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Article

Profitability of the First Commercial Thinning, a Simulation Study in Northern Finland

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Abstract: Despite positive signals from increasing growing stock volumes and improved roundwood trade, first commercial thinnings (FCTs) tend to be a bottleneck in Finnish forest management and forestry. The reasons are many, but probably the most crucial would be the lack of simultaneous economic incentives for participating agents, i.e., private forest owners and forest machine contractors. This is due to poor stand characteristics in most FCT cases: low cutting removal with small average stem size. There are five predetermined management options: (1) Industrial wood thinning with only two timber assortments, pulpwood and saw logs, (2) Integrated procurement of industrial and energy wood, (3) Energy wood thinning solely consisting of delimbed stems, (4) Whole-tree energy wood thinning with an energy price of 3 € m^{-3} and (5) Whole-tree energy wood thinning with energy price of 8 € m^{-3}, that were applied for six separate forest stands located in Northern Finland, and derived from a database representing stands with an urgent need for FCT. Then, a two-phase financial analysis consisting of stand-level optimization (private forest owners) and profitability assessment (contractor) was conducted in order to find out whether there would be simultaneous economic incentives for both participants of FCT. The stand-level optimization revealed the financially best management options for a private forest owner, and then, for a contractor, the profitability assessment exposed the profit (or loss) associated with the particular management option. In brief, our results demonstrated that conducting either an industrial wood thinning (1) or an integrated procurement (2) resulted in a positive economic incentive for both the private forest owner and the contractor in all six cases (stands). Further, applying energy wood thinning with delimbed stems (3) would even generate a financial loss for the contractor, given the roadside prices applied in this study.

Keywords: stand-level optimization; first thinning; pine; spruce; profitability; energy wood; commercial timber

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1. Introduction

The growing stock volume of the Finnish forest resources has been accumulating steadily during the last decades, reaching a value of almost 2500 million cubic meters [1], and so too has the roundwood trade increased during recent years, ranging between ca. 60 and 71 million cubic meters *per annum* [1]. Despite these positive signals, first commercial thinnings (FCTs) tend to be a bottleneck of the Finnish silviculture—the area of managed/conducted FCTs falls distinctively short of the planned/scheduled area which is based on the silvicultural status and urgency [2]. For instance, in Lapland (the northernmost province of Finland), the need for FCTs within the next five years corresponds to a total of app. 470,000 hectares, while during the last five years there have been carried out app. 190,000 hectares of FCTs [3]. Such a gap between the need for FCTs and actually managed hectares of FCTs—the backlog of FCTs—would in time create problems at aggregate levels in the form of, e.g., a reduction in mean annual increment and decreased timber supply ("passive management", see [4]). In order to avoid the problems stemming from the backlog of FCTs, potential financial incentives need to be discovered and further revealed for various stakeholders involved in FCT operations. In addition, managing young forests could generate positive socio-economic impacts both at the regional as well as on the national level [5].

In general, stand density is controlled through thinnings to increase growth and to improve stem quality by removing low-quality stems (e.g., [6]). More precisely, FCT in conifer stands affects the diameter growth of dominant trees and, in general, the vigorousness of trees—so that neglecting FCT would delay the diameter growth and, in some cases, would increase the mortality at stand level [7,8]. On the other hand, one of the main reasons for the neglected FCTs is the generally low profitability due to the small stem size and high harvesting costs [9,10]. During the years, there have been several attempts to improve the profitability of FCT, for instance, by applying delimbed-tree [11–14], or whole-tree harvesting [14–18], integrated harvesting of energy wood and pulpwood [14,19–21] or rationalizing integrated harvesting of small-diameter wood by introducing a new technical prototype [22,23]. Regardless of various attempts and existing subsidies (for subsidies, see [24,25]) to improve the profitability of FCT, there still exists a challenge to carry out a financially viable FCT, at least so that each actor (forest owner, forest machine contractor and forest industry company) involved would have a solid financial incentive to venture into business. Further, we consider that the scope of this study (to discover financial incentives related to participating actors of FCT) is eminently country-specific due to, e.g., different legal and operational practices between countries (see [18,24]) facing seemingly similar FCT problems. Thus, the primary goal is to discover the financial incentives associated with FCT country-wise, and only after comparing the results between countries.

In order to assess the financial viability of forest management in a theoretically sound way, one needs to apply stand-level optimization [26], through which the bare land value is maximized (e.g., [27]). In brief, maximizing the bare land value (BLV) yields the discounted economic surplus over an infinite time horizon [28]. In the case of rotation forestry, RF (for terminology, see, e.g., [29]) stand-level optimization reveals the timing and intensity of thinnings as well as the length of the rotation. In this study, the RF approach was adopted, and five options to conduct a FCT were simulated and further optimized (to maximize the BLV) for discovering their financial performance from the viewpoint of a private forest owner. The five options present commonly-used practices applied for FCT, ranging from pure industrial roundwood procurement to a 'whole trees for energy wood' alternative. The real-life data for the analyses were derived from a silvicultural database consisting of non-industrial private forest owners' and NIPFs' forests in Finland [30]. When stand-level optimization is executed by applying stumpage prices (here), the results, i.e., optimal solutions, refer to the profitability from the private forest owner's point of view (e.g., [31]).

