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Simulation of Geometric Thinning Systems and Their Time Requirements for Young Forests

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In Fennoscandia, large areas that have not been subjected to pre-commercial thinning (PCT), and thus support dense stands, are becoming suitable for harvesting biomass. However, efficient systems for harvesting biomass from young stands have not yet been developed. In order to optimise biomass harvesting it is here hypothesized that the handling unit should not be a single tree but a corridor area, i.e., all trees in a specific area should be harvested in the same crane movement cycle. Three types of corridor harvesting approaches (using accumulating felling heads for geometric harvesting in two different patterns) were compared in terms of time required to fell a corridor of standardised size. Corridors are defined as strips of harvested areas between conventional strip-roads. Harvests were simulated in two types of stands, first thinning (FT) and delayed PCT stands, in which the spatial positions of the trees had been mapped. The differences in simulated time consumption per corridor were minor when the only variable changed was the corridor pattern. However, there were ca. 2-fold and 3-fold differences in simulated time consumption per corridor between the harvesting approaches for the FT stand and the PCT-stand, respectively. Furthermore, area handling (felling head accumulating all trees corridor-wise, with no restrictions on the accumulated number of trees except for a certain load limit) was found to give up to 2.4-fold increases in productivity compared to a single-tree (reference) approach for the FT stand.

In conclusion, the simulation results clearly show the benefits of applying area-harvesting systems in young, dense stands.

Keywords forest technology, multi-stem, bioenergy
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1 Introduction

The value of raw forest materials is currently based essentially on the suitability of trees for manufacturing sawn wood or pulp and paper. Managing stands for these purposes has been profitable for a long time, and there has been little incentive for investigating other possible commercial uses of the wood. Consequently, in Fennoscandia there is thorough knowledge of the effects of different technological and silvicultural systems on the production of pulpwood and saw timber. It is generally recommended that pre-commercial thinning (PCT) operations should be performed when the height of the main stems is ca. 3 m, and the residual stand should be widely spaced, often with 2000–3000 stems per hectare, to promote large diameter growth and to create stable forest stands (Claesson et al. 1999, Varmola and Salminen 2004). Since the cost of PCT increases with increasing stem density and stand height (cf. Ligné et al. 2005), a high stem density may even be considered indicative of mismanagement; PCT should aim to create relatively open, low-density forests. On the other hand, high stem density in young forests can be a sign of high biomass growth potential. In order to maximise tree biomass production, the stand must have a high leaf area index and a good supply of plant nutrients (Linder 1987, Berg et al. 2005). Over a whole rotation period, biomass production can be increased considerably by maintaining high density in young forest stands (Pettersson 1992). To meet future demands for raw material, it is important to increase biomass growth in the forest (cf. Swedish Forest Agency 2003). In a few decades when oil supplies decline, there will be a change in society's energy sources, and considerable increases in the supply of biomass are likely to be required (cf. NREL 2002).

Costs of harvesting by conventional techniques, where trees are felled and processed individually, are strongly dependent on the size of the trees removed (Fig. 1a and b). If PCT-harvested wood can be used commercially there is a chance that profits, rather than losses can be made from PCT. Indeed, some methods have already been developed for exploiting the biomass cut during conventional PCT. The method most often used is to construct a strip road system for a mobile chipper equipped with a container for the chips (cf. Asplund et al. 1999, Brunberg et al. 1998, Talbot and Suadicani 2005). This system has also been used sometimes when relatively large-dimension trees have been thinned and the price ratio between energy-chips and pulpwood has exceeded a certain threshold (Suadicani and Nordfjell 2003). However, such chipping systems cause many logistic problems, and usually there are high costs when a machine in this chain is standing idle, and only small, low-productivity chippers can be used in the field. Chips are also perishable, and storage results in substance losses and fungal decomposition (Thörnqvist and Jirjis 1990). Therefore, in Sweden and Finland chipping mainly takes place at the roadside or at industrial sites (cf. Asplund et al. 1999).

