A simulation approach to determine the potential efficiency in multi-tree felling and processing

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Abstract:
The theoretical potential for increased efficiency in early thinning by using accumulating harvester heads was investigated through simulation. Thinning was performed in corridors perpendicular to the strip road in 75 artificially generated stands with varying average tree size and density. The work pattern and work time in the crane work for five sizes of heads, with grapple diameters in the range of 10 to 50 cm, was estimated by the simulation model. The efficiency increased rapidly when the grapple diameter increased from two to four times the average diameter in the harvested stand, reducing the work time per tree by 15 to 50 percent compared to the single tree handling harvester head. Further increases in grapple dimension also increased the efficiency, but not at the same rate. In real work, the efficiency increase by an accumulating harvester head will probably be slightly lower due to less optimal harvesting conditions, operator skills and other non-productive work tasks that are not affected by work method.

Keywords: accumulating harvester heads, early thinning, efficiency, simulation

1 Introduction

Political actions to meet increasing energy demand, diminishing fossil fuel reserves, and the awareness of the probable link between anthropogenic release of fossil carbon and climate changes has made energy-wood a standard assortment from Nordic forestry in recent decades. Several forms of energy-wood are fetched in the forest and delivered directly to heating or CHP plants, where the largest is logging residues followed by small trees from early thinning operations and stumps (Kärhä et al., 2009). Energy wood from early thinning is probably the most economically demanding production system (Kärhä et al., 2009) because of the low efficiency in the initial felling and collection phase. Feasible methods and technology for mechanization of early thinning operations has been sought since the late 1960’s (Bjaanes, 1970), and in the early 1970’s it was demonstrated that multiple tree handling could increase the productivity in early thinning substantially (Bredberg & Moberg, 1971).

A number of empirical studies exist comparing accumulating harvester heads (AHH) with the traditional harvester heads (HH) (Brunberg et al., 1989; Johansson & Gullberg, 2002; Gingras, 2004), and a large number of studies have presented productivity figures for accumulating felling heads and accumulating harvester heads in different machine configurations (Peters, 1991; Kärhä et al., 2005; Kärhä, 2006; Laitila & Asikainen, 2006; Rottensteiner et al., 2008). In a simulation study of accumulating feller-bunchers by Winsauer et al. (1984) the importance of accumulation capacity was demonstrated. However, the technical potential for increased efficiency of accumulating harvester heads has apparently not been illustrated as yet.

Computer simulations have been shown to be a useful tool to analyze forest machine concepts and work techniques (Santesson & Sjunnesson, 1972; Winsauer et al., 1984; Eliasson, 1999; Eliasson & Lageson, 1999; Talbot & Suadicani, 2005; Bergström et al., 2007). A reliable model reduces the need for empirical data to predict the behaviour of a certain system under varying conditions. In addition, sources of noise in empirical studies are avoided (Eliasson, 1999), or can be introduced in a controllable way. The effect of changes in work strategy, machine performance, or even hypothetical machine concepts may be evaluated and compared with existing systems (Winsauer et al., 1984; Bergström et al., 2007).

In this paper, a simulation model for thinning with a single grip harvester equipped with an accumulating harvester head (AHH) or, alternatively, a conventional "single tree" harvester head (HH) is described and discussed. These heads should not be confused with accumulating felling heads, which do not have the capability of delimbing and crosscutting directly after felling. The aim of the study is to evaluate the possible reductions in time consumption per tree when an AHH is used.

2 Material and Methods

Eliasson's (1999) model of a single tree cut-to-length thinning machine was used as the basis for our approach, and was adjusted to cope with accumulating several trees. The simulation model was applied to artificial thinning stands, with randomized spatial distribution and size distribution of trees. Corridor thinning has proven to be more efficient than selective thinning in small dimension stands (Bergström, 2009), and is probably also a thinning strategy that provides optimal operational conditions for accumulating heads. Therefore corridor thinning was assumed in this simulation.

2.1 Modelling the accumulation capacity of an accumulating harvesting head

The accumulation capacity of the accumulating harvester head has to be determined and related to head size and tree size. Harvester heads are designed for delimbing trees, hence the grapple cross area is approximately circular. In the following, the head size is described with the maximum closure grapple diameter DAHH and the corresponding maximum grapple area AAHH. One way to describe the accumulating capacity is to calculate the cross area of the maximum number of trees of a given stump diameter that fit within the maximum closure area of the harvester head. Finding the maximum number of circles or cylinders that fit inside a given boundary is often referred to as a circle packing problem (Weisstein, 2010). Specht (2010) provides an overview of the best known packing of equal circles within a boundary circle. The radius (r) intervals for which one to four equal circles fit within a unit circle is listed in table 1 together with the corresponding packing density (ρ).