Conducting a FCT requires that all agents involved find financial incentives to participate. Thus, a financially viable result for a private forest owner does not necessary guarantee that a FCT actually takes place—for example, if there is no economic incentive for a forest machine contractor to employ a thinning, i.e., cut the trees (cf. [32]). In this study, each optimal solution (from the private forest owner's point of view) was further dismantled so that the diameter distribution of removed trees in FCT was used in calculating the logging costs (incl. cutting and forwarding) and logging revenues. Then, the five options were ranked according to financial feasibility related to logging, i.e., net revenues (gross revenues from logging—logging costs). Finally, the two different profitability measures (max BLV and net revenues from logging) were compared to find out whether any of the five options to conduct a FCT would generate financial incentives for a private forest owner and a contractor simultaneously.

2. Materials and Methods

2.1. Forest Data

The simulations and, further, the financial analyses were based on stand characteristics of six individual stands located in northern Finland (Figure 1). The six stands were derived from a database consisting of NIPF (non-industrial private forests) stands with an urgent need for the first commercial thinning, FCT [30]. The chosen stands belong to specific clusters of postponed FCTs. The clusters (consisting of individual stands) were derived from the project "Timber from postponed first thinnings in Northern Finland", implemented by the Natural Resources Institute Finland (Luke) and Finnish Forest Centre (Metsäkeskus), and funded by the Centre for Economic Development, Transport and the Environment (ELY) of Northern Ostrobothnia. The stands were selected according to: (*i*) the stand has passed the juvenile development phase but is not yet a mature stand (technically representing category 2 or 3 in the Finnish system) and (*ii*) a FCT had been suggested to be conducted in the stand within the past five years. The six chosen stands were quite similar with respect to stem number (trees per hectare) and soil type, but there was a distinctive difference in basal area and mean diameter (DBH) among the stands (Table 1).

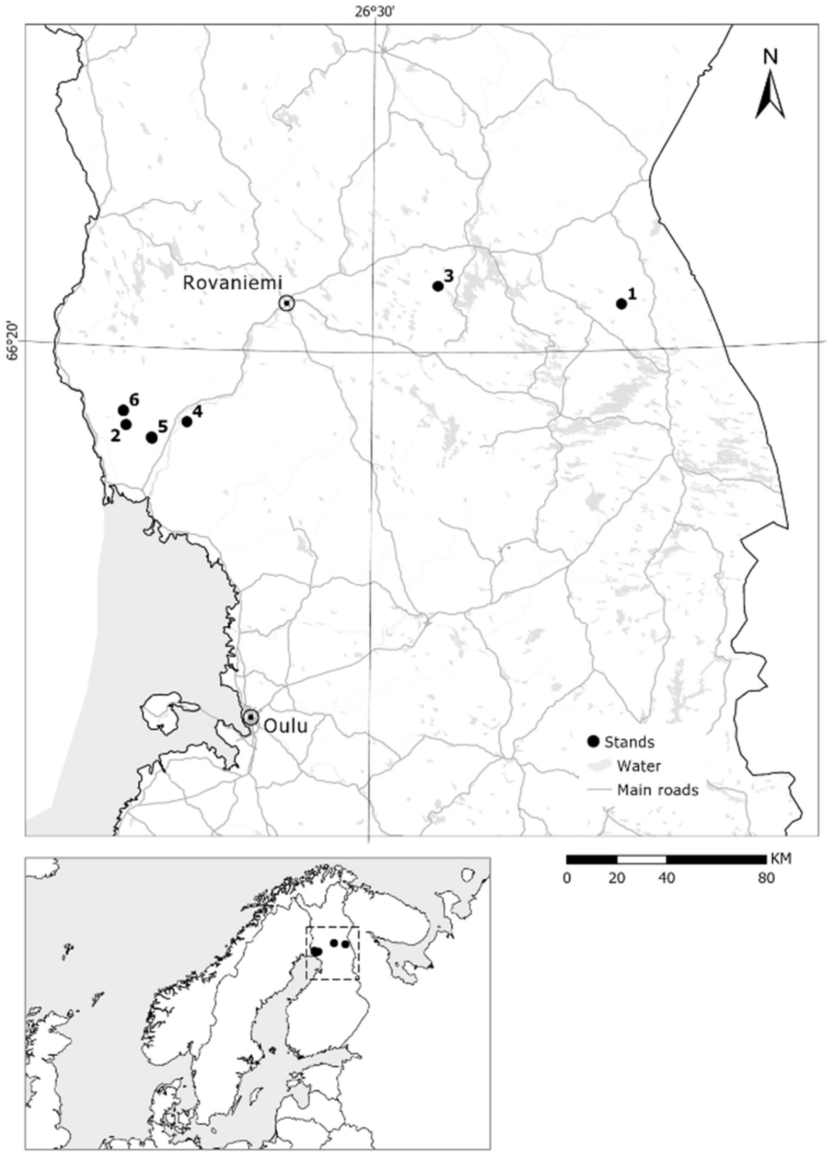

Figure 1. A map presenting the locations of Stands 1–6 under study.

Table 1. Stand characteristics of stands 1–6.