The machines for harvesting trees in younger stands that have received most interest are Accumulating Felling Heads (AFH) for multi-tree handling, mounted on single-grip harvesters or specially designed feller-bunchers (Johansson and Gullberg 2002, Kärhä et al. 2005). However, the efficiency of the equipment must be increased since the desired high productivity can only be currently attained in stands with very high standing volumes. The productivity in the cited studies varied between 3.0 and 7.2 $m^3 \times E_0 - hour^{-1}$ at densities of 1828–5889 stems/ha and tree heights of 4.9–12.5 m, where productivity is defined as the total volume of whole trees harvested during one hour of effective harvesting. Theoretically, higher productivity could be achieved if all trees in a certain area could be cut in almost the same time as a single tree is currently cut (Fig. 1c). Generally, with a conventional multi-tree handling technique, the head has to be re-positioned to fell every single tree when accumulating a number of trees up to the capacity of the head. In contrast, in geometric area-based felling, the head only has to be positioned once for the same operation. Previous studies on geometric thinning have mainly considered strict line/row-thinning systems. In some systems the base machine is driven in the corridors that it produces (cf. Rummer 1993), in other systems cut trees are pulled to the corridor using cables (cf. Bennecke 1985), or rows of trees parallel to the strip-road (at a distance of, e.g., three rows from the strip-road) are harvested (cf.

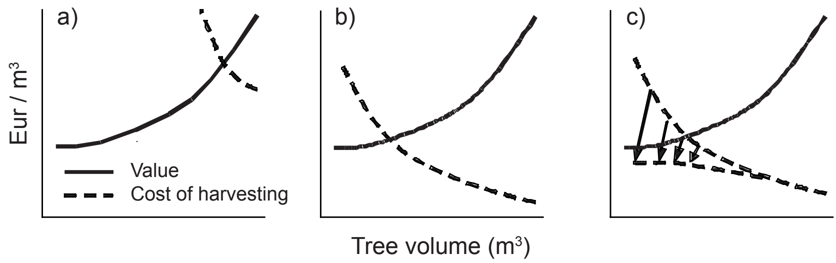

Fig. 1. Schematic diagrams of harvesting costs relative to the value of the individual harvested trees, showing: a) the situation in ca. 1900 when it was only profitable to harvest large trees; b) the current situation, when costs have been reduced, but it is still not profitable to harvest trees with stem volumes < 0.05 m^3 and c) probable changes in costs if techniques for harvesting small trees based on area instead of single trees are applied.

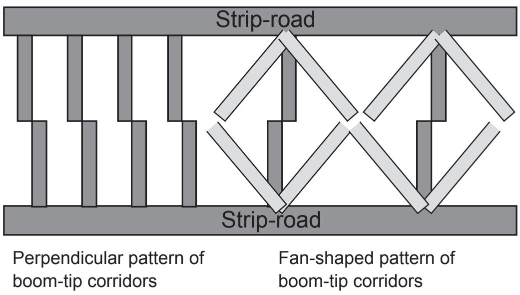

Fig. 2. Schematic description of the two analysed boom-tip corridor harvesting work-patterns.

Suadicani and Nordfjell 2003).

A possibility for the future could be to develop a strip-road and corridor system for thinning, bunching and bundling, instead of PCT, in young stands with high biomass. The narrow corridors between the strip-roads could be created with an area-based felling and accumulating harvester head, mounted at the boom-tip of a machine with a long crane reach. Up to a certain stem volume, harvesting techniques based on area instead of single-tree positioning would probably be more cost efficient. The cost reductions should be large, if techniques are developed to fell, cut-to-length, and bundle within almost the same time regardless of the number of trees in the handled area. Various geometric corridor patterns could be used, for example a strictly perpendicular pattern or a fan-shaped pattern (Fig. 2).

In this paper, the productivity of corridor harvesting approaches in two typical young stands was compared in simulations. Corridors are here defined as strips of harvested areas between conventional strip-roads. The objective of the work was to quantify, using simulations, the potential effects on harvesting time consumption of developing and implementing more area-based machines and techniques than those currently used. The hypothesis addressed is that time consumption per harvested corridor is significantly reduced when using more area-based harvesting techniques than present, especially in delayed PCT stands.