Table 1: Maximum accumulation for a given tree diameter

N circles	rinterval1)	ρinterval2)
1	0.500 – 1.00	0.25 – 1.00
2	0.464 – 0.500	0.43 – 0.50
3	0.414 – 0.464	0.51 – 0.65
4	0.370 – 0.414	0.54 – 0.68
etc	According to best packing solution	0.56 – 0.90

1 denotes the radius interval for which N is the maximum number of circles that fit within a unit circle

2 packing density, as a share of max area of a boundary unit circle

This way of restricting the potential of accumulating depends on equally sized trees and perfect packing. The assumption of perfect packing might be reasonable up to three trees, but for further accumulation the packing structure becomes more random, hence lowering the effective potential of accumulation.

One other approach for restricting the potential of accumulation is to define a maximum packing density threshold of the harvester head. Looking to table 1, a limit of 0.65 could serve as a maximum for tree dimensions less than 0.5 times the maximum diameter of the accumulating harvester head (DAHH). Applying this limit for larger dimensions (> 0.5 DAHH) would result in accumulating trees where the sum of diameter of two trees could exceed the maximum grapple diameter (DAHH) in question, so two restrictions are needed; the sum of diameters of two trees cannot exceed DAHH, and the packing density can not exceed 0.65.

The two approaches are compared in Figure 1 for DAHH = 30 cm. For this head size, the maximum closure grapple area (AAHH) is 707cm2. The area threshold based approach will not allow accumulation beyond the best packing solutions for equally sized circles within a circle. For stump diameters larger than 0.417 times DAHH (here 30 cm) the two approaches will limit the accumulation equally, while for smaller tree sizes the area based approach will be restricted to equal or lower accumulation (Figure 1)

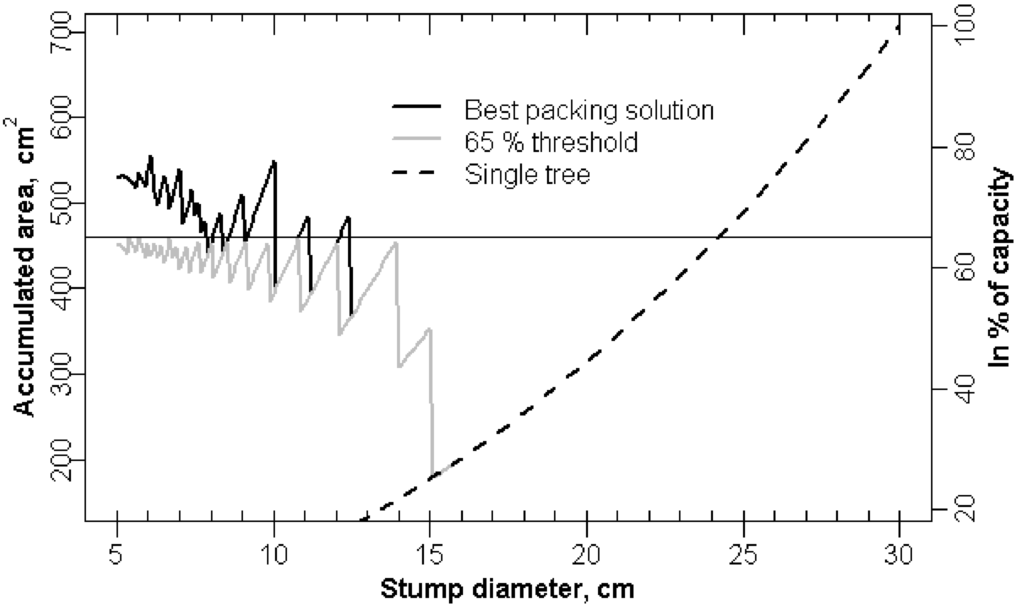

Figure 1: Max accumulated area for equally sized trees for two possible ways of restricting the capacity; one by the best packing solution for equal circles, the second by limiting 1) the accumulation to 65 percent of the grapple area and 2) the average diameter to maximum 0.5 times the grapple diameter (DAHH) which in this case was set to 30 cm.

The area threshold based approach also allows for uneven tree sizes to be handled, corresponding better to the situation in real stands. The capacity utilization regarding load when using the area based approach and accumulating trees of uneven dbh is illustrated in Figure 2. Here, Marklunds (1988) biomass function for stemwood of pine is used to estimate stem mass assuming the dbh to be 0.85dstump and the moisture content to be 50 percent. The AHH head size DAHH = 30 cm diameter.