Stand Number	Main Tree Species	Site Type *	Stem Number/ha	Basal Area, m^2/ha	Mean Height, m	Mean DBH **, cm
1	Scots pine	MT	2044	24.63	9.58	15.13
2	Norway spruce	MT	1434	33.28	14.05	19.70
3	Scots pine	MT	1664	25.98	10.57	15.58
4	Norway spruce	MT	1689	35.68	13.67	18.33
5	Norway spruce	Mtkg	1320	32.95	14.29	20.21
6	Norway spruce	Mtkg	1481	26.72	12.47	17.71

* *Myrtillus* type (MT) on mineral soils and the corresponding site type on peatlands *Myrtillus* type (Mtkg) both indicate a fertile site type. For the Finnish forest site type classification, see [33]. ** Mean diameter at breast height.

2.2. Simulations

For each stand, five options to conduct the first commercial thinning (FCT) were simulated. The FCT options were: *(1)* Industrial wood thinning with only two timber assortments, pulpwood and saw logs (traditional), *(2)* Integrated procurement of industrial and energy wood (integrated), *(3)* Energy wood thinning solely consisting of stems (energy wood, delimbed stems), *(4)* whole-tree energy wood thinning with energy price of 3 € m^{-3} (energy wood, whole I) and *(5)* whole-tree energy wood thinning with energy price of 8 € m^{-3} (energy wood, whole II). Further, in options *(2)*, *(4)* and *(5)*, 30% of foliage and branches was assumed to be left on site after thinning, and in option *(3)* all, i.e., 100%, was assumed to be left. The timing and intensity of the first commercial thinning according to the above-mentioned options *(1–5)* were obtained through a stand-level optimization. For the rest of the rotation, the management regime was unbounded, i.e., the optimization algorithm sought the management regime (a solution) which resulted in the maximum value of discounted net revenues (see, e.g., [4,26]). In brief, the first commercial thinning was constrained to be conducted according to five predetermined options, the optimization algorithm only seeking the optimal timing and intensity for the first commercial thinning while for the rest of the rotation the optimization algorithm sought the optimal solution freely, without any constraints. The rationale was to discover which option to conduct the first commercial thinning would financially outperform other options.

Technically, the simulations (stand projections) were conducted by a Motti stand simulator, so that the simulator provided the objective function values for the optimization algorithm PIKAIA (see [34] for detailed technical description and [35] for an application of PIKAIA in forestry) to seek the maximum of net present values. An identical approach has been applied earlier, see, e.g., [4,27]. Since the simulations—as well as the optimization—started with a standing timber (see [36]), we had to conduct both the simulations and optimization separately for the ongoing rotation and for the future generations, and then sum up the results.

Motti is a stand-level decision-support tool for assessing the effects of forest management on stand dynamics [37–39]. In brief, Motti consists of two sets of models: stand-level and individual-level tree models, both based on an empirical–statistical modelling approach. Natural regeneration and early growth models are based on stand-level modelling, while for mature trees (Hdom > 7 m) predictions are simulated according to individual-tree models [40]. The Motti stand simulator has been widely applied in discovering various effects of forest management in boreal forests (to name a few, bioenergy: [19], peatland forestry: [41], biodiversity: [42], carbon policy: [39,43] and peatland cutaways: [44]). In addition, the Motti stand simulator has been applied in stand-level optimization, as well [4,31,35,39,45].

2.3. Financial Analyses

2.3.1. Private Forest Owner

The profitability for a private forest owner was assessed by applying the optimization algorithm integrated into the Motti stand simulator, as described above. The optimization problem was described as a discrete-time system of state and control variables (see, e.g., [39], [46]). Since the simulations and optimization started with an ongoing generation, juvenile stands (resulting in different time horizons) had to be explicitly separated from the ongoing rotation of future generations. This was accomplished by the following: First, we had to maximize the net present value of bare land over an infinite time horizon to correspond with future tree generations. For that purpose, let Z_{t_i} describe a stand state before the *i*th thinning at stand age t_i, $I = 0, \ldots, T$ (so that t_T presents the time for clear-cut and t_0 a bare land). Further, Z_{t_i} denotes the growing stock (expressed as m^3 ha^{-1}) which is a result of earlier thinnings and tree growth and is further affected by silvicultural measures sc_{st_l}, such as precommercial thinning occurring at time $t_l = 0, \ldots$ M. Then, k presents timber assortments ($k = 1, \ldots, K$) and a stumpage price (€ m^{-3}); for each timber assortment, k is denoted by p_k. Let b be the discount factor *s.t.* $b = 1/(1 + r)$, where r is the interest rate in real terms (i.e., without inflation). The removal (in m^3) of each timber assortment k in *i*th thinning is denoted by h_{ki}. Thinning intensity (removal relative to growing stock) in *i*th thinning is g_i, so that $g_T = 100\%$. Stand establishment costs (at time t_0) are denoted by w, reflecting a fixed amount of seedlings and a fixed cost of site preparation in artificial regeneration, according to prevailing silvicultural guidelines [47]. Optimized variables include the number of thinnings, the timing of thinnings, the intensity of thinnings, the number and timing of silvicultural measures, and the rotation period. Applying the [28] rotation model, the objective function is to maximize the net present value of bare land over an infinite time horizon:

$$MaxLEV_{\{t_i, T, g_i, M, sc_{st_i}\}} = \frac{\sum_{i=0}^{T} b^{t_i} \sum_{k=1}^{K} p_k h_{ki}(Z_{t_i}, g_i) - \sum_{l=0}^{M} b^{t_l} \sum_{s=1}^{S} SC_{st_l} - w}{1 - b^{t_T}} \quad (1)$$

