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Comparison of Two Working Methods for Small Tree Harvesting with a Multi Tree Felling Head Mounted on Farm Tractor

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In this study, the efficiency of a small multi-tree felling head, mounted on a farm tractor with a timber trailer was studied, when harvesting small trees for energy in thinnings. Both separate loading and direct loading of the felled trees was studied.

Time studies were carried out in a mixed stand of Norway spruce (*Picea abies* (L.) Karst) and birch (*Betula pubescens* Ehrh.). The time consumption of the work elements in the different work methods was formulated by regression analysis, where the independent variables were tree size and degree of accumulation. The average size of the harvested trees was 0.035 m^3. The time consumption for the harvesting and loading were similar for the two studied methods, 20 minutes per m^3 at a tree size of 0.035 m^3, but the two methods showed different characteristics for different tree sizes and level of accumulation. The direct loading method had the highest productivity when more than 0.1 m^3 were collected in the felling cycle, whereas the separate loading method had the highest productivity when less than 0.05 m^3 were collected in the felling cycle. The total effective time consumption for harvesting and forwarding the biomass 300 meters to roadside landing was 27 minutes per m^3. The efficiency of the initial felling and collecting of the small trees was the main challenge. Both the harvesting technique and harvesting technology needs further development to provide a feasible production chain for woodfuel from energy thinning.

Keywords cost functions, forest biomass harvesting, multi-tree handling, young stands, Norway spruce

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1 Introduction

Pre-commercial thinning (PCT) of dense young stands is an important operation in ensuring the future production of high quality timber in these stands (Kuusela 1990, Hamilton 1992, Enström 1996). The aim of PCT is to favour the chosen crop trees, accelerating their growth rate and increasing the future yield of high value timber. PCT is also considered to render more robust and healthy stand with less susceptibility to windfall and snow break (Hamilton 1992, Enström 1996). In addition, the economy of subsequent harvesting in thinning and final felling will be improved by the larger tree sizes (Hamilton 1992, Enström 1996).

In spite of these strong motives, there is a tendency amongst forest owners to neglect a timely PCT. In Norway, PCT has decreased by 50 per cent from a steady level of 40 000 ha yr^{-1} in the period 1996–2000 (Skogstatistikk 2007). In Finland PCT has been reduced from 250 000 (which is still the national target) to 150 000 ha yr^{-1} (Finland's national forest programme 2010, 1999). The development is similar in Sweden where almost one million hectares is reported to be in "acute need of PCT" (Kempe 2002).

In Nordic conditions, PCT of young forest is normally carried out at a stand height of 1,5–6 m, leaving 1400–3000 potential crop trees/ha, depending on species and yield class (Hamilton 1992, Enström 1996, Braastad et al. 1997). Currently, PCT is often carried out motor-manually, and costs increase with increased tree size (Overenskomst 2006).

A way to counteract the development towards reduced and postponed PCT activities is the combination of early stand thinning and wood fuel production (Hakkila 2005, Heikkilä et al. 2007). Thus, revenues from fuel chip sales could subsidize the costly PCT. The demand for wood chips is increasing in all Nordic countries, and Finland has even set a national goal to produce 1.7 million m^3 fuel chips from early "energy thinning" by 2010 (Hakkila 2005).

The economy of harvesting small trees is a classical challenge. Hourly operation costs of the production equipment are not sensitive to tree size, while the productivity and the value of the product is highly dependent (Sundberg and Silversides 1988). Mechanised harvesting of small trees with the conventional single-tree approach is particularly challenging due to the direct relation between tree size and productivity. To alleviate the problem, multi-tree technologies have been developed, aiming at distributing the harvesting costs onto several trees. Felling heads that can perform consecutive felling cuts in one crane cycle and accumulate the felled trees, were studied in Sweden as early as 1971 (Brunberg 1989).

Another challenge is the extensive and costly crane handling of the harvested material. As a possible solution, it has been proposed to load the harvested material directly to the trailer, e.g. in a "harwarder system", denoting a combined harvester-forwarder (Bergkvist et al. 2003, Laitila and Asikainen 2006).

Currently, multi-tree heads are available on the market in a large number of brands and models. The multi-tree heads have different working principles, e.g. harvesting heads capable of processing the accumulated trees into delimbed shortwood or exclusive felling heads, producing whole tree bunches, and normally capable of bucking the trees into transport lengths. The latter type has met particular interest from the market. These multi-tree felling heads are typically low-weight (250–500 kg) with moderate demands on hydraulic performance and engine capacity. They can therefore be mounted on smaller base machines and farm tractors.

