Forest Research Institute, Vantaa, p. 666.

Rönnqvist, M., D'Amours, S., Weintraub, A., Jofre, A., Gunn, E., Haight, R.G. *et al.* 2015 Operations research challenges in forestry: 33 open problems. *Ann. Oper. Res.*, **232**, 11–40.

Shahi, S. and Pulkki, R. 2013 Supply chain network optimization of the Canadian forest products industry: a critical review. *Am. J. Ind. Bus. Manag.* **3**, 631–643.

Sjølie, H., Latta, G., Trømborg, E., Bolkesjø, T. and Solberg, B. 2015 An assessment of forest sector modeling approaches: conceptual differences and quantitative comparison. *Scand. J. For. Res.*, **30**, 60–72.

Strandström, M. 2018 Puunkorjuu ja kaukokuljetus vuonna 2017 (Timber Harvesting and Long-distance Transportation of Roundwood 2017). *Metsätehon tuloskalvosarja 8a/2018*.

Suomen metsäteollisuuden kilpailukyky 2012 *Metsäalan strategien ohjelma*. Työ- ja elinkeinoministeriö, taustaselvitys.95 p in Finnish). http://docplayer.fi/4500496-Suomen-metsateollisuuden-kilpailukyky.html accessed on 22 March, 2016).

Toppinen, A. and Kuuluvainen, J. 2010 The state of the art in forest sector modelling in Europe and directions for future research. *Forest Policy Econ.*, **12**, 2–8.

Viitala, E., Saarinen, V-M., Mikkola, A. and Strandström, M. 2004 Metsäteiden lisärakentamistarpeen määrittäminen paikkatietoaineistojen avulla. *Metsätieteen aikakauskirja,* **2** 2004: 175–192. (in Finnish)

Weintraub, A. and Romero, C. 2006 Operations research models and the management of agricultural and forestry resources: A review and comparison. *Interfaces*, **36**, 446–457.

Ylitalo, E. 2018 Metsäteollisuuden puunkäyttö 2017: Metsäteollisuus (Forest industries' wood consumption in 2018) http://stat.luke.fi/metsateollisuuden-puun-kaytto in Finnish) accessed on 5 November, 2018)

Appendix

In J, the special structure of the Model I type LP problem (Johnson and Scheurman, 1977; Dykstra, 1984) for tracking individual management units throughout the length of time horizon is inherent.

Mathematically, the optimization problems under consideration can be defined as follows:

$$\text{Max or Min } z_0 = \sum_{k=1}^{p} a_{0k}x_k + \sum_{k=1}^{q} b_{0k}z_k + \sum_{k=1}^{p}\sum_{f=1}^{F} \alpha_{0kf}x_{kf} + \sum_{k=1}^{p}\sum_{f=1}^{F} \beta_{0kf}y_{kf} \tag{A1}$$

subject to the following utility constraints which are of interest to the decision maker (note that the objective row is formulated as utility constraint $t = 0$):

$$c_t = \sum_{k=1}^{p} a_{tk}x_k + \sum_{k=1}^{q} b_{tk}z_k + \sum_{k=1}^{p}\sum_{f=1}^{F} \alpha_{tkf}x_{kf} + \sum_{k=1}^{p}\sum_{f=1}^{F} \beta_{tkf}y_{kf} \quad \le C_t, \quad t = 1, \ldots, r \tag{A2}$$

Technical constraints which J takes into account automatically and which are not assumed to be of interest to the decision maker:

$$x_k - \sum_{i=1}^{m}\sum_{j=1}^{n_i} x_k^{ij}w_{ij} = 0, \quad k = 1, \ldots, p \tag{A3}$$

$$\sum_{j=1}^{n_i} w_{ij} = A_i, \quad i = 1, \ldots, m \tag{A4}$$

$$x_{kf} - \sum_{i=1}^{m} x_{kf}^{i} = 0, \quad (k, f) \in \mathbf{R} \tag{A5}$$

$$y_{kf} - \sum_{i=1}^{m} \gamma_{kf}^{i} x_{kf}^{i} = 0, \quad (k, f) \in \mathbf{B} \tag{A6}$$

$$\sum_{f=1}^{F} x_{kf}^{i} - \sum_{j}^{n_i} x_k^{ij}w_{ij} = 0, i = 1, \ldots, m \quad k \in \mathbf{K} \text{ and} \tag{A7}$$

$$w_{ij} \ge 0, i = 1, \ldots, m, j = 1, \ldots, n_i, z_k \ge 0$$

$$\text{for } k = 1, \ldots, q, x_{kf}^{i} \ge 0, (k, f) \in \mathbf{R}, x_k^{ij} \ge 0, k \in \mathbf{K},$$