For the ongoing rotation, including the five options for the first commercial thinning, stand management was optimized by maximizing the net present value, NPV. The starting point for simulation differed among the stands due to stand characteristics (see Table 1), *a priori* resulting in different timing for clear-cutting of the ongoing rotation. Since the time horizon might vary among simulated management regimes of the ongoing rotation, the discounted *MaxLEV* (Equation (1)) was included into the financial analysis commensurate with the management regimes (see [26] for technical details). Finally, the financial performance associated with the five management regimes was assessed according to:

$$MaxNPV_{p^{\{t_i, T, g_i, M, sc_{st_i}\}}} = \sum_{i>0}^{T} b^{t_i - n} \sum_{k=1}^{K} p_k h_{ki}(Z_{t_i - n}, g_i) + b^{t_T - n}(maxLEV) \quad (2)$$

where $MaxNPV_p$ represents the maximum net present value according to an option p for the first commercial thinning, $p = 1, \ldots, 5$ and n is the stand age (in years) at the starting point of the simulation in ongoing rotation (*Note* that there are no silvicultural measures in ongoing rotation, since the starting point in each stand 1–6 is beyond a tending phase (see Table 1)).

2.3.2. Contractor

Having achieved the *MaxNPV* through stand-level optimization (Equations (1) and (2)), the first commercial thinning was further dissolved into diameter distributions, enabling the calculation of the logging costs. In this study, we assume that the contractor is an independent operator seeking a profit on procuring the feedstock (industrial timber, energy wood or both depending on the option) to market (see, e.g., [32]). Further, we apply roadside prices for industrial timber and price of delivery sales for energy wood (see Section 2.4

for detailed values). Then, the profitability of the first commercial thinning for a contractor is:

$$\prod_p = \sum_{k=1}^{K} h_k p_k' - \sum_{k=1}^{K} v_k \quad (3)$$

where Π_p is the profit of FCT option p, $p = 1, \ldots, 5$, h_k is the harvested amount h of timber assortment k (m^3 ha^{-1}), $p_k{}'$ is the roadside unit price for timber assortment k (€ m^{-3}) and v_k is the logging cost (incl. cutting and forwarding) associated with the harvested h_k (€ ha^{-1}). The cutting productivities in all options were calculated by applying the time consumption model of [21]. The forwarding productivity of industrial roundwood and delimbed energy wood was calculated using the model of [48]. When forwarding whole trees and tree tops the function of [49] was applied. The load size of the medium-sized forwarder was set at 9.3 m^3 for industrial roundwood and delimbed energy wood, 6.5 m^3 for whole trees and 4.7 m^3 for undelimbed tree tops [49,50]. The total length of the strip road network at stand was assumed to be 600 m ha^{-1}, based on an average strip road spacing of 20 m [51]. The productive machine hour (PMh) productivities of harvester and forwarder were converted to operating hour productivities—also known as scheduled machine hour (SMh) productivity—by the coefficients of 1.39 and 1.30 [52]. The hourly cost of a thinning harvester and a medium-sized forwarder were 102.3 € SMh^{-1} and 81.0€ SMh^{-1} [53]. The logging costs associated with each option 1–5 were calculated according to the above-mentioned values.

2.4. Economic Data

Financial analysis conducted for the private forest owner's viewpoint was based on stumpage prices (Lapland) and silvicultural costs derived from a nominal time series of 2015–2019 [54], representing the latest available statistics during the preparation of this study. Annual roadside prices and quarterly price of energy wood time series covering years 2015–2019 were applied to assess contractor's revenues. The nominal time series was deflated by the cost-of-living index [55] to attain real prices and costs (Table 2). Then, for option 4 (energy wood, whole I) and option 5 (energy wood, whole II) unit prices of 3 and 8 € m^{-3} were applied in the first commercial thinning, respectively.

Table 2. Stumpage prices (€ m^{-3}), silvicultural costs (€ ha^{-1}), roadside prices (€ m^{-3}) and price of energy wood (€ m^{-3}) in real terms (base year 2019). Price of energy wood is at roadside. Shading refers to prices applied only for a contractor.

Felling Method	Pine Logs	Spruce Logs	Birch Logs	Pine Pulpwood	Spruce Pulpwood	Birch Pulpwood
Regeneration felling	53.54	51.70	45.86	18.37	20.01	17.53
Thinning	47.18	48.78	38.59	14.85	16.23	14.04
First thinning	40.90	42.69	33.76	12.35	12.21	12.23
First thinning Roadside prices [1]	57.31	53.17	–	27.79	32.12	–
First thinning Price of energy wood [2]	23.18	23.18	23.18	23.18	23.18	23.18
Silvicultural costs						
Mounding	405.90 € ha^{-1}					
Planting	640.23 € ha^{-1}					
Seeding	251.13 € ha^{-1}					
Early precommercial thinning	369.96 € ha^{-1}					
Precommercial thinning	452.68 € ha^{-1}					
Improvement of young stands	458.64 € ha^{-1}					

[1] roadside prices and the price of energy wood were applied when assessing the profitability for the contractor (see Equation (3)). [2] identical price applies for stem, foliage and branches.