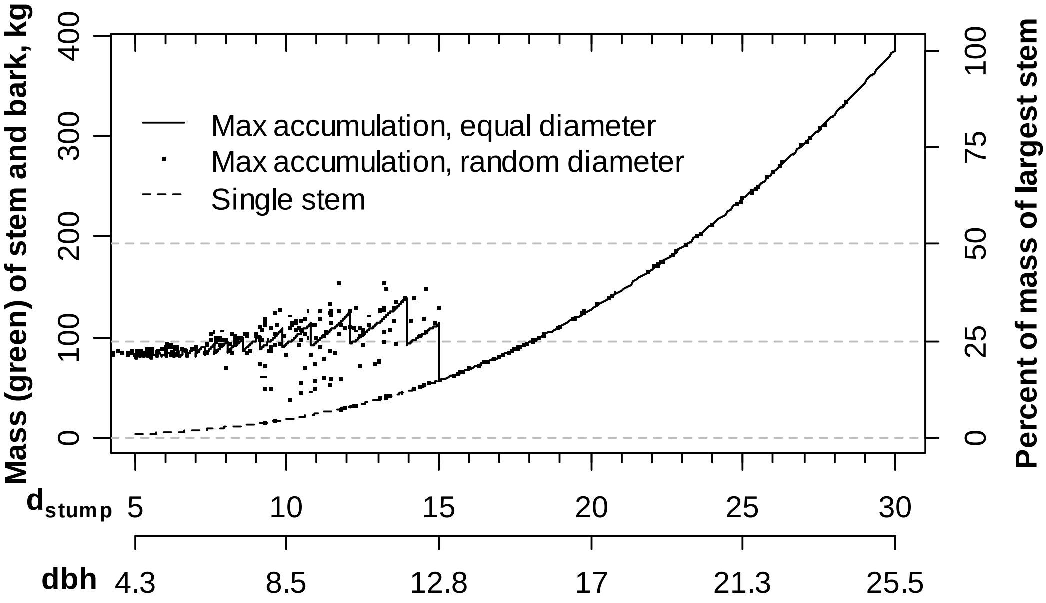

Figure 2: Accumulation capacity of pine stemwood as percent of maximum head capacity. The points of randomized stem sizes denote the average diameter (cm) of the accumulated trees and the total accumulated stem mass (kg).

To randomize tree sizes, trees were taken from a uniform diameter distribution where the breast height diameter (dbh) varied with 50 percent of predefined mean values in the range 5 to 30 cm. The mass of a tree increases exponentially with diameter, and this explains why the mass of a number of trees of unequal diameter sometimes exceed the mass of the same number of trees with equal diameter when the average diameter is the same in both cases. The points where the accumulated mass is lower than the theoretical capacity of equal diameter trees occur when the next tree of randomized dbh is too large to fit in the grapple. According to Figure 2, the capacity utilization regarding load in the AHH will seldom exceed 40 percent of the maximum rated tree when accumulating several trees.

2.2 Thinning stands

Artificial stands were generated for the simulations. In a dense young stand with an average breast height of 10 cm, the basal area (BA) may be in the range 25-35 m2 ha-1. To emulate real stands, trees were randomly distributed on an area of 0.1 hectare, where the stand width was defined as twice the crane reach of the harvester plus the average distance between trees, derived from the target basal area and the intended average dbh. Tree size (in terms of dbh) distributions may be approximated by a Gamma, Exponential, Lognormal or Weibull distribution, where the Weibull have been the most promising (Schreuder & Swank, 1974). For convenience, the two parameter gamma distribution was used in this case. This is a left skewed light tailed distribution where the mean (μ) is the product of the scale (θ) and shape (k) parameter, and the scale basically determines the variance.