The aim of this study was to investigate the productivity of a small multi-tree felling head, mounted on a farm tractor with a timber trailer, while harvesting small trees in energy thinning of a mixed stand of spruce and birch. Two work methods were studied; conventional felling and bunching of the trees, with subsequent loading to trailer and forwarding to roadside, and direct loading of the felled trees onto the trailer with subsequent forwarding to roadside.

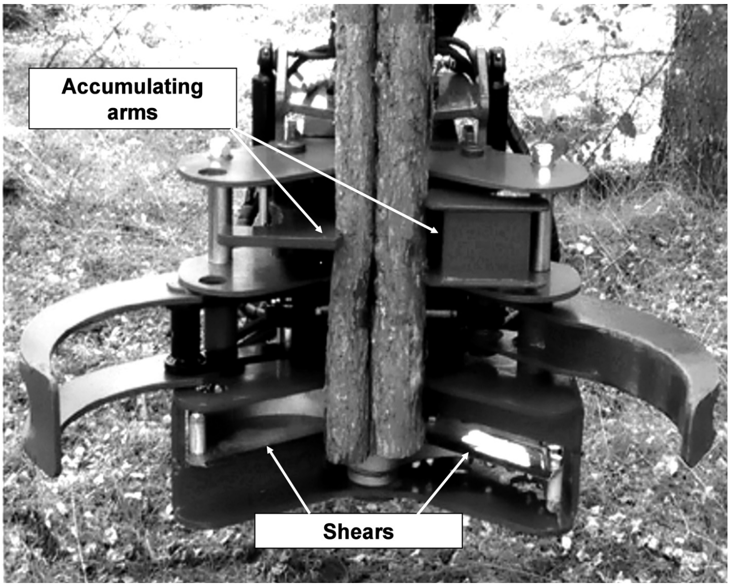

Fig. 1. Picture of the Nisula 280E felling head. The height from bottom plate to top plate is 56 cm. The diameter of the shears (inside the supporting profiles) is 26 cm. Photo: Nisula Forest Oy.

2 Material and Methods

2.1 Felling Head and Base Machine

The base machine was a 150 hp Valmet XM frame-steered farm tractor (2006 model). The crane was a 9 m Cranab FC 80 forwarder crane, rated 79 kNm gross lifting torque. The felling head was a Nisula 280E with hydraulic shears and accumulating arms (Fig. 1). The height of the felling head was 56 cm, the inner diameter of the shears was 26 cm and the maximum opening of the grapple arms was 70 cm. Forwarding capacity was provided by a 4 wheel drive timber trailer with extended frame and 10 ton load capacity. The procurement cost of the whole equipage was € 211 250 in 2007 (information provided by the contractor). The machine operator was well experienced with regular mechanized thinning with purpose-built thinning harvesters, and had one month of practice with the tested equipment and work methods before the study was done.

2.2 Work Methods

Two different work methods were studied.

The separate loading method implies that the stand was harvested and forwarded the same way as when using conventional two-machine systems. All harvested trees were first felled and bunched along the strip road, and the tractor was working without the timber trailer mounted. The felled trees were then loaded into the trailer and forwarded in a second operation.

The direct loading method implies that the strip road was opened first, without the trailer mounted on the tractor. Then the timber trailer was coupled to the tractor, and the stand between the strip roads were thinned and loaded directly into the trailer. At the same time the "striproad trees" felled in the first operation were loaded into the trailer.

2.3 Time Study

The time study material was collected by using an Allegro handheld field computer employing

Table 1. Overview of recorded variables.

Work element	Descriptive variable
Fell-bunch, separate loading method: Time consumption from when the crane starts a new felling cycle to the last accumulated tree is felled, and all trees are bucked and piled alongside the striproad.	Species and diameter at breast height ($d_{1,3m}$) for each accumulated tree.
Fell-load, direct loading method: Time consumption from when the crane starts a new felling cycle to the last accumulated tree is felled, and the whole tree-bunch is loaded into the timber trailer. Tall trees were bucked standing, bucking time for these trees are embedded in the felling cycle time for this work element.	Species and diameter at breast height ($d_{1,3m}$) for each accumulated tree.
Loading: Time consumption for loading bunches from ground into the timber trailer.	
Moving: Time consumption for moving the machine during harvesting or loading.	Moving distance, m
Forwarding and unloading: Forwarding the load to landing terminal by road side, unloading and return driving.	Driving distance, m Load weight, kg
Miscellaneous: Other activities in the harvesting and forwarding work. Check of equipment, preparation, planning, change of cheer position in the tractor etc.	
Loss time: Equipment failure, repair of equipment.	
External loss time: Loss time caused by research activity.	

continuous time study software called SDI, which was provided by Haglof AB in Sweden. Time study of mechanized harvesting of young stand is a demanding task because of the high intensity of the work. This might lead to bias in the data collection (Nuutinen et al. 2008). To avoid biased data the same researcher, with some 30 years experience with time studies in forest operations, was collecting all the time study data. Each work element was recorded with the time consumption (cmin) and supplementary descriptive variables. An overview of the recorded work elements can be found in Table 1.