2 Material and Methods

Data on two stands, a young first thinning (FT) stand and a delayed PCT stand from Bredberg (1972) and Gustavsson (1974), respectively, were used in the simulations (Table 1), and two different corridor patterns (perpendicular and fan-shaped, Fig. 2) were included. The positions of the trees were identified using Cartesian coordinates. Three different corridor harvesting approaches were compared, all with a maximum load limit of 350 kg per crane cycle: i) *AFH-5tr*, felling head cutting trees one-by-one and accumulating up to five trees; ii) *AFH-2m²*, felling head cutting and accumulating trees within two square metres, 1×2 m, per movement, with the head set to accumulate up to 20 trees per cycle; and iii) *AFH-corr*, felling head cutting and accumulating all trees corridor-wise, with no restrictions on the

Table 1. Characteristics of the stands used in the simulations. FT is first thinning and PCT is pre-commercial thinning (Bredberg 1972, Gustavsson 1974).

Stand data		Stand type FT	Delayed PCT
Age	(years)	24	17
Annual increment[1)]	($m^3 \times ha^{-1} \times year^{-1}$)	6.0	10.4
Number of trees	($no. \times ha^{-1}$)	3590	8600
Future crop trees	($no. \times ha^{-1}$)	1000	1200
Proportion of tree species[2)]	(%)	50/50/0	0/80/20
DBH[3)]	(cm)	9.3	4.8
Average height	(m)	8.7	6.0
Basal area	($m^2 \times ha^{-1}$)	26.1	22.6
Total stem volume	($m^3 \times ha^{-1}$)	126	90,5
Average stem volume	(m^3)	0.035	0.011
Total biomass volume	($m^3 \times ha^{-1}$)	165.2	152.8
Average tree volume	(m^3)	0.046	0.018
Simulated area	(m×m)	20×43	20×30

[1)] Stem volume incl. bark
[2)] The proportions of pine, spruce and birch
[3)] Arithmetic diameter at breast height

accumulated number of trees, except for the load limit. The *AFH-5tr* felling head is equivalent to the small accumulating felling heads currently available from commercial suppliers (cf. Kärhä et al. 2005). As a reference harvesting approach for the FT stand a conventional selective treatment using the *AFH-5tr* head was simulated, designated *iv*) *AFH-5tr selective*. In *AFH-5tr selective* none of the trees classified as "future crop trees" were harvested, beside those on strip-roads.

The base machine (a standard medium-sized harvester) was the same in all of the approaches (*i–iv*). The machine-width was set to 2.6 m, and the maximum reach of the crane was set to 10 m. The strip-road and corridor widths were set to three metres and one metre, respectively, and the length of each corridor was 10 m from the strip road centre.

The starting-position of the crane and the landing site for the accumulated trees was set to 1.7 m from the crane-pillar where the corridors meet the strip-road. The boom-reach in the driving direction was restricted to 5 m for the perpendicular pattern and 7 m for the fan-shaped pattern. These restrictions were imposed to avoid unnecessary boom movements, which is important in operational harvesting (Eliasson 1999). Regardless of whether or not the felling-head was filled with the maximum number of trees it had to unload the harvested trees before starting to harvest the next area (corridor or strip-road). The strip-road was harvested in the same way as the corridors, except that trees were unloaded into the nearest corridor, perpendicular to the strip-road. After harvesting at one position, the machine was repositioned, and the procedures were repeated. In the *AFH-corr* approach, half of the times when harvesting the strip-road the machine had to be reversed a certain distance to find a corridor in which to place the trees. For the reference concept, *AFH-5tr selective*, harvested trees from the stand between the strip-roads were placed at an angle of ±45° to the perpendicular direction from the strip-road. One simulation per stand and approach was performed.

The time taken for machine repositioning (T_{move}) was calculated as:

$$T_{move} = C_{move} \times N_m + \Sigma S_m / V_m \qquad [s]$$

where S_m is the distance between two machine-positions, V_m is the machine's speed, C_{move} is the time required for the machine to prepare for moving, and N_m the number of machine positions per simulation (Eliasson 1999).