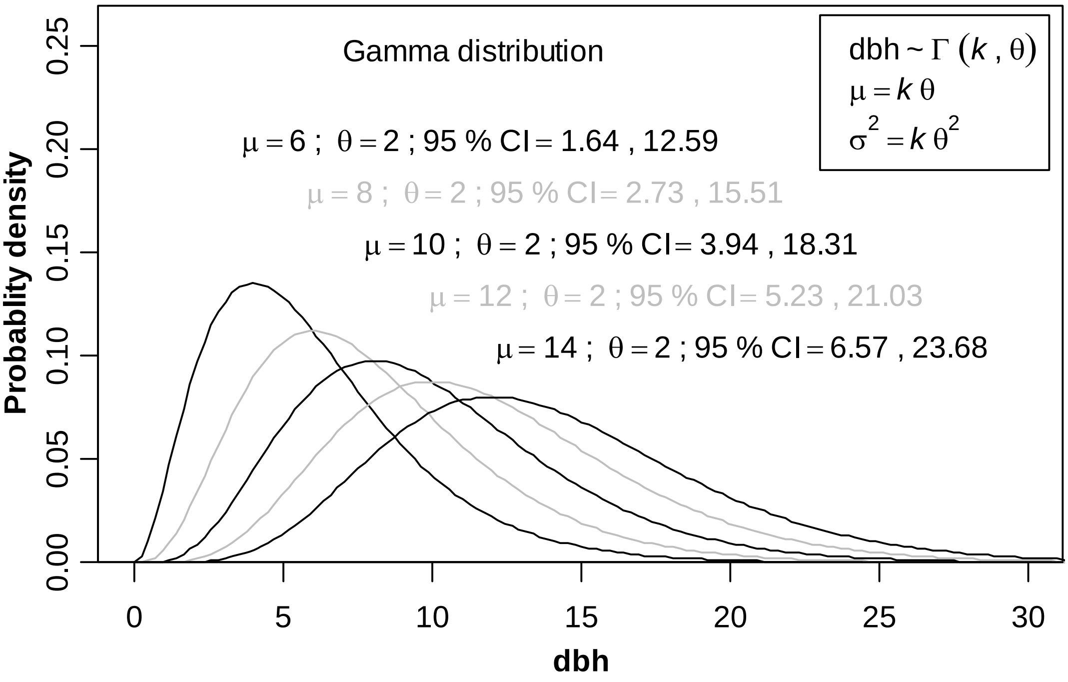

Figure 3: Distributions used for generating tree sizes. The shape (k) is given by the fraction of mean (μ) and scale (θ).

Trees were added to the stand until the target BA was reached, each tree added was given a random diameter from the gamma distribution and random x and y position. Tree height was estimated by the equation h = 3.71 + 3.91*log(dbh) (derived from own sample plots in a previous study), and the volume of stemwood under bark was estimated using Brandels volume equation for Scots pine (Volume eq. 174

in Zianis et al., 2005). 75 stands of 0.1 hectare were generated using five levels of average dbh (6, 8, 10, 12 and 14 cm), three levels of initial basal area (25, 30, and 35 m2 ha-1) and five replicates of each dbh and basal area combination. Trees were tagged for felling in the following manner: The thinning target was to cut 40 percent of the basal area in the stand. All trees in a four meter wide strip road zone were tagged for felling, and the basal area of these trees was summed. Then the distance between felling corridors perpendicular to the strip road was set to four times the average distance between the trees in the stand, and the basal area to fell in each corridor (left plus right side) was estimated by the remaining basal area to cut and the number of corridors within the stand. In each corridor, trees within the reach of the boom were tagged at increasing distance from the corridor centre line (cf. the horizontal dashed lines in Figure 4) until the target basal area was reached.