3. Results

3.1. Logging Costs

The resulting logging costs (reflecting the optimal first commercial thinning) are presented in Table 3. The lowest logging costs (expressed in € m^{-3}, incl. cutting and forwarding) were for energy wood, whole II where the stumpage price of energy wood was set to 8 € m^{-3} for a private forest owner. The highest logging costs were associated with traditional and industrial wood procurement (Table 3).

Table 3. Average stem volumes (dm^3), cutting removals (m^3 ha^{-1}) and logging costs (€ m^{-3}) associated with the five options for first commercial thinning (FCT) according to stand-level optimization.

Option	Stem/Tree Volume. dm^3	Cutting Removal. m^3 ha^{-1}	Logging Cost. € m^{-3}
Traditional	129.58 (44.28) [1]	64.44 (14.83) [19.6] [4]	20.51 (2.94)
Integrated	131.30 (35.05)	75.81 (16.00) [18.9]	19.97 (2.74)
Energy wood, d.tems [2]	110.67 (126.31)	50.87 (6.60)	20.10 (2.30)
Energy wood I [2]	138.30 (29.40)	59.91 (7.92)	17.97 (1.57)
Energy wood II [3]	145.00 (31.89)	64.85 (8.68)	17.66 (1.62)

[1] in parenthesis standard deviation. [2] stumpage price of energy wood 3 € m^{-3}. [3] stumpage price of energy wood 8 € m^{-3}. [4] in brackets average saw timber removal of total cutting removal, traditional and integrated option, m^3 ha^{-1}.

3.2. Growth and Yield

As expected, the timing of the final cutting of the ongoing rotation fluctuated considerably, depending on the option (1–5) used to conduct the first commercial thinning (Figure 2, Table 4). For simplicity, optimal management associated with options 1–5 is presented only for stand 1 (Figure 2). In the integrated option (option number 2) the optimal rotation was 94 years, while in option 5 (energy wood, whole II) the corresponding rotation was as high as 107 years (Figure 2). Options 1 (traditional) and 3 (energy wood, stems) resulted in almost identical rotation periods of 101 and 102 years, respectively (Figure 2).

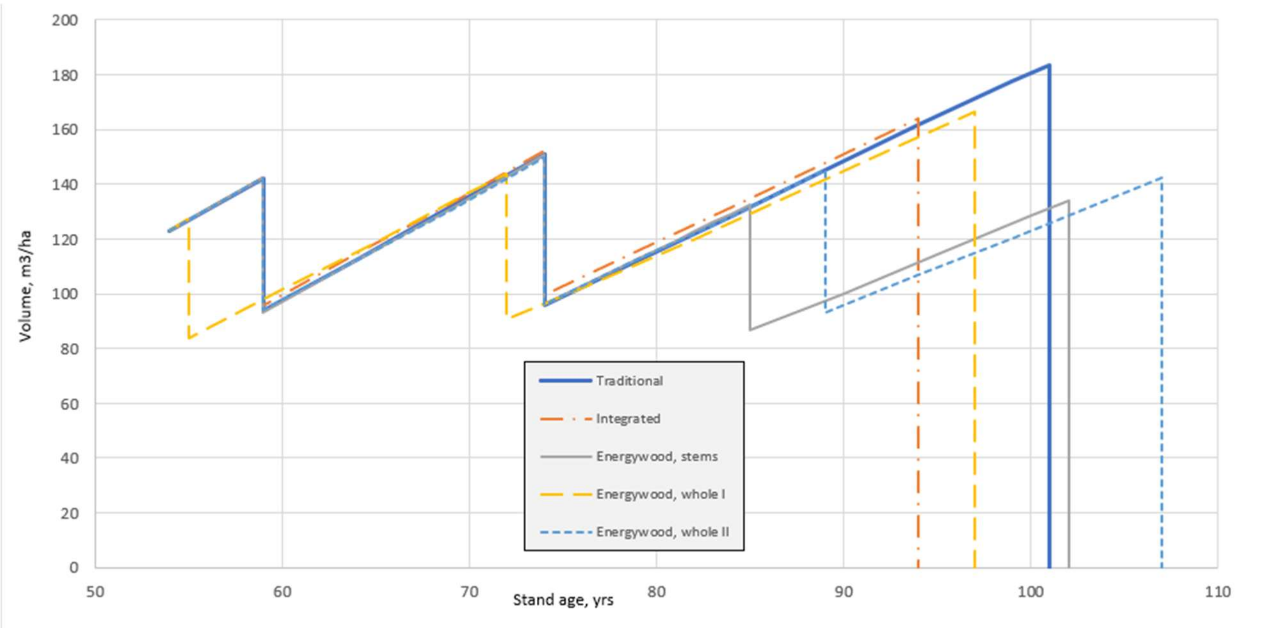

Figure 2. Volume of a growing stock associated with option 1 (traditional), 2 (integrated), 3 (energy wood, stems), 4 (energy wood, whole I) and 5 (energy wood, whole II) according to stand-level optimization in stand 1, m^3 ha^{-1}.FCT conducted at the stand age between 54 and 59 years, depending on the option.

