SIMULATION OF BOOM-CORRIDOR THINNING USING A DOUBLE-CRANE SYSTEM AND DIFFERENT LEVELS OF AUTOMATION

ABSTRACT

This study evaluates the productivity of a harvester equipped with a double crane system for thinning with continuous felling and accumulation of whole small-diameter trees for bioenergy at different levels of automation. The simulations were performed using a discrete event simulation tool that has been developed recently and is specifically designed for simulations in forestry, incorporating spatial awareness of the simulated world.

The study shows that introducing boom-corridor thinning with a semi-automatic double-crane system can significantly increase the productivity compared to conventional thinning and harvesting. For the specific harvester model used in this study, the modification that yielded the biggest productivity increase was automating the release and placement of the harvested trees. Studies on the effects of implementing automation for other forest machine operations could be analyzed using a similar approach.

Keywords: automation, early thinning, discrete event simulation, productivity, forest operations

INTRODUCTION

In the Fennoscandian countries, young stands are often harvested for energy purposes. In Sweden, the annual harvesting potential from such stands amounts to about 20 TWh, if the tree biomass above ground and stands up to a height of 15 m are included (Nordfjell et al. 2008). The thinning is normally performed from below using a strip-road harvester-forwarder system, where harvesters are equipped with conventional harvesting heads that have been modified to handle several trees in each crane cycle.

Trees between strip-roads are cut by single tree selection and then put in piles by the side of the strip-road. Depending on the technology used, the trees can be bunched as whole trees, logs of different length or roughly delimbed tree parts before being hauled by the forwarder to the roadside. Alternatively, the forwarder can be equipped with a grapple-saw for bucking and loading. The development of heads with multi-tree handling capacity, where trees are cut one-by-one until the cumulative capacity of the head (MTH-one-by-one) is reached, makes it possible to increase the productivity by 40% compared to single-tree handling (Belbo 2011, Sängstuvall et al. 2012). Today, such harvesting systems become profitable when the harvested mean tree breast height diameter (dbh) exceeds 8 - 9cm (Di Fulvio et al. 2011).

A significant part of the biomass potential is, however, found in stands with a smaller average dbh and therefore only a small part of the harvesting potential is currently exploited (cf. Nordfjell et al. 2008). Development of cost-efficient harvesting technology and methods are therefore being encouraged in order to meet some of the increasing demands for bioenergy.

By harvesting the trees with linear crane movements, for example in boom-corridors, the productivity of the MTH-one-by-one handling head can be increased by between 16% and 44% compared to harvesting by selection between strip-roads (Bergström et al. 2007, Bergström et al. 2010, Sängstuvall et al. 2012). Further increases in productivity are limited by the fact that the harvesting head still needs to be positioned and standing still at each tree position prior to cutting and mostly cuts one tree at a time. Using technology able to harvest all the trees with, say, a 1m wide and 2m long swath in a single moment (termed MTH-2m^2) (i.e. area-based harvesting), the productivity can be increased by between 30% and 100% compared to selection harvesting between strip-roads using MTH-one-by-one (Bergström et al. 2007, Sängstuvall et al. 2012). The next step would then be to harvest a full corridor, for example 1 m wide and 10 m long, in one single crane movement (termed MTH-corridor). Such technology would increase the productivity by about 200% compared to harvesting with MTH-one-by-one with thinning by selection between strip-roads (Bergström et al. 2007, Sängstuvall et al. 2012). Harvester heads that are able to fell and accumulate all the trees in a boom-corridor are currently being developed. However, it is important to analyze the potential of harvesting and thinning young dense stands using new machine configurations (concepts) that significantly improve productivity (Forsberg & Wennberg 2011, Nordfjell et al. 2011, Bergström et al. 2012).

A further increase in productivity would come from equipping a harvester with two cranes, for felling and accumulating trees in boom-corridors simultaneously on each side of the strip-road (Bergström 2009). Such technology would require the machine operator to handle two cranes at the same time. In practice it would most likely be too difficult if every individual operation of each crane needed to be fully controlled by the operator. However, technology for semi-autonomous shared control of cranes has been demonstrated (Hansson & Servin 2010) and this enables a human operator to control several independent work tasks simultaneously. The productivity of such a machine would be affected by factors such as the type of head used (e.g. MTH-one-by-one, MTH-2m^2 or MTH-corridor), the felling and accumulation speed and the capacity of the crane heads. Furthermore, the degree of implementation of shared controls/automation, i.e., to what extent an entire crane work cycle is controlled by the operator, would also be an important factor. For example, the selection of corridor position (trees to be harvested) and steering of the crane during felling and accumulation could be performed by the operator while the bunching and re-positioning of the crane to the next corridor to be harvested is computer-controlled and thus done automatically. The computer controls the operation until all the trees in one corridor are harvested and bunched at the side of the strip-road. Depending on whether the operator or the computer is in control, the time requirements for the work tasks may also differ, since operations have varying levels of complexity. The times of the tasks when using two cranes, including the crane waiting time due to the operator being occupied with the other crane, is best analyzed using discrete event simulations (cf. Cassandras & Lafortune 1999). There are several studies where harvester work has been simulated and where models and data on harvesters performing different work tasks have been described (Eliasson 1999, Eliasson & Lagesson 1999, Wang et al. 2005, Bergström et al. 2007, Belbo 2011, Sängstuvall et al. 2012). Thus, it is possible to analyze the effects of using a double-crane system using simulations.