In the separate loading method the new felling cycle started when the empty felling head started seeking the first tree to cut, in most cases this was when a bunch of trees was piled on the ground. The felling cycle included felling, accumulation, bucking of the tree bunch and piling the bunch on ground.

In the direct loading method the new felling cycle also started when the empty felling head started seeking the first tree to cut. In most cases this is when a bunch of trees were unloaded from the felling head into the timber trailer. The felling cycle included felling, accumulation, and loading to trailer. When the trees were too tall for direct loading (taller than 6–7 m) the felling cycle included top-bucking, cutting, accumulation and loading to trailer.

2.4 Study Plots

Both work methods were studied in the same stand, which was a 24 year old dense mixed stand of planted Norway spruce (*Picea abies* (L.) Karst.) and naturally seeded birch (*Betula pubescens* Ehrh.) in the Hadeland region in the mid-eastern part of Norway (60º30'N, 10º31'E). No pre-commercial thinning had been done since the spruce seedlings were planted. Therefore there was a relatively large variation of tree size and tree density within the stand. Diameter at breast height (dbh) and tree height was measured to generate height curves. Nearly all trees inside the planned strip road zone and 40 % of the trees in the thinning zone between the strip roads were tagged with their dbh. On un-market trees that were felled during the study the dbh was deter-

Table 2. Stand characteristics of the studied plots.

	Study plot Sep. loading	 Direct loading
Area, m^2	1040	1950
Strip road width, m	4	4,2
Operation width, m	18,4	17,1
Before thinning		
Volume per ha, m^3	182	210
Tree per ha	6300	4700
Average dbh (arithmetic mean)	6	8
Composition of species (s,p,d)[a]	3,0,7	4,0,6
Removal		
Volume per ha, m^3	95	124
Tree per ha	4500	3100
Average dbh	5,4	7,2
Average volume per tree, m^3	0.021	0.040
Composition of species (s,p,d)[a]	1,0,9	3,0,7

[a] s,p,d = 10-% fraction of spruce, pine and deciduous

mined by the study man by visual comparison to neighbouring tagged trees. The biomass and volume for each tree was estimated using biomass equations based on tree height and dbh. All equations were found in the synoptic in Silva Fennica Monographs 4, 2005 (Zianis et al. 2005). Marklunds (1988) biomass equations were used for spruce and birch, while Johansson's (1999, 2000) equations were used for alder. To check the estimated biomass values some of the loads were weighed. Some trees were sampled and tested for moisture content by the standard oven dry method (CEN/TC-335 2004). The deviation between estimated load weight and measured load weight were for all loads less than 10%. The volume of the trees (including stem volume on bark, top and branches) was estimated by the calculated dry matter content and basic density, where density numbers were obtained from the Norwegian forestry handbook "Norsk Skoghåndbok" (Heje and Nygaard 1995). Stand characteristics before and after operation are listed in Table 2.

2.5 Analysis

Models describing the effective (E_0) time consumption in min m^{-3} of the crane work in the different work methods were found by regression analysis using the SAS 9.1 statistical software package. Tree size and number of trees in each felling cycle were used as independent variables. For the work elements which could not be tied to each harvested tree, i.e. loading from ground and moving during harvesting, the average time consumption for the whole operation was used.

3 Results

3.1 Felling Head and Accumulation

The average degree of accumulation was 1.7 trees per felling cycle for the direct loading method, while the corresponding number was 2 trees per felling cycle with the separate loading method. The difference is explained by the difference in average tree size in the two plots. There was no difference between the two work methods regarding degree of accumulation when comparing felling cycles with similar tree sizes. The maximum recorded volume in the felling head when trees were accumulated was 0.26 m^3, but in 83% of the felling cycles the total volume was less than 0.1 m^3. Compared to the maximum observed accumulation, the accumulation capacity was utilized to a rather limited extent (Fig. 2).

3.2 Felling and Loading Productivity

The average productivity for felling and loading for the two work methods was 3 m^3 per effective hour (E_0-hour), with an average whole tree size of 35 dm^3 and average density of removal of 3644 trees ha^{-1}.