Table 4. Thinning removal of the first thinning. Total cutting removal and rotation period associated with optimal solutions according to management options. Total cutting removal and rotation period associated with future generations also shown. Stand-level optimizations simulated with 3% interest rate.

Stand	Management option	Cutting Removal of the 1st Thinning, $m^3\ ha^{-1}$	Total Cutting Removal $m^3\ ha^{-1}$ Ongoing [b]	Future [c]	Rotation Period, yrs Ongoing	Future
Stand 1	Traditional	45.0 (0.0)	279.1	324.0	101	98
	Integrated	54.0 (10.7) [a]	266.2	356.3	94	104
	Energywood stems	46.0 (46.0)	275.2	304.7	102	95
	Energywood whole I	52.0 (52.0)	268.9	346.3	101	102
	Energywood whole II	52.0 (52.0)	299.2	314.4	107	96
Stand 2	Traditional	76.0 (0.0)	303.7	404.3	110	78
	Integrated	88.0 (12.5)	312.8	381.0	110	78
	Energywood stems	52.0 (52.0)	311.9	426.0	111	81
	Energywood whole I	59.0 (59.0)	319.2	442.6	111	83
	Energywood whole II	60.0 (60.0)	315.8	420.3	110	80
Stand 3	Traditional	58.0 (0.0)	352.0	355.9	91	87
	Integrated	69.0 (11.6)	361.6	369.9	91	89
	Energywood stems	47.0 (46.6)	352.3	363.0	91	87
	Energywood whole I	57.0 (56.8)	362.8	388.1	91	91
	Energywood whole II	68.0 (67.9)	364.0	391.6	91	92
Stand 4	Traditional	82.0 (0.0)	325.3	390.8	112	79
	Integrated	95.0 (13.5)	330.3	414.6	111	82
	Energywood stems	64.5 (64.5)	320.9	413.1	110	82
	Energywood whole I	76.0 (75.7)	335.9	437.8	112	85
	Energywood whole II	75.5 (75.5)	332.4	423.3	111	83
Stand 5	Traditional	79.0 (0.0)	304.7	402.6	110	78
	Integrated	91.0 (13.3)	317.0	413.8	111	79
	Energywood Stems	51.0 (50.9)	317.6	425.7	112	81
	Energywood whole I	63.0 (62.5)	323.3	442.8	112	83
	Energywood whole II	75.0 (74.5)	332.4	423.3	111	83

Table 4. *Cont.*

Stand	Management option	Cutting Removal of the 1st Thinning, m^3 ha^{-1}	Total Cutting Removal m^3 ha^{-1} Ongoing [b]	Future [c]	Rotation Period, yrs Ongoing	Future
Stand 6	Traditional	48.0 (0.0)	295.7	381.2	111	77
	Integrated	58.0 (9.5)	325.5	428.7	111	81
	Energywood Stems	45.2 (45.0)	298.2	372.4	111	76
	Energywood whole I	53.3 (53.0)	303.8	385.8	111	78
	Energywood whole II	54.0 (53.6)	312.6	399.2	114	80
	Traditional	**64.4 (0.0)** [d]	**310.1**	**376.5**	**105.8**	**82.8**
	Integrated	**75.8 (11.8)**	**318.9**	**395.4**	**104.7**	**85.5**
Average	**Energywood stems**	**50.8 (50.8)**	**312.7**	**384.2**	**106.3**	**83.7**
	Energywood whole I	**59.9 (59.9)**	**319.0**	**407.2**	**106.3**	**87.0**
	Energywood whole II	**64.9 (64.9)**	**326.1**	**395.3**	**107.3**	**85.7**

[a] (of which energy wood). [b] ongoing rotation. [c] future rotations. [d] arithmetic average of stands 1–6.

On average, the integrated option (2) resulted in the highest cutting removal at the first thinning: 75.8 m^3 ha^{-1} (Table 4). The lowest cutting removal at the first thinning was associated with option 3 (energy wood, stems), 50.8 m^3 ha^{-1} (Table 4). However, with respect to total cutting removal of the ongoing rotation, the options 1–5 were quite close to each other, the range being from app. 310 to 326 m^3 ha^{-1} (Table 4). For the future generations, the rotation period varied only mildly: from app. 83 to 87 years depending on the option (Table 4). The cutting removals of future generations, however, fluctuated a bit more, relatively: from ca. 376 to 407 m^3 ha^{-1} (Table 4).