Table 2. Model coefficients used in the simulations. i) *AFH-5tr*, felling head cutting trees one by one and accumulating up to five trees; ii) *AFH-2m²*, felling head cutting and accumulating all trees within an area of two square-meters (1×2 m) in one movement; iii) *AFH-corr*, felling head cutting and accumulating all trees corridor-wise, with no restrictions on the accumulated number of trees; iv) *AFH-5tr selective*, same as *AFH-5tr* but operates/harvests selective (this treatment is a reference treatment for the first thinning stand).

Simulation elements		Harvesting approaches: Corridor treatments *AFH-5tr*	Corridor treatments *AFH-2m²*	Corridor treatments *AFH-corr*	Selective treatment *AFH-5tr selective*
C_{move}	(s)	5.0	5.0	5.0	5.0
V_m	$(m \times s^{-1})$	1.0	1.0	1.0	1.0
$V_{boom\text{-}out}$	$(m \times s^{-1})$	1.2	1.2	1.0	1.2
T_{pos}	(s)	7.0	5.0	7.0	7.0
T_{fell}	(s)	4.0	7.0	–	4.0
$V_{boom\text{-}int}$	$(m \times s^{-1})$	0.5	0.5	–	0.5
$V_{boom\text{-}in}$	$(m \times s^{-1})$	1.0	1.0	1.0	1.0
T_{land}	(s)	5.0	7.0	10.0	5.0
$T_{30°}$	(s)	1.0	1.2	1.5	1.0
T_{angle}	(s)	–	–	–	2.0

The time for boom movement and processing consists of up to eight different elements:

1) $T_{boom\text{-}out}$ is defined as the time required for the felling-head to reach the first tree to be cut:

   $T_{boom\text{-}out} = S_{m\text{-}tree} / V_{boom\text{-}out}$ [s]

   where $S_{m\text{-}tree}$ is the linear distance between the start position of the felling-head and the first tree to be cut and $V_{boom\text{-}out}$ is the velocity of the boom, unloaded.

2) T_{pos} is the positioning time constant before the felling operation. [s]

3) T_{fell} is the felling-time constant. [s]

4) $T_{boom\text{-}int}$ is the time required for a linear movement between two felling operations:

   $T_{boom\text{-}int} = S_{int} / V_{boom\text{-}int}$ [s]

   where S_{int} is the linear distance between two trees, and $V_{boom\text{-}int}$ is the velocity of the loaded boom between two trees.

5) $T_{boom\text{-}in}$ is the time required to move from the last felled tree to the place of landing:

   $T_{boom\text{-}in} = S_{last} / V_{boom\text{-}in}$ [s]

   where S_{last} is the linear distance from the last harvested tree to the place of landing, and $V_{boom\text{-}in}$ is the velocity of the loaded boom from the last harvested tree to the place of landing.

6) T_{land} is the time constant required for the landing operation. [s]

7) $T_{30°}$ is the time constant for turning the boom 30° horizontally. [s]

8) T_{angle} (especially for *AHH-5tr selective*) is the extra time constant for moving the loaded felling head (after the first tree) at an angle (not in a straight line). [s]

The total-time-consumption (T_{tot}) for each harvesting approach was calculated as:

$$T_{tot} = T_{move} + \Sigma(T_{boom\text{-}out} + T_{pos} + T_{fell} + T_{boom\text{-}int} + T_{boom\text{-}in} + T_{land} + T_{30°} + T_{angle}) \quad [s]$$

Harvesting productivity was calculated as:

$$(\text{Harvested volume}) / (T_{tot} / 3600) \quad [m^3 \times E_0\text{–}hour^{-1}]$$