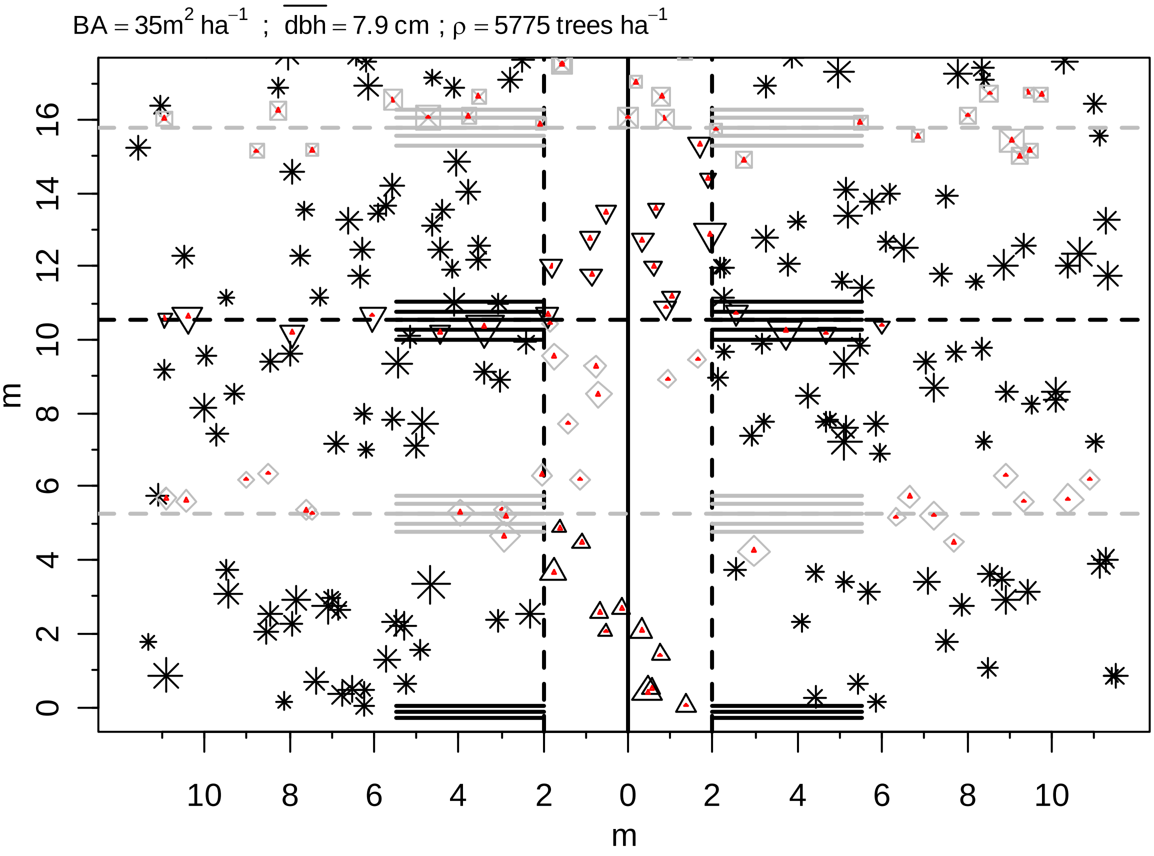

Figure 4: An example of the stands generated. Point size indicates tree size, polygons are felled trees, and the horizontal bars indicate tree piles along the strip road.

2.3 Model structure

The boom tip and felling device has to move to each tree to cut, and when the head is full the tree bunch is moved to a processing place. The crane base is located on the machine at the centre of the strip road (figure 4). Trees may be processed at both ends of the piles, and the processing position nearest to the cut tree is always used. The very first crane movement starts from the “zero position”, in front of the base machine between the right and left corridors (Figure 4). The corridors (right side, strip road and left side) are cut counter clockwise, while the cut order within the corridor is determined by the distance from the crane base to the trees, starting with the tree closest to the crane base position. The straight line distance from each tree to all possible pile positions is determined by the coordinates of the tree and the piles, and each tree is allocated to the nearest pile position. Then, the distance from the processing location for tree 1 to the location of tree 2 is calculated from their respective coordinates, and this is repeated for all felled trees. Boom movement, felling and processing time is then estimated for each crane cycle. In the simulation, the accumulating harvester head's maximum grapple diameter (DAHH) was set to 0, 10, 20, 30, 40 and 50 cm. The head diameter limits the capability of accumulating trees, not the capability of felling one tree. Hence, the DAHH = 0 cm head emulated a single tree harvesting head. 10 and 20 cm represent heads with small accumulation capacity compared to head diameters of 30-50 cm, which is a typical size class for existing heads. Trees are felled consecutively until the next tree to fell would make the accumulated area surpass the accumulation capacity, or all trees to cut in the respective corridor are cut. When trees are accumulated, the boom movement distances are estimated by the straight line distance between the accumulated trees. The accumulated trees are then processed at the pile position closest to the last felled tree. Each stand was cut once with each head size (DAHH = 0, 10, 20, 30, 40 and 50 cm diameter). The algorithm to limit the accumulation is described in table 2.

Table 2: Algorithm to limit the accumulation in the AHH where all trees in a given corridor are of known size (stump diameter), and the order of felling is predefined.

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for all trees to cut in a given corridor
    if ((D_stumpi + D_stumpi+1) < D_AHH) & ( (Area in head + A_stump i+1) < A_AHH ) then
        Move to tree i+1
        Accumulate tree_i+1
        Area in head = Area in head + Astump_i+1
    else
        move the distance tree_i to nearest pile for processing
    end if
    Move from pile to next tree
end for
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2.4 Time consumption models

The time consumption models are adapted from those presented by Eliasson (1999), and will be described briefly in this session. The machine movement time (tmove) between machine positions is calculated as:

$$t_{move} = C_{move} + \frac{S_m}{v_m} \tag{1}$$

where Cmove is a constant counting for start-up and stop time, Sm is the movement distance and vm is the machine speed.

The boom movement time (tboom) in one felling cycle is determined by the function;

$$t_{boom} = C_{boom} + \max\left(\left(C_s + \frac{s_b}{v_b}\right), \left(C_\alpha \frac{\alpha_b}{\omega_b}\right)\right) \tag{2}$$

where Cboom is a constant for start-up and stop time for each cycle, Cs and Cα are constants for linear and angular movements of the boom tip, sb and αb are linear and angular distances, and vb and ωb are the corresponding linear and angular boom-tip velocities.

The processing time for a tree consist of the elements felling time (tfell), delimbing time (tlimb) and crosscutting time (tcc). The time consumption is dependent of the stump area, the length of the tree, the number of crosscuts and crosscut area, and the mass of the stem. Felling time (tfell) is the time for fixing the tree in the head and sawing through the tree, estimated by the constant Cfell, the stump cross area astump and the cutting pace vcut (eq 3).

$$t_{fell} = C_{fell} + \frac{a_{stump}}{v_{cut}} \tag{3}$$

The delimbing time (tlimb) is dependent on the commercial length of the tree (lc), delimbing speed (vlimb), the number of cross cuts (N) and the volume of the tree (Voltree), and estimated by the equation:

$$t_{limb} = C_{limb} + \frac{l_c}{v_{limb}} + N \times t_{ar} \times \frac{Vol_{tree}}{Vol_r} \tag{4}$$

where Climb is a constant counting for the start-up time before delimbing, tar is the acceleration and retardation time for each crosscut for a reference tree of known tree size (Volr).