3.3. Financial Performance

From the private forest owner's point of view, the best performer (expressed as *MaxNPV*, Equation (2)) was option 1, traditional, where only saw logs and pulpwood are procured (Figure 3a). For instance, the highest *MaxNPV* was reached with option 1, the value of 6999 € ha^{-1}, while the lowest *MaxNPV* value was associated with option 4 (Energy wood, whole I), 2665 € ha^{-1} (Figure 3a). For pure energy wood alternatives (option 3, 4 and 5), the best performer was option 5 (energy wood, whole II) with a median of 4879 € ha^{-1} (Figure 3a). Two options (traditional and integrated, options 1 and 2, respectively) distinctively outperformed the other three options (3, 4 and 5) from the contractor's point of view (Figure 3b). The highest profit among the six stands for a contractor at the first thinning was as much as ca. 2000 € ha^{-1} in option 1 (traditional), while in option 3 (energy wood, stems) a contractor might even operate at a loss (Figure 3b). Further, in option 4 (energy wood, whole I) and 5 (energy wood, II) the contractor barely makes a profit at the first commercial thinning (Figure 3b).

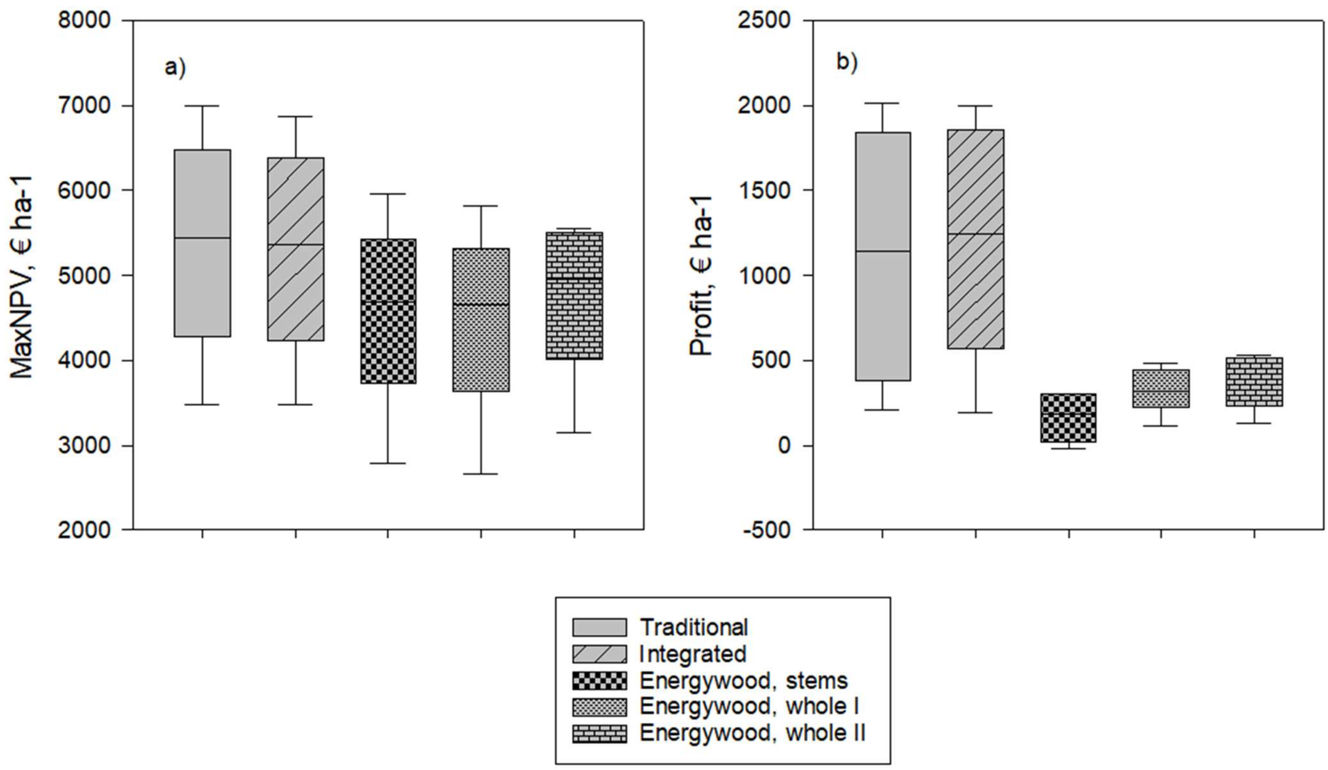

Figure 3. (**a**) Boxplots presenting the maximum NPV of options 1–5, € ha^{-1} (private forest owner's viewpoint), and (**b**) profit associated with options 1–5 at the first commercial thinning (contractor's point of view). (Note that bottom edge of each box illustrates the 25th percentile, upper edge the 75th percentile, a line within a box marks the median and whiskers of the boxplots indicate 5th and 95th percentiles.)

4. Discussion

It is a known fact that the profitability of timber harvesting improves with increased stem volume and removal of harvested trees per hectare, indicating that the profitability would be better in clearcutting (e.g., progressive strip clearcut system) than in, e.g., the first commercial thinning or shelterwood cutting, especially in peatland forests (for a concise literature on the topic, see [56]). Thus, the first commercial thinning in even-aged boreal forests can be challenging with respect to financial performance—to find a profitable option depends both on the harvesting method and stand characteristics (e.g., [22,52,57–59]). It appears that there is no generic method applicable, rather, one has to choose a management option conditional on stand characteristics (such as stand density and average stem volume). Further, there is a lack of papers which would tackle the problem of the first thinning by applying a stand-level optimization (cf. [59])—to our knowledge this study is the first attempt in boreal forests (cf. [60,61]).