Data presented in time-studies of the EnHar and Naarva-Grip harvester-heads were used (Gullberg et al. 1998, Kärhä, et al. 2005), together with results from a simulation of single-grip harvesters (Eliasson 1999), to set values for the *AFH-5tr* and *AFH-5tr selective* approaches (Table 2). Gullberg et al. (1998) have shown that the time required for re-positioning to cut a new tree is 1.5–2 times longer if there are other trees between the two consecutive positions, and the results were used to set values for T_{angle}, which is the extra time required to manoeuvre between other trees. This extra time was added for every change in the movement direction. The velocities of the boom during the various movements were based on values supplied by Eliasson (1999), adjusted according to the assumptions that its velocity would be: relatively fast when moving away (unloaded) from the machine; relatively slow when moving (loaded) between trees and intermediate when moving (loaded) towards the landing point for the bunch. The time-consumption for landing a bunch (T_{land}) was assumed to be about 60% of the time required for positioning (T_{pos}). The time required to turn the boom horizontally through 30º was assumed to be 1 s.

To set values for the hypothetical *AFH-2m²* and *AFH-corr* approaches, for which no empirical data are available, their properties relative to those of *AFH-5tr* were considered as follows. The *AFH-corr* harvester-head was intended to harvest towards the base-machine, and first had to be positioned at full boom-reach in the stand at slow speed. The landing operation, and horizontal boom-movements, should be slower for the approaches with a high load of accumulated trees (since more weight is being handled), so *AFH-2m²* should be relatively slow and *AFH-corr* slower still. However, the preparative movements before the cutting operation would not need to be as accurate in *AFH-2m²* (since all of the trees in a given area are supposed to be harvested, so there is no need to be careful about damaging remaining trees) and thus T_{pos} should be shorter. The felling-time in *AFH-2m²* was assumed to be 75% longer than the time in *AFH-5tr* since 2 m² areas would be harvested in each operation instead of a single tree.

Available stand data enabled us to simulate harvests in 27 and 30 perpendicular and fan-shaped corridors, respectively, in the FT stand, and 16 and 20 perpendicular and fan-shaped corridors, respectively, in the PCT stand. Data from these initial simulations were then used to calculate and simulate harvests giving adequate harvesting intensities. The spacings of the corridor patterns were thus chosen to give a total harvested target intensity of 35% of the total area, including the strip-road. In the perpendicular pattern the starting points for corridors were marked out every 4.26 m throughout the stand, perpendicular to the strip-road, and the simulated initial starting-point for the harvester was placed 2 m outside the stand. In the fan-shaped pattern the starting-points for corridors were marked out every 12.0 m throughout the stand. Angles between the strip-road and corridors were set to 60, 90 and 120 degrees, and the initial starting-point was placed 5 m outside the stand. The total number of perpendicular and fan-shaped corridors was 18 in the FT stand and 12 in the PCT stand in this case.

The distances required for the simulations were obtained by measuring them on a map showing the Cartesian coordinates of the trees in the stand, after drawing the corridor structures on it. To simplify the manual work involved in the simulations all trees were considered to have the average volume (same size) of the trees in their respective stands. Simulations were then made by hand according to the procedure described above. Statistical calculations were done using SPSS. Data regarding time consumption per corridor were tested for homogeneity of variances (Levene's statistic), and an analysis of variance was performed (Norusis 1996). When significant treatment effects were found, Dunnet's T3 test was used, due to non-homogeneity of variances, to test for significant differences ($p \leq 0.05$) between treatments. Time consumption data were used to calculate productivity at the stand level. Since this was merely a transformation based on time consumption per corridor, only average values are presented here. For one complete simulation (including harvesting of strip-roads) the proportions of time spent on different work elements were calculated. Also, the resulting intensity and harvested volume per machine position for harvesting with the target intensity of 35% were calculated as averages at the stand level.

3 Results

Significant differences in time consumption per corridor between *AFH-corr* and the other two corridor harvesting approaches were found for both thinning patterns in both stands (Table 3). These differences were about twofold in the FT-stand and about threefold in the PCT-stand. However, there

Table 3. Effects of stand type, harvesting approach and thinning pattern on time consumption per corridor and productivity on stand level. For definitions, see Tables 1 and 2.