The following model describes the time consumption for the felling cycle for the separate loading method, where the coefficients can be found in Table 3.

$$\text{Log}_{10}\,(T_{\text{fell-bunch, sep. loading}}) = a + b * \log_{10}(V_t) + c * (N_a + 2)^{-1}$$

Where

$T_{\text{fell-bunch, sep. loading}}$ = time consumption for boom out, felling, bunching and bucking the trees (min/m^3)
V_t = average volume per tree (m^3) in the felling head
N_a = number of trees in the felling head

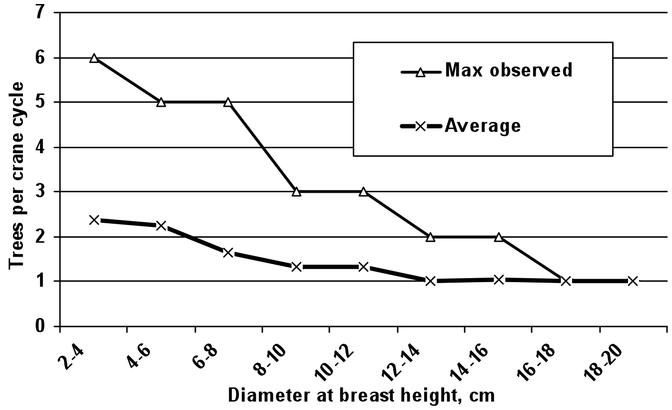

Fig. 2. The figure shows the degree of accumulation at different diameters in breast height.

Table 3. Statistical characteristics of the regression models for time consumption.

Work element	Dependent variable	R^2	F-test F-value p	N	Term	Constant / Coefficient Estimate	Std error	t-test t-value	p
Fell-bunch	LOG ($T_{\text{fell-bunch, sep. loading}}$)	0.7522	658.53	437	a	–0.5542	0.07373	–7.52	***
	***				b	–0.75041	0.02096	–35.81	***
					c	2.09631	0.17534	11.96	***
Fell-load	LOG ($T_{\text{fell-load, dir. loading}}$)	0.7603	310.82	199	a	–0.18265	0.08023	–2.28	0.02
			***		b	–0.77657	0.03134	–24.78	***
					c	0.91798	0.11619	7.9	***

* $p< 0.01$ ** $p<0.001$ ***$p<0.0001$

To be able to compare the two methods, the loading time for trees loaded from ground were added to the felling cycle time for the separate loading method. The average loading time for trees loaded from ground was 6.4 minutes per m^3, and the average crane load in this operation were 0.165 m^3.

The following model describes the time consumption for felling and loading trees when using the separate loading method.

$$T_{\text{fell-load, sep. loading}} = T_{\text{fell-bunch, sep.loading}} + T_{\text{loading}}$$

The following model describes the time consumption for the felling cycle when using the direct loading method, where the coefficients can be found in Table 3.

$$\text{Log}_{10}\,(T_{\text{fell-load, dir. loading}}) = a + b * \log_{10}(V_t) + c * (N_a + 1)^{-1}$$

Where

$T_{\text{fell-load, dir. loading}}$ is time consumption for top-bucking, felling and loading the trees to the timber trailer (min / m^3)

V_t = average solid whole tree volume per tree (m^3) in the felling head

N_a= number of trees collected

The time consumption for felling and loading onto the timber trailer according to the models are shown in Fig. 3. Accumulation of trees gives a higher reduction in time consumption, both in absolute and relative terms, in the direct loading method than in the separate loading method.

The time consumption for moving during harvesting and loading was similar for the two methods; 2.6 min m^{-3} for the direct loading method and 2.8 min m^{-3} for the separate loading method. The average speed for driving full and empty load at the tractor road from the harvesting site to roadside landing was 4.9 km h^{-1}, and the terminal time

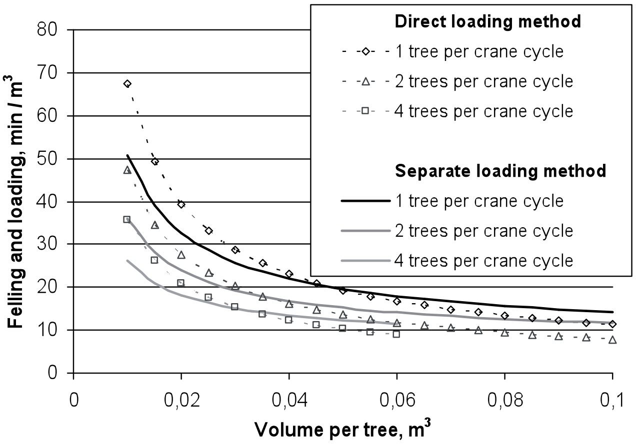

Fig. 3. Time consumption, in minutes per m^3, for felling and loading to timber trailer for increasing tree size and for an increasing number of accumulated trees in each felling cycle, according to the models for time consumption.