Table 3: Machine specifications and other model specifications used in the simulations

Parameter	Value
Cmove	5 s
Cboom	1.5 s
Cα	0.1 s
Cs	0.1 s
Cfell	1 s
Climb	2 s
Ccc	1 s
Cll	4.2 m
vm	1.0 m s-1
vboom	2.5 m s-1
vω	20° s-1
vlimb	1.5 m s-1
vcut	800 cm2 s-1
tar	0.8 s
volr	180 dm3
Boom reach	11 m
Top length	1.5 m

The number of cross cuts is the integer part of the commercial length of the tree lc divided by the average log length Cll:

$$N = \left\lfloor \frac{l_c}{C_{ll}} \right\rfloor \tag{5}$$

The crosscutting time is estimated by the equation

$$t_{cc} = N \times C_{cc} + \frac{\sum_{i=1}^{N} cca_i}{v_{cut}} \tag{6}$$

where N is the number of logs, Ccc is a constant counting for the start up time for each cross cut, ccai is the cross cut area at the point where the tree is crosscut, and vcut is the cutting pace, similar as in eq. 3.

The cross cut area at a given log length was estimated by assuming the stem form to follow the taper curve in Figure 5.

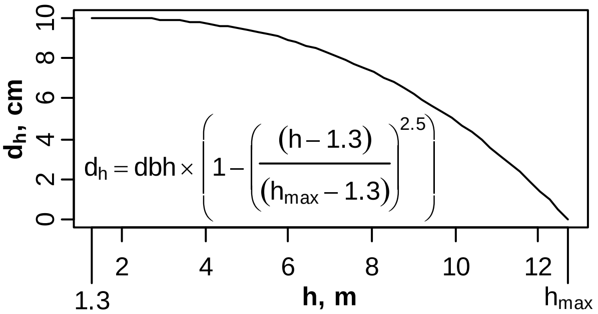

Figure 5: Taper curve used in the simulation to estimate cross cut area at a given tree height.

Accumulation of several trees affected the way to estimate time. To estimate delimbing and crosscutting time, the length of the tallest accumulated tree, the total volume of all accumulated trees, and total crosscut area for all accumulated trees were used in equation 4, 5 and 6.

3 Results

For stands with a mean dbh of 6 cm harvested with an AHH of 30 cm diameter, an average of six trees was accumulated in each crane cycle. Compared to a head without accumulation, the boom tip movement distance per hectare was reduced from 6700 m to 1700 m on average (Figure 6), i.e. 75 percent reduction. At 10 cm dbh the boom tip movement was reduced from 3200 m to 1600 m. When the dbh was 14 cm, the average accumulation fell to 1.3 trees per crane cycle and the reduction in boom tip movement was 21 percent.

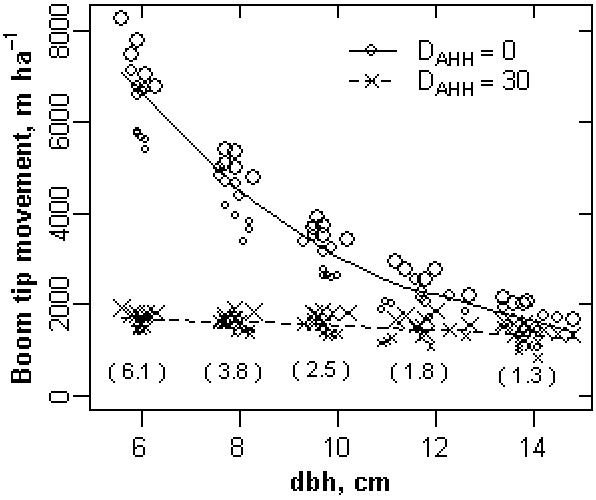

Figure 6: Total boom tip movement distance per hectare using a single tree harvester head (DAHH=0) and an AHH rated 30 cm grapple diameter (DAHH=30). Numbers in parentheses are the average number of accumulated trees for the AHH. The size of the points indicates the three levels of initial basal area of the stands, in the range 25 to 35 m2 ha-1.

The total time consumption was considerably reduced (40-60 percent) for trees smaller than 10 cm dbh (Figure 7). The largest reduction in time consumption was made in the delimbing and crosscutting time, which was reduced by a factor approaching 1: N accumulated trees. Boom movement time (tboom) was reduced, but not as much as the boom tip movement distance. This was because of the lower average speed over shorter movement distances.