Stand type	Harvesting approach	Thinning pattern	Number of corridors	Time per corridor [1] (s, SD)	Crane cycles per corridor (no, SD)	Productivity ($m^3 \times E_0$ – $hour^{-1}$), (rel. values in%) Biom. [2]	Stem vol. [3]
FT	*AFH-5tr*	P*	27	69.3(32.8) a	1.2 (0.4)	8.5	6.5 (100)
		F**	30	62.6(23.7) a	1.0 (0.2)	8.0	6.1 (94)
	AFH-2m²	P	27	56.7(15.7) a	1	11.1	8.5 (131)
		F	30	49.2(14.1) a	1	11.6	8.9 (137)
	AFH-corr.	P	27	38.0 (4.3) b	1	12.8	9.8 (151)
		F	30	32.1 (3.7) b	1	14.0	10.7 (165)
	AFH-5tr selective	Sel***		–	–	5.9	4.5 (70)
Delayed PCT	*AFH-5tr*	P	16	127.3(76.2) a,b	1.8 (1.0)	3.7	2.2 (100)
		F	20	103.0(44.9) a	1.8 (0.8)	3.8	2.2 (101)
	AFH-2m²	P	16	64.0 (9.8) b,c	1.1 (0.2)	7.4	4.4 (200)
		F	20	60.8 (9.6) c	1	7.0	4.2 (190)
	AFH-corr.	P	16	40.3 (2.7) d	1	8.8	5.2 (237)
		F	20	41.1 (1.5) d	1	8.7	5.1 (233)

*P = Perpendicular, **F = Fan-wise, ***Sel = Selective, no corridors.
[1] Within stand-type, treatments with different letters are significantly different according to Dunnet's T3 (p≤0.05).
[2] Total biomass volume.
[3] Stem volume incl. bark.

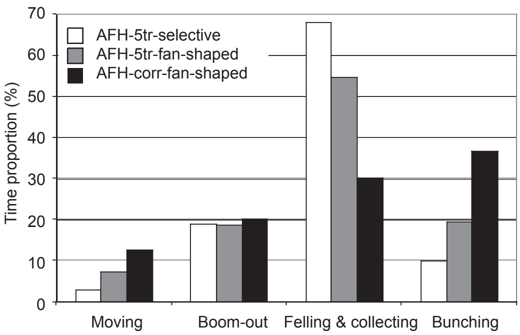

Fig. 3. Proportions of time spent in one complete simulation on each of the work elements involved in harvesting by the contrasting harvesting approaches *AFH-5tr* and *AFH-corr* in the FT-stand. See Tables 1 and 2 for explanations of the abbreviations.

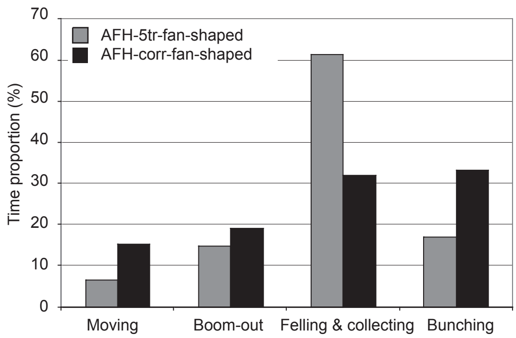

Fig. 4. Proportions of time spent in one complete simulation on each of the work elements involved in harvesting by the approaches *AFH-5tr* and *AFH-corr* in the delayed PCT-stand. See Tables 1 and 2 for explanations of the abbreviations.

were no significant differences between thinning patterns for any of the harvesting approaches. On average 1.03–1.83 crane cycles were needed per corridor in the *AFH-5tr* harvesting approach, while both the *AFH-corr* (by definition) and the *AFH-2m²* approaches could handle all, or almost all, of the trees in every corridor in a single crane cycle. The productivity was 1.5–2.3 times higher in the FT stand than in the PCT stand (Table 3).