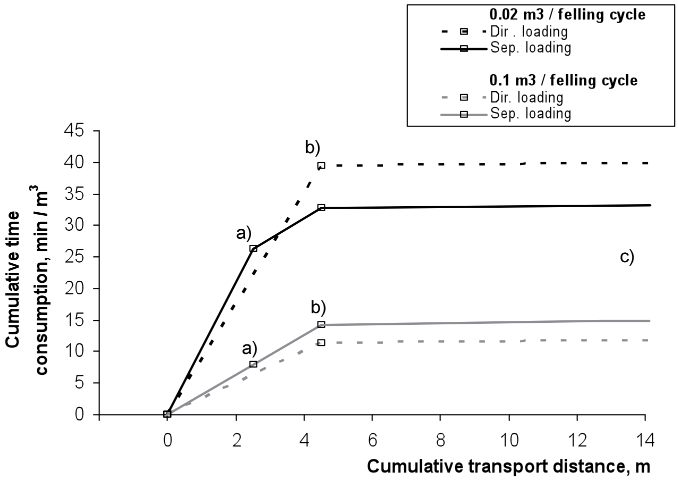

Fig. 4. Time consumption per m^3 for the transport from stump to roadside landing for the two studied methods, with small (0,02 m^3) and large (0,1 m^3) load in the felling cycle. a) is the time consumption for movement from stump to striproad side, b) is the transport time from stump to trailer and c) is the transport time from stump to landing.

for unloading at landing was 2.2 min m^{-3}.

The average straight line distance from the harvested area to the centre of the striproad is one quarter of the working width (Sundberg and Silversides 1988). In this study the working width was 18 m, thus the ideal average straight line boom movement distance from stump to trailer was 4.5 m. The real boom movement distance from stump to trailer was not recorded during the studies, but it is reasonable to assume that it deviates from this, both because the thinning intensity is higher in the striproad than between the striproads, but also because the actual boom movement distance from stump to trailer may deviate for the two working methods. However, to compare the two working methods the straight line distance is used in Fig. 4. For the separate loading method the time consumption for cutting and transporting single trees of 20 dm^3 to the strip road was, according to the time consumption model, 26 minutes per m^3. The additional time consumption for loading tree bunches from strip road side to trailer was 6.4 minutes per m^3. The time consumption for cutting and direct loading single trees of the same size was 39 minutes per m^3, making the separate loading method most efficient. When the tree size was 100 dm^3 the corresponding time consumption for the separate loading method was 14 minutes per m^3, and the time consumption using the direct loading method was 11 minutes per m^3.

4 Discussion

Both work methods were studied in the same stand to provide similar harvesting conditions. The variation in tree size and tree density within the two studied plots was very similar, but the average tree size deviated considerably between the two plots. This could possibly affect the working conditions, and thereby crane speed and the degree of accumulation. Because only two plots were studied, the impact of the actual deviation in stand characteristics on the results could not be revealed. The study material is also too small to make generically valid models for the productivity with the tested equipment.

The study shows that tree size is of vital importance for harvesting productivity, which is in line with other published studies of small tree harvesting (Kärhä et al. 2005, Kärhä 2006, Laitila and Asikainen 2006). The harvested trees smaller than 0.011 m^3 represented 5 % of the harvested volume, 30 % of the harvested number of trees and 16 % of the harvesting time.

The productivity obtained in this study seems to be considerably lower than what is reported from other studies of similar operations (Kärhä 2006, Laitila et al. 2007). These differences might be explained by the fact that purpose-built harvesters are more stable, more articulate, and able to provide better working conditions for the driver. One additional reason might be that the visibility in dense spruce stands is lower than in other types of stands. The machine operator is also an important factor, and one might expect that more practice on the studied machine and working methods would increase the productivity.

Work Method

According to the results (Fig. 3), both the work method, tree size and the number of trees treated in each felling cycle has great influence on the productivity. The separate loading method had the highest productivity when smaller amount of biomass were collected in each felling cycle. This tendency is reasonable and congruent with the findings of the harwarder vs two-machine system comparison by Laitila (2008) (Laitila 2008), since the movement of the trees to the trailer and the unloading of the felling head will be more efficient the more volume that is transported in each loading cycle. Break even in this particular study seems to be in the interval 0.05 to 0.1 m^3 per felling cycle (Fig. 3).