The objective of this study was to analyze the effects on harvester productivity when using a double-crane system, with continuous felling and accumulation of trees, at different levels of shared control in comparison to a one-crane system with a boom-corridor thinning head or a conventional head.

MATERIALS AND METHODS

The simulations were performed using a discrete event simulation tool that has been developed recently, specifically designed for simulations of forestry models and incorporating spatial awareness of the simulation entities (Jundén 2011). The tool is based on the Python library SimPy, with plotting using Matplotlib and calculations and programming in Python.

A high level of abstraction was chosen since the simulations were mostly intended to simulate a machine, not yet in existence. Obviously, the mechanical details of such a machine could not be specified but a proposed method of working could be investigated and evaluated. The semi-autonomous process was identified as being critical to model correctly.

The spatial information about the trees was taken from research by Bredberg (1972) where the trees for several stands suitable for thinning had been carefully measured in areas of 25 m × 40 m. Tree position, dbh, stem mass and volume were all given. Six suitable, young, stands were chosen on the basis of the stands' average tree sizes, densities and species distribution, with different clustering of trees (Table 1).

Two different harvesters were simulated: one equipped with one crane and another equipped with two cranes, see Figure 1. Furthermore, two different cutting heads were simulated: a conventional head (Conv) and a hypothetical boom-corridor head (BC), resulting in four different machine configurations. Figure 1 shows a sketch of the multi-arm harvester concept. Since the different working methods mostly affect the harvester, the forwarder part of the harvesting system was omitted. Five different automation configurations (A - E), with different degree of automation, were modeled (Table 2). The one crane machine concept, 1-Conv and 1-BC, were only simulated with configuration A, i.e. no automation, since no queuing situation ever occurs when using only one crane. The two crane machine concepts were all simulated with configurations A - E. These variations resulted in a total of 12 different machine configurations. As the simulation is stochastic, 20 simulations were performed for each configuration. and 95% confidence intervals were calculated for the comparison of machine concepts and configurations. Each simulation includes three or four entities, depending on the number of cranes: the vehicle, the crane head(s) and the operator (working algorithms in Tables 3-6).

The functionality and size of the BC head were based on Forsberg and Wennberg (2011) (Table 7). The BC head(s) are able to fell and accumulate trees along the corridor with a continuous movement of the crane. The Conv head cuts one tree at a time and carries it back to the machine. The time usage functions for these were taken from Sängstuvall et al. (2012), see Table 8.