In general, for each harvesting approach, the difference in productivity between thinning patterns was small. However, the productivity of the harvesting approaches differed, in the order *AFH-5tr*<*AFH-2m²*<*AFH-corr*, especially for the PCT stand, where there was a 2.4-fold difference between *AFH-5tr* and *AFH-corr*. In the FT-stand, the productivity of the selective treatment (*AFH-5tr selective*) was 30% lower than that of

Table 4. Effects of stand type and thinning pattern on harvest results at the harvest intensity target of 35%. Corridors were made perpendicular or fan-wise to the strip-road (see Figure 2). For definitions, see Tables 1 and 2.

Stand type	Thinning pattern	Number of corridors	Harvested trees per corridor (no, SD)	Harvested volume * from corridors at one machine position (m^3, SD)	Harvested volume * per ha and harvesting intensity ($m^3 \times ha^{-1}$, %)
FT	Corridor, perpendicular	27	3.39 (1.89)	0.31 (0.24)	60.8 (36.8)
	Corridor, fan-wise	30	3.29 (1.47)	0.90 (0.69)	63.4 (38.4)
	Selective				61.5 (37.3)
Delayed PCT	Corridor, perpendicular	16	7.38 (4.94)	0.24 (0.15)	48.4 (31.7)
	Corridor, fan-wise	20	6.95 (3.46)	0.74 (0.44)	53.8 (35.2)

* Total biomass volume

AFH-5tr (Table 3).

The individual work elements for which the proportions of total time required (for one simulation) differed most between the approaches were "felling and collecting" and "bunching" (Fig. 3 and 4). Generally, the proportions of time spent on the various work elements did not differ greatly between perpendicular and fan-shaped patterns for any of the approaches (data not presented).

The harvesting intensity (target 35%) for the FT stand varied from 36.8 to 38.4% due to variations in tree distribution. Corresponding values for the PCT stand were 31.7 and 35.2%, respectively (Table 4). The total harvested volume per machine position (including strip roads and corridors) was 3.0–3.2 times higher for the fan-shaped than for the perpendicular corridor pattern. The reference treatment, *FT-selective*, yielded almost the same volume per machine position as the perpendicular corridor pattern (Table 4).

4 Discussion

The simulation method used here was chosen to obtain indications of the productivity of different harvesting approaches under certain technical and stand conditions, e.g., all trees within a stand were standardized on the basis of their mean size to simplify the simulations and calculations. Consequently, in a real situation, with variations in tree size, the parameters for individual operational moments, movements and cycles would differ somewhat from those obtained in the simulations. However, we believe that the simplification should not affect the average results. In addition, the specifications of the equipment strongly affect the results, and further validation is of course needed. For example, harvesting with a fan-shaped pattern and a harvest-intensity of 35% resulted in relatively long distances between machine-positions and, consequently, the corridors from different machine-positions did not overlap. To enable corridors to overlap without increasing the harvest-intensity, fan-shaped corridors should be narrower, or a v-shaped corridor pattern should be introduced instead (cf. Fig. 5). However, the presented results seem to give adequate approximations to expectations. For example, the productivity of the *AFH-5tr-selective* approach was close to the measured productivity in a study of a similar stand, i.e., in accordance with the regression model based on the tree size/productivity relationship derived by Kärhä et al (2005). This indicates that the coefficients used were well calibrated and that the simulation results are relevant. The number (27) of corridors in the FT stand with a perpendicular pattern is odd because one of the proposed corridors did not contain any trees (Table 4).

The *AFH-corr* approach is clearly more efficient in these simulations than the other approaches in terms of time consumption per corridor (exclud-

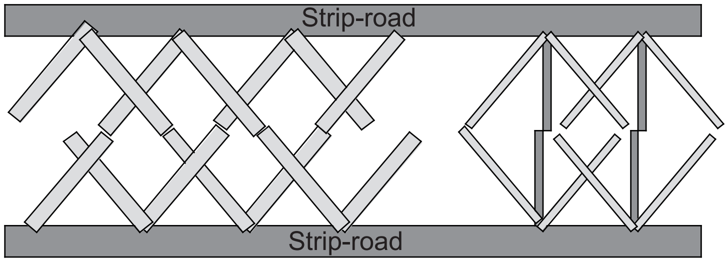

Fig. 5. Suggested boom-tip corridor harvesting work-patterns for further studies.

ing strip roads). Significant differences were also found between time consumption in the simulations of the *AFH-5tr* and *AFH-2m²* harvesting approaches in the PCT stand. These findings indicate that the efficiency of harvesting young, dense forests in which individual trees have low stem volumes could be increased by using area-based methods, even if they only involve changing the work patterns of current harvesting techniques. The time spent on each work element are based on the total time consumed per one complete simulation, and since only one simulation per harvesting approach was performed at the stand level, no information on variations in the elements could be obtained. For future expanded simulations, work element time distributions should be included.