where m = number of treatment units; n_i = number of management schedules for unit *i;* w_{ij} = the area of the treatment unit *i* managed according to the management schedule *j*; x_k^{ij} = amount per unit area of item (commodity) *k* produced by unit *i* if schedule *j* is applied (constants produced by the treatment simulator); x_k = obtained amount of item *k*, $k = 1, \ldots, p$, z_k = an additional decision variable, $k = 1, \ldots, q$ (e.g. slack and surplus variables in goal programming); a_{tk} = fixed real constants for $t = 0, \ldots, r$, $k = 1, \ldots, p$; b_{tk} = fixed real constants for $t = 0, \ldots, r$, $k = 1, \ldots, q$; α_{tkf} = fixed real constants for $t = 0, \ldots, r$, $k = 1, \ldots, p$, $f = 1,..,F$; β_{tkf} = fixed real constants for $t = 0, \ldots, r$, $k = 1, \ldots, p$, $f = 1, \ldots, F$; r = number of utility constraints, x_{kf}^{i} = amount of item *k* transported from unit *i* to factory *f;* y_{kf} = utility obtained when item *k* is transported to factory *f* (the transportation cost is taken into account);γ_{kf}^{i} = utility when one unit of item *k* is transported from unit *i* to factory *f* (the transportation cost is taken into account); F = number of factories; A_i = area of unit *i*; R = set of (*k*, *f*) such that $\alpha_{tkf} > 0$ or $\beta_{tkf\,>}$ 0 for some *t*; B = set of (*k*, *f*) such that $\beta_{tkf} > 0$ for some *t*; K = set of such *k* that $\alpha_{tkf} > 0$ or $\beta_{tkf} > 0$ for some *t* and *f*.

Note that time does not appear in the problem definition. Time is taken into account implicitly in the item *k*; e.g. item *k* refers to harvested pulp wood at the second subperiod. Eq. (A3) defines the aggregated variable x_k as the sum over all units and schedules. Eq. (A4) (area constraint) states that the areas under different schedules add up to the total area of the unit. If constant x_k^{ij} is expressed as the total amount in the unit (instead of per area), then w_{ij} is proportion and each area A_i is 1. Eq. (A5) states that item *k* assigned to factory *f* is obtained by adding up all unitwise assignments. Eq. (A6) tells that the utility of item *k* when transported to factory *f* is obtained by summing up unitwise utilities. Eq. (A7) (transportation constraint) tells that all of item *k* in unit *i* is transported to factories. Note that constraint $\boldsymbol{x_k^{ij} \ge 0, k \in K}$(stating that transported items are non-negative) is not a standard LP constraint, because it constrains the values of the problem coefficients, not variables. Note that taking into account Eq. (A6), $\beta_{tkf}\boldsymbol{y}_{kf} = \sum_{i=1}^{m} \beta_{tkf}\gamma_{kf}^{i}\boldsymbol{x}_{kf}^{i}$. Thus, multiplying γ_{kf}^{i} for each *k* and *f* by a constant and dividing each β_{tkf} by the same constant, we can get an equivalent problem. Thus we can assume without loss of generality that each β_{tkf} is 1. A typical value of a_{tk} or b_{tk} is 1 or -1 for the constraint rows ($t > 0$). If the net present value is maximized, α_{0kf} is the discounted factory price of item *k* in factory *f*.

Usually, y_{kf} -variables appear in the objective row as a part of the definition of the net present value. When trying to understand the formulas, it might be easier to consider that y_{kf} is the total discounted transportation cost for item *k*, and γ_{kf}^{i} is the discounted per unit transportation cost when item *k* is transported from unit *i* to factory *f*. When also the utility of having item *k* transported to factory f (discounted factory price) is taken into account in y_{kf} and γ^{i}_{kf}, we get more efficient k_f computations and a more compact problem definition in J. Note that we can have different factory groups for different timber assortments by properly setting zeroes to alphas and betas. In typical problems, the utility constraints including x_{kf} are of form $x_{kf} \leq C$, which states that the capacity of factory f has an upper bound C for a period-specific timber assortment. There can also be a lower bound stating a minimum demand.

In J, the user specifies only the objective function (formula (A1)) and the utility constraints (formula (A2)) and gives information on how the program can compute or access coefficients γ^{i}_{kf}. The software then automatically takes care of the technical constraints (formulae (A3)–(A7)). In J, the area constraints (formula (A4)) are taken into account using the GUB technique of Dantzig and Van Slyke (1967). The GUB technique was extended also for transportation constraints (formula (A7)) by Lappi and Lempinen (2014a, b). Because the definitions of x_k-variables and factory variables x_{kf} and y_{kf} are written directly into the objective row (formula (A1)) and constraints (formula (A2)), the effective number of constraints is very small compared with the original problem formulation.