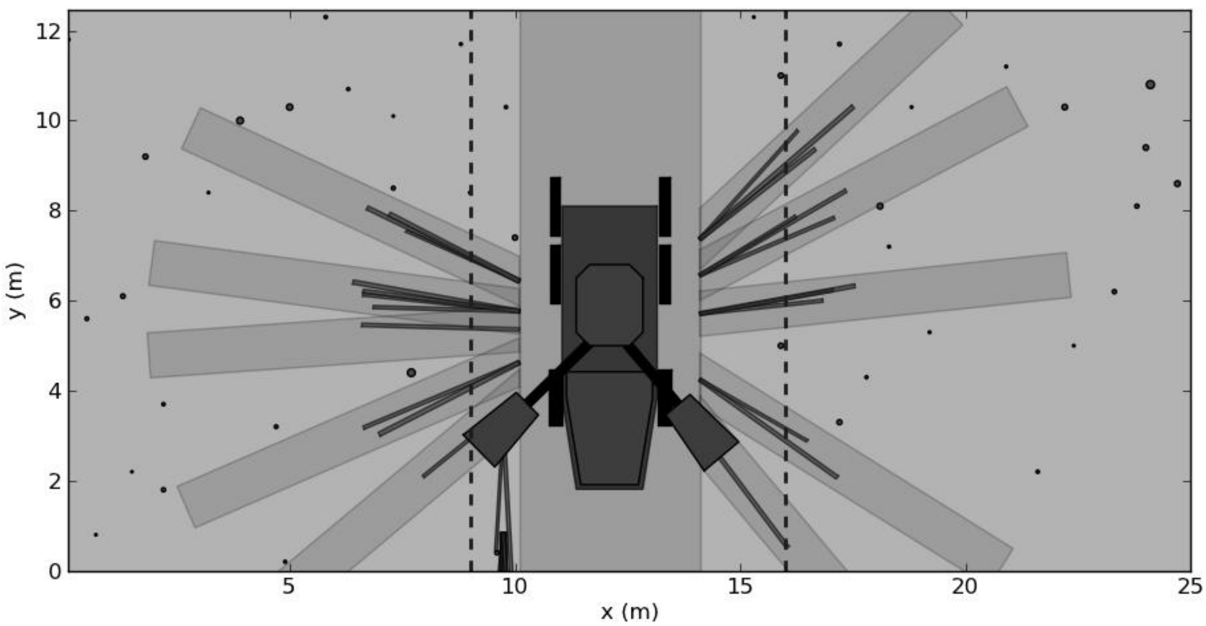

Figure 1. The double-craned harvester concept simulated with the limits for the stochastic strip-road (vertical dashed lines).

The simulated harvester moved along a preset strip-road in the y-direction starting at a point that was randomly set from the continuous interval $x \in [9, 16]$, which limits are shown as dashed lines in Figure 1. This random point on the x-axis, corresponding to the middle of the strip-road, is the only stochastic element in the simulation. The used measurements by Bredberg (1972) have a resolution of 0.1m, which means that some pairs of the random x-values resulted in identical road and corridor shapes. However, since x is a continuous random number, the distances to the trees from the main road were unique for every simulation.

The working method for the BC head was boom-corridor thinning i.e., the trees were cut with linear crane movements where the width and length of the corridor were equal to the width of the head and the maximum reach of the crane respectively (cf. Bergström et al. 2007, Sängstuvall et al. 2012). The strip-road was also harvested in this manner i.e. continuously as the machine moved along it. The conventional head harvested one tree at a time and could only carry one tree. Although multi-tree harvesting heads exist, this work pattern was chosen for simplicity. When the harvester with two cranes cut trees in the strip-road, only one of the cranes was used and the other one was left idle beside the machine.

It is reasonable to assume that a geometrical work pattern is easiest to automate in comparison to a strictly selective work method, since it does not require any artificial intelligence to control the crane. In the case of double-cranes, each crane had its own side of the strip-road when harvesting the corridors, which resulted in a queuing situation if one side had more trees suitable for harvest than the other. If the crane head had reached its storage capacity, the crane moved back to the machine, left the trees next to it and then continued into the same corridor again, harvesting the remaining trees.

The location of the corridors was determined by the algorithm in Table 6. This algorithm mimics the decisions that a driver would make, that is, it maximizes the number of trees that can be harvested in the corridor. The width of the corridors was set to 2 m when simulating the use of a conventional crane head. The maximum number of corridors per stop and side of the strip-road was set to five for the BC head and three for the Conv head, to compensate for the narrower corridors used by the BC head. Standard polygon-circle collision detection was used for determining whether trees were inside the corridor or not (Ericson 2005).The corridor algorithm (Table 6) also shows how the machine movement was handled (row 11). By moving to the same y-value as the corridor furthest away in the driving direction, good corridors were achieved with mostly non-harvested interiors, although some corridor overlaps was inevitable. The simulations were performed with a thinning intensity of around 40 - 50% of the total number of trees in the stand, varying slightly between the stands and head types since the width of the corridors were different for the different heads.

The machine operator was modeled as a resource, i.e. something that the tasks have to queue for (working algorithm in Table 5). This resulted in a convenient model for studying the different automation steps. The operator working steps were categorized (Table 8). The automation was varied in four different parts of the work flow, resulting in a total of 16 possible configurations, five of which were chosen for further analyses (Table 2). The times for the different tasks are given by the simple linear equation:

$$t = C + \frac{x}{v} \quad (1)$$

where C is a constant, v is the velocity of the task and x is the quantity that the task depends on (Table 8).

The harvester and crane model mainly follows Eliasson's (1999) work, where the maximum crane reach was set to 11 m. The time taken to move a crane is the maximum of the radial movement and the angular movement. With linear movements, this results in a slight modification of equation (1):

$$t_{crane} = C + max\left(\frac{\theta}{\omega}, \frac{r}{v_r}\right) \quad (2)$$

Where ω is the angular velocity and v_r is the velocity in the radial direction of the crane, θ is the angular movement and r is the radial movement (Table 8). The cranes were limited by the mass, diameter and height of the trees (Table 7).

RESULTS