It is apparent that harvesting young, dense stands efficiently requires new harvesting approaches that can cut and accumulate many small-dimension stems at high capacity. Already, large areas of young forests are suitable for harvest, and these stands are costly to treat by current forest management systems (conventional PCT) even if they contain high volumes of biomass (Claesson et al. 2001). In Sweden, young forests, 11–30 years old, account for 22% (5.0 million ha) of the total forestland (Swedish Forest Agency 2006). The key to reducing harvesting costs seems to be to treat one area/corridor at a time as one handling unit, i.e., a bundle, and the potential gain in productivity seems to be very high.

An important aspect of corridor thinning is its effects on the remaining trees in the stand. These effects are related to both the distance from the trees to the nearest corridor or strip-road, and the stand properties. Thus, they could be described as edge-effects in relation to stand properties (age, leaf area, stem density, height, etc.). Generally, growth and property effects are likely to be more strongly related to stem density, leaf area and nutrient conditions than to the corridor pattern and the distances between the trees and corridors (Gerrand and Neilsen 1998, Persson et al. 1995, Petterson 1992, Salminen and Varmola 1993, Varmola and Salminen 2004). In this study, the corridor treatments reduced the number of future crop trees by approximately 35%. However, after treatment approximately 2300 and 5500 trees per ha remained in the FT and PCT stands, respectively, from which 1000–1200 good future crop trees could probably be selected for retention in future thinnings. By applying corridor thinning with an overlapping pattern (Fig. 5), using a felling head that can be turned sideways; it should also be possible to remove single trees or groups of trees over almost the entire area, and thus attain higher selectivity. However, to enable corridors to overlap without increasing the harvest-intensity, fan-shaped corridors should be narrower than the width used in this simulation study, or a v-shaped corridor pattern should be introduced instead.

It is probably necessary to compress and bundle a bunch of small trees into manageable units to maximise productivity in the subsequent transport and processing chain (cf. Nordfjell and Liss 2000). Bundles of trees could be used not only as sources of bio-energy, but also for other end-uses, especially if the bundle properties are known (for instance, proportions of coniferous and deciduous trees, tree properties and wood properties, including fibre characteristics, heating value, cellulose and lignin contents). With such information, processing parameters could be optimised to maximise the fuel value, fibre characteristics, fermentability or other desired characteristics of the material. Depending on the techniques applied, processing could even start during the bunching or/and bundling phase, i.e. when needles and small branches are to some extent separated from the wood (cf. Bohm-Larsson 2004).

5 Conclusions

The simulations showed the benefits of applying area-harvesting systems in young, dense stands. Combining existing accumulating felling techniques with corridor harvesting systems reduced time consumption and increased the productivity by up to 30%, and when these measures were combined with area-harvesting (*AFH-2m²*, *AFH-corr*) time consumption could be further reduced and productivity could be more than doubled. If the harvesting operation is well planned and performed (e.g., in overlapping patterns), the conditions for further growth of the remaining trees could be acceptable even if the trees are thinned in corridors.

A future goal should be to develop a technological system that enables the high amounts of biomass that can be produced in young dense stands to be harvested and utilized, making the first pre-commercial thinning profitable, unlike the procedures routinely applied today. Because of the high stem density in the young stands, this would also provide scope to develop silvicultural systems that allow appropriate crop-trees, with desirable wood properties for many end uses, to be selected as main stems for cutting in later thinnings or the final felling. Producing bundles with known/designed properties would facilitate property-based end-use of bundles.

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