When loading from ground there was an average of 0.16 m^3 biomass in each loading cycle. The time consumption for loading from the ground was 6.4 minutes per m^3 on average, which is considerably higher than what is recently reported in a Finnish study of medium sized forwarders doing the same operation under similar conditions (Laitila et al. 2007). One reason for this difference might be that the farm tractor is less stable and less customised for this operation compared to a forwarder, and also that the felling head was smaller than a forwarder grapple. However, this means that the separate loading method would presumably be the most efficient even with larger accumulated volume in the felling cycle when using a forwarder for forwarding the trees.

The time consumption and thus the costs connected to harvesting and transporting the trees from stump to roadside landing could be assigned to two variables; transport costs and terminal costs (Sundberg and Silversides 1988). The variable transport cost is the cost of moving the material over a certain distance, and is dependent of the hourly operation costs, the transport capacity in terms of load and speed and the transport distance. The terminal cost is the cost of unloading and loading material, changing from one transport mode to another. The terminal is profitable if the total transport cost is reduced.

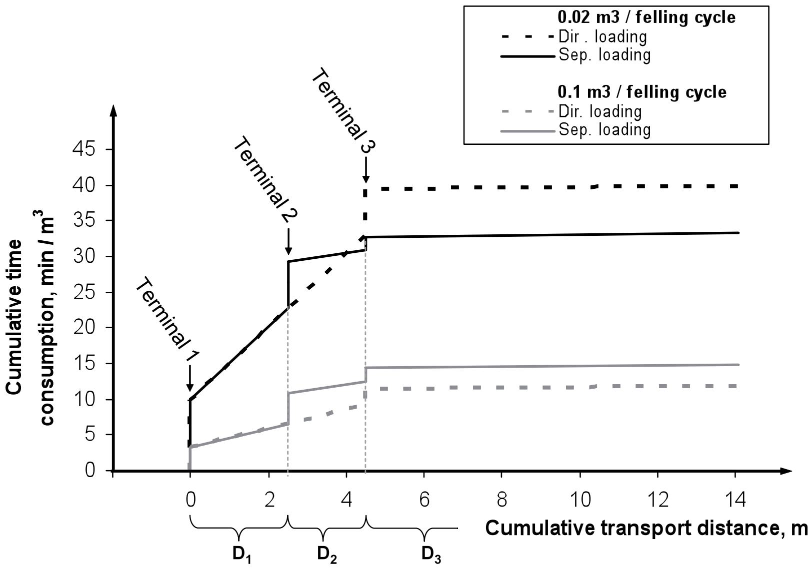

Fig. 5. Cost components for the two studied methods, with small (0.02 m^3) and bigger (0.1 m^3) load / felling cycle. D_1 is the average transport distance from stump to striproad side, D_2 is the transport distance from striproad side to trailer and D_3 is the transport distance from forest to roadside landing.

When the harvesting machine is a combined harvester and forwarder, the piles of trees along the strip road are terminals where the goal is to change transport mode; from a smaller bunch of trees to a larger bunch of trees in the crane movement from stump to trailer. The work connected to create the piles and grab the trees for loading is then terminal time, creating a terminal cost component. To describe the principal difference of the two work methods one could look at the different transport and terminal cost components for the two methods. The hourly operational cost of the machine is assumed to be equal for all work elements; hence the costs of each work element are solely dependent of the time consumption. The cost components and variables affecting them are outlined in Table 4.

The interaction between accumulated volume in the felling cycle and the time consumption of the different work methods is illustrated in Fig. 5. The total time consumption from stump to trailer is in line with the results from the study. Because of the way the time study was set up, the values for the different variables in the cost functions could not be obtained. More detailed studies are needed to confirm and quantify the illustrated interactions more precisely. However, the figure illustrates the principal difference in the two working methods regarding time consumption fairly well. The terminal handling creates a vertical cost in the transport route, and is beneficial if the total transport costs are reduced.

When using the direct loading method most of the trees felled in the thinning zone between the strip roads were loaded directly into the timber trailer, while all trees felled in the strip road were bunched in piles along the strip road. In this study 50 % of the harvested volume was loaded directly into the timber trailer. A combined harvester-forwarder with rotating cab and crane would be able to load directly, also when harvesting the strip-road.

Felling Head and Accumulation

The design of the accumulating arms limited the number of accumulated trees to some extent (Fig. 1). These arms had a reach of 6–7 cm from the back of the aggregate, and kept the trees in

Table 4. The different cost components in the two working methods.