This study focused on the profitability of the first commercial thinning by introducing a stand-level optimization with five predetermined options to conduct the first thinning. The rationale was to discover the best financial outcome for a private forest owner to conduct the first commercial thinning, and then to find out whether the solution would be financially viable for a contractor, as well (for a similar approach dealing with simultaneous financial incentives, see [32,45]). The optimization algorithm primarily solved the timing and intensity of the first thinning (according to the constraints relevant for each option 1–5), and, secondarily, the timings and intensity of other thinnings and the timing for a clearcut in ongoing rotation. Additionally, the bare land value (reflecting future tree generations) was maximized through optimization (see, e.g., [26,46,62]), and it was further summed up with the financial result of the ongoing rotation. The five options to conduct the first commercial thinning can be seen as good representatives of the current practices applied in Finnish forestry, ranging from pure industrial wood procurement to a whole-tree energy wood option. Further, the stands (to be simulated) were derived from an updated database of postponed FCTs, with the emphasis on hot issues (timing and intensity) associated with the FCT.

Since first commercial thinning (FCT) is, in practice, the first silvicultural action to generate immediate income to a forest owner [63,64], it would be reasonable to maximize the profit associated with the FCT as well. Among the five options (technically, set-ups) to conduct the FCT, the best financial performer from the private forest owner's point of view was traditional procurement focusing solely on industrial wood, i.e., saw logs and pulpwood. This option financially outperformed the other four, indicating also that the result would hold for the rest of the ongoing rotation as well as for future rotations. Earlier studies (e.g., [14,20])—without applying a stand-level optimization—somewhat contradict this outcome, suggesting that integrated harvesting (procuring both pulpwood and energy wood) in the first thinning would be financially feasible to apply. In this connection, however, it should be highlighted that we ignored the effect of stem quality and the spatial distribution of remaining trees. The former relates to the fact that different thinning methods applied in the FCT usually generate slightly different overall stem quality in the future [60], resulting in a different timber grade distribution in thinnings and clearcut [65]. This has a clear effect on stand-level optimum and financial performance, as well [46]. The latter (spatial distribution) refers to sufficient dominant and co-dominant crop trees left growing in the FCT, and the spatial arrangement which either contributes to or debilitates that, depending on the applied thinning method in FCT [61]. Further, forest management (e.g., in a form of alternative thinning profiles) has a clear impact on abiotic and biotic risks related to forestry [66]. Namely, it has been demonstrated that stand-level optimization with distance-dependent growth models (including spatial distribution) results in a different outcome than that with distance-independent growth models [67].

Having resolved the optimal management for a private forest owner through stand-level optimization, the next step was to check whether the solution would be financially desirable for a contractor, too. Thus, we analysed the optimal solutions of each stand (1–6) by dismantling the thinning removal of the FCT into diameter distribution and, further, into cutting incomes and logging costs associated with the contractor responsible for the procurement. The results of those analyses revealed that two options were distinctively better performers than the other three. Namely, the traditional and integrated options (options 1 and 2, respectively) were, financially, the most attractive for a contractor, resulting in profits from the FCT in each stand simulated. This result was clear, since the other three options (options 3, 4 and 5) even generated losses for a forest machine contractor and were, generally, distinctively less attractive with respect to financial outcome. Combining the results from the stand-level optimization (private forest owner) and the profitability analysis of the CFT (contractor), one could conclude that there might be a *win-win* option, or even two *win-win* options, applicable to conduct the FCT, namely traditional (solely industrial timber) and integrated procurement of industrial timber and energy wood.

Then, the interpretation of the results is conditional for separate issues. First, the simulations started with ongoing stands, implying that the stand development might have already departed from an optimal path (e.g., [68]). However, the more important topic (than starting from bare land—see [26]) was to describe presentable cases of typical postponed FCTs and to discover the best financial management option to conduct a postponed FCT. Then, the results are conditional to applied supply chains (time consumption related to machinery in cutting and to the forwarder), reflecting the productivity of the applied machinery. In this study, we applied time consumption models and productivity parameters based on studies [21,48–50,52] which might be considered a bit outdated. Undoubtedly, there has been some progress (improvements) in operators' professional skills, technical solutions and changes in the working environment during the last decade. However, a recent study on the integrated harvesting of industrial roundwood and energy wood (clearcuttings on peatland) demonstrates that the models applied in this study would not drastically differ in terms of harvesting productivity from the latest models available [56].

Third, harvesting trees with branches reduces the quality of the chips, but this is a critical issue only for small heating plants, which require stick free chips to operate properly [12]. Further, whole tree harvesting indicates somewhat higher chipping and transportation costs than supply chains based on delimbed wood material [12].

Finally, although we found a *win-win* situation (financial incentives for both participants, private forest owner and contractor), for conducting a FCT the ultimate decision is vitally dependent on the market situation: is there enough demand for roundwood at the regional level [69] and, evidently, at a global scale [70]? Further, integration of roundwood markets between countries (namely, Sweden and Finland) might generate a boost to local timber supply, as well [71].

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