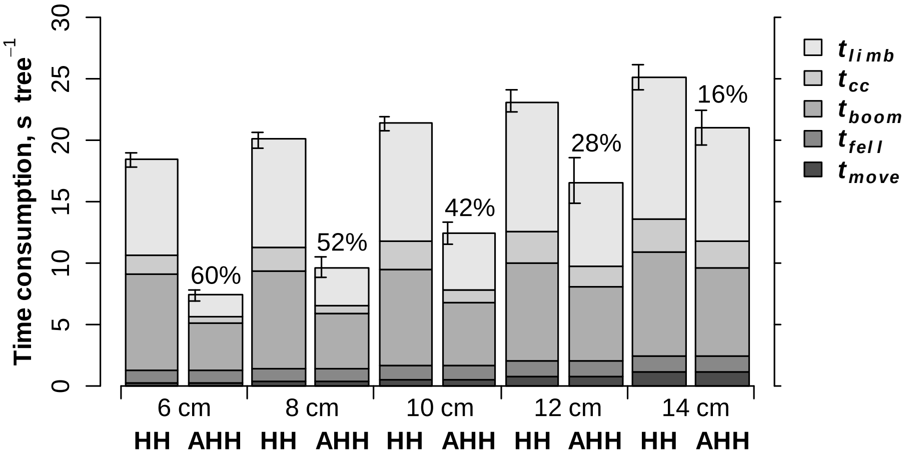

Figure 7: Mean time consumption in the boom-processing cycle for the single tree HH and the 30 cm AHH head for increasing dbh (6 – 14 cm). The numbers above the AHH bars indicate the reduction in time consumption of the AHH compared to the HH at similar mean tree size. Also the 95 percent quartiles of mean total time consumption are indicated.

A function of appropriate form relating total (E0) time consumption (s tree-1) to stand average tree size (dbh) and basal area (BA) was developed for the DAHH = 30 head through non-linear least squares (NLS) regression (eq. 7).

$$t_{E_0}\,(\text{s tree}^{-1}) = 5.59 + 0.122 \times dbh^{1.882} - 0.0597 \times BA \qquad (7)$$

The effect of increasing accumulation capacity of the AHH is illustrated in figures 8 and 9, where each point denotes the average time consumption for all stands with similar average tree size and head size.

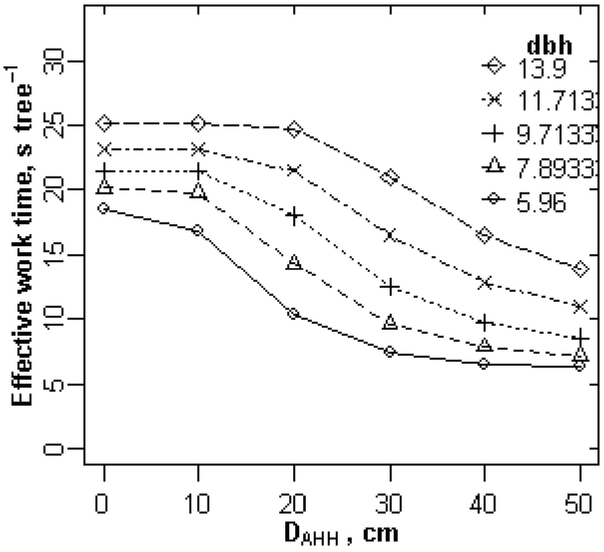

Figure 8: The points in the figure represent the average time consumption per tree for all stands of a given predefined mean diameter and accumulation capacity. (DAHH = 0 emulates no accumulation capacity, all trees are felled in individual work cycles)

For the smallest trees, the time was considerably reduced when the accumulation potential of the head increased from 10 cm to 20 cm, and levelled out at 6-7 seconds per tree, a time-saving of 60-65 percent for heads larger than 30 cm. For the stands with largest tree sizes, i.e. with an average stump diameter of 15.6 cm, time consumption was reduced by 21 percent when a head with 30 cm accumulation capacity was used compared to a non-accumulating head. For this tree size, the time consumption seems to level out at some 14 seconds per tree when the head size is 50 cm or more in diameter. The time saving in this situation was 39 percent.

The relative time consumption was compared to the ratio between maximum rated tree diameter for the AHH's and the average stump diameter in the stands, using the null diameter head (single tree harvesting) as the reference level (Figure 9).