Place or travel distance	Cost component	Description	Cost function, min / m^3	
			Separate loading	Direct loading
Stump	Terminal time 1	Time consumption for grabbing and cutting the trees	$T_{t1} = C_1*V_1^{-1}$	
Stump to roadside	Transport time 1	Time consumption for the boom transport of the trees from stump to roadside	$T_{tr1} = D_1*v_1^{-1}*V_1^{-1}$	
Striproad side	Terminal time 2.1	Time consumption for piling the trees alongside the striproad	$T_{t2.1} = C_{2.1}*V_1^{-1}$	0
Striproad side	Terminal time 2.2	Time consumption for grabbing the tree bunch to be loaded to trailer	$T_{t2.2} =C_{2.2}*V_2^{-1}$	0
Striproad side to trailer	Transport time 2	Time consumption for the boom transport of the tree bunch from striproadside to trailer	$T_{tr2} = D_2*v_2^{-1}*V_2^{-1}$	$T_{tr2\_} = D_2*v_2^{-1}*V_1^{-1}$
Trailer	Terminal time 3.1	Time consumption for unloading the tree bunch in the trailer	$T_{t3} = C_{3.1}*V_2^{-1}$	$T_{t3} = C_{3.1}*V_1^{-1}$
Trailer	Terminal time 3.2	Time consumption for getting the harvester-forwarder into position to harvest the trees and load them into the trailer	$T_{t3.2} = C_{3.2}*V_3^{-1}$	
Trailer transport striproad to landing	Transport time 3	Time consumption for transporting the load from forest to landing	$T_{tr3} = D_3*v_3^{-1}*V_3^{-1}$	

T is the time consumption per m^3, C is the time consumption for a specific terminal work element, V is the volume transported over the specific transport distance or handled within the specific terminal work element, D is the transport distance and v is the average transport speed for the transport distance.

position with constant force on the arms. The low height of the felling head (56 cm) and the relatively small accumulating arms are positive as regards weight and crane manoeuvrability, but will also make a large torque in the accumulating arms if the trees start to spread out.

The limitations of the felling head may not explain why the actual accumulation capacity was utilized to only a limited degree. When working in dense stands the crane manoeuvring gets both heavier and more difficult the more trees that are accumulated in the felling head and the denser the remaining stand is (Johansson and Gullberg 2002). Additionally, the visibility limited in dense stands, especially in spruce stands and in stands with dense undergrowth. These factors also affect the degree of accumulation and the utilization of the accumulation capacity in the felling head.

By using a more schematic area-based thinning pattern, as suggested in several publications (Gullberg et al. 1997, Bergström et al. 2006), for the selection of trees to harvest or set back, both the mental work load and the crane work might be simpler and more trees might be accumulated in each felling cycle.

Improved accumulation capability of the felling head could possibly decrease the time consumption for the movement from stump to roadside (transport time 1 in Table 4) because of the larger load accumulated in the crane. This would also favour the direct loading work method. Improved felling technique towards a technique where trees are felled and accumulated in a non-stop crane movement could possibly reduce the terminal time for felling the trees (terminal time 1 in Table 4 and Fig. 5).

Economics

The entrepreneur charged an hourly fee of 100 € (exclusive VAT, year 2008) for the machine and operator. As the current value of low-quality biomass at roadside is some 9.5 € MWh^{-1}, which equals some 19 € per m^3, the total time consumption from stump to road side should be less than 12 minutes per m^3. In this study, the total effective time consumption for harvesting, loading and forwarding the biomass 300 meters at a tractor road was 27 minutes per m^3, giving a cost of 50 €/m^3 or 25 € MWh^{-1}. The cost of the operation was therefore higher than the income from the fuel.

5 Conclusion

The productivity was too low to be economically feasible. The Achille's heel is the initial felling-collecting and boom movement work element (Figs. 4 and 5), which will need considerable development both regarding technology and work method to provide a feasible production chain for woodfuel from energy thinning. Direct loading seems to be an interesting work method, but is dependent of the accumulated volume of biomass in each felling cycle. The strong relationship between tree size and productivity requires good timing of the energy thinning operation. The economical output will be higher the longer the operations can be postponed without jeopardising the future production of high quality timber.

References

Bergkvist, I., Hallonborg, U. & Nordén, B. 2003. Valmet 801 Combi i gallring och slutavverkning med roterbart lastutrymme för fallane längder. Skogforsk, Uppsala. Arbetsrapport. 526. 20 p. (In Swedish).

Bergström, D., Bergsten, U., Nordfjell, T. & Lundmark, T. 2006. Simulation of geometric thinning systems and their time requirements for yong forests. Silva Fennica 41(1): 137–147.

Braastad, H., Pettersen, J. & Johnsrud, T. 1997. Ungskogpleie. Aktivt Skogbruk. Skogbrukets Kursinstitutt, Oslo, Norway.

Brunberg, B. 1989. Flerträdsteknik – en litteraturstudie. Forskningsstiftelsen Skogsarbeten, Kista. Redogörelse 1. 71 p. (In Swedish).

CEN/TC-335. 2004. CEN/TS 14774-1 Solid biofuels – Methods for determination of moisture content – Oven dry method – Part 1: Total moisture – Reference method. European Committee for Standardization.

Enström, J. 1996. Grundbok för skogsbrukare. Skogsstyrelsen, Jönköping, Sweden.

Finland's national forest programme 2010. 1999. Ministry of agriculture and forestry, Helsinki. Publication 2/1999: 40 p.

Gullberg, T., Johansson, J. & Liss, J.-E. 1997. Pilotstudie av skogsbränsleuttag med flerträdshanterande falldon i klen skog. Sveriges lantbruksuniversitet, Institutionen för skogsteknik. Arbetsdokument 2

Hakkila, P. 2005. Fuel from early thinnings. International Journal of Forest Engineering 16(1): 11–14.

Hamilton, H. 1992. Praktisk skogshandbok. Sveriges Skogsvårdsforbund, Djursholm, Sweden.

Heikkilä, J., Sirén, M. & Ärjälä, J.O. 2007. Management alternatives of energy wood thinning stands. Biomass and Bioenergy 31(5): 255–266.

Heje, K.K. & Nygaard, J. 1995. Norsk skoghåndbok. Landbruksforlaget, Oslo.

Johansson, J. & Gullberg, T. 2002. Multiple tree handling in the selective felling and bunching of small trees in dense stands. International Journal of Forest Engineering 13(2): 25–34.

Johansson, T. 1999. Dry matter amounts and increment in 21- to 91-year-old common alder and grey alder and some practical implications. Canadian Journal of Forest Research 29(11): 1679–1690.

— 2000. Biomass equations for determining functions of common grey alder growing on abandoned farmland ans some practical implications. Biomass and Bioenergy 18(2): 147–159.

Kärhä, K. 2006. Whole-tree harvesting in young stands in Finland. Forestry Studies | Metsanduslikud Uurimused 45: 118–134.

— , Jouhiaho, A., Mutikainen, A. & Mattila, S. 2005. Mechanized energy wood harvesting from early thinnings. International Journal of Forest Engineering 16(1): 15–26.

Kempe, G. 2002. Ungskogar. In: Ståhl, G. (ed.). Skogsdata 2002. SLU, Umeå. p. 5–16. (In Swedish).

Kuusela, K. 1990. The dynamics of boreal coniferous forests. Finnish National Fund for Research and Development, SITRA, Helsinki.

Laitila, J. 2008. Harvesting technology and the cost of fuel chips from early thinnings. Silva Fennica 42(2): 267–283.

— & Asikainen, A. 2006. Energy wood logging from early thinnings by harwarder method. Baltic Forestry 12(1): 94–102.

— , Asikainen, A. & Nuutinen, Y. 2007. Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinnings. International Journal of Forest Engineering 18(2): 29–39.

Marklund, L.G. 1988. Biomassafunktioner för tall, gran och björk i Sverige. Sveriges Lantbruksuniversitet, Institutionen för skogtaxering, Umeå. Rapporter – Skog 45 (45). 75 p. (In Swedish).

Nuutinen, Y., Väätäinen, K., Heinonen, J., Asikainen, A. & Röser, D. 2008. The accuracy of manually recorded time study data for harvester operations shown via simulator screen. Silva Fennica 42(1): 63–72.

Overenskomst, for Naturbruk. 2006. Overenskomst for Naturbruk 2006–2008 mellom Næringslivets Hovedorganisasjon og Skogbrukets Landsforening på den ene side og Landsorganisasjonene i Norge, Fellesforbundet og vedkommende avdelinger av forbundet på den annen side. Fellesforbundet, Oslo, Norway. Overenskomst 370. 96 p. (In Norwegian).

Skogstatistikk. 2007. [URL]. Statistics Norway. Available at: http://www.ssb.no/emner/10/04/20/skog/. [Cited 30.05.2007].

Sundberg, U. & Silversides, C.R. 1988. Operational efficiency in forestry. Forestry Sciences. Kluwer Academic Publishers, Dordrecht.

Zianis, D., Muukkonen, P., Mäkipää, R. & Mencuccini, M. 2005. Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs 4(1): 1–63.

Total of 28 references