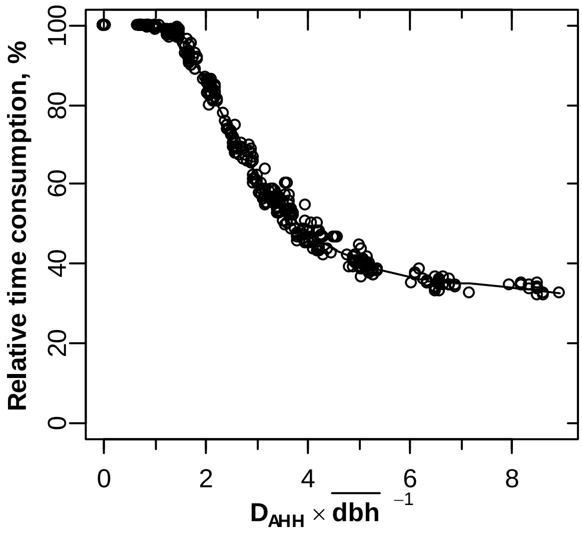

Figure 9: The figure illustrates the reduced time consumption (using single tree harvesting as the reference level) versus the ratio between the maximum rated tree diameter for the AHH (DAHH) and the average breast height diameter of each stand (dbh, cm).

4 Discussion

4.1 The model

The modelling approach was similar to that described by Eliasson (1999), with a few modifications. In Eliasson's model, the trees were assumed to be processed at stump, and no time was calculated for boom movement from the stump to a processing position. In the present study, it was assumed that all trees felled in one machine position were processed to two piles (either left or right side of the strip road), and that all crane cycles terminated at the pile end closest to the recently felled tree. This will increase the crane movement time compared to Eliassons model. Another difference is that the corridor length in the strip road direction was determined by the average distance between trees. This made the distance between machine positions vary between 3.8 and 9.0 m, dependent on the BA and average tree size. A third difference from Eliassons approach was that in the present simulation the cross cut area (equation 6, figure 5) was estimated by a taper curve, while Eliasson estimated the cross cut area from an assumption of the stem form being a truncated cone.

The boom movement time was assumed to depend only on boom tip movement distance. The boom speed is probably also dependent of the load in the boom tip, and a reasonable estimate on how the load affects the boom speed would improve the simulation model. This would probably lower the difference in efficiency between a HH and an AHH to some extent. However, as the load in the boom tip (when accumulating) will hardly exceed 40 percent of the maximum rated tree for the machine (Figure 2), the difference is likely to be relatively small.

Delimbing time was calculated the same way and by using the same parameters as in Eliasson, who argued for the use of delimbing time functions based on measured feeding times rather than from the manufacturers' specifications on their harvesting heads. As can be seen in Figure 7, the time for delimbing and crosscutting counts for some 60-70 percent of the crane work time in single tree handling, and this part of the work made the largest gain in time consumption when accumulating several trees. If the parameters in the time consumption model for delimbing and crosscutting are wrong, this will have a substantial impact on the estimated time consumption both with and without accumulation, and make the comparison of the two work methods erroneous. In the same manner as for the boom movement time, no interaction was included between delimbing time and accumulation besides the increased cross cut area and tree volume (in equation 4 and 6). Delimbing several trees at a time may cause random disturbances of feeding through the head, and including a reliable estimate on this effect would improve the model.

4.2 The results

The study showed that accumulation substantially reduced time consumption for crane work, and that choosing a sufficiently large head is crucial for the efficiency. Winsauer et al. (1984) made a similar conclusion in a simulation study of (among other things) the effect of feller-buncher head size in corridor thinning of plantations. The present study indicated that the AHH should have a grapple diameter at least four times the average breast height diameter in the thinning stand to utilize the potential of the AHH technology. Increasing the head size will increase the demand on crane strength and base machine stability, hence increasing the cost of the base machine. Finding the break even for increased efficiency versus increased machine costs is an important task for future research.

Both tree size (dbh) and basal area (BA) were significant to time consumption per tree (equation 7); time consumption was positively correlated to dbh and negatively correlated to BA. However, when applying relevant values to the independent variables, e.g. dbh = 8 and 12 cm and BA = 25 and 30 m2 2 h-1, and when looking to the 95 percent quantiles in figure 7, one can see that compared to tree size the basal area exert only modest effect to the time consumption per tree. This is reasonable for single tree handling, as the average transport distance from an area to a point does not depend on the density within the area (Sundberg & Silversides, 1988). This observation was more surprising for the accumulation approach, as a larger degree of accumulation could be expected in stands of larger density. The average number of trees felled at each machine position increased by some 10-15 percent when the initial basal area increased from 25 to 35 m2 ha-1. The low correlation between density of removal and cut trees per machine position was probably due to the way the distance between felling corridors was determined, which narrowed the corridor widths and the distance between machine positions (figure 4) for increasing tree density.

The simulation presupposed corridor thinning of the stands. This is unusual in northern European forestry, and an obvious extension of the model would be to incorporate and compare selective thinning, corridor thinning and perhaps some intermediate approaches. This would allow for different thinning strategies to be evaluated, as demonstrated by Eliasson & Lageson (1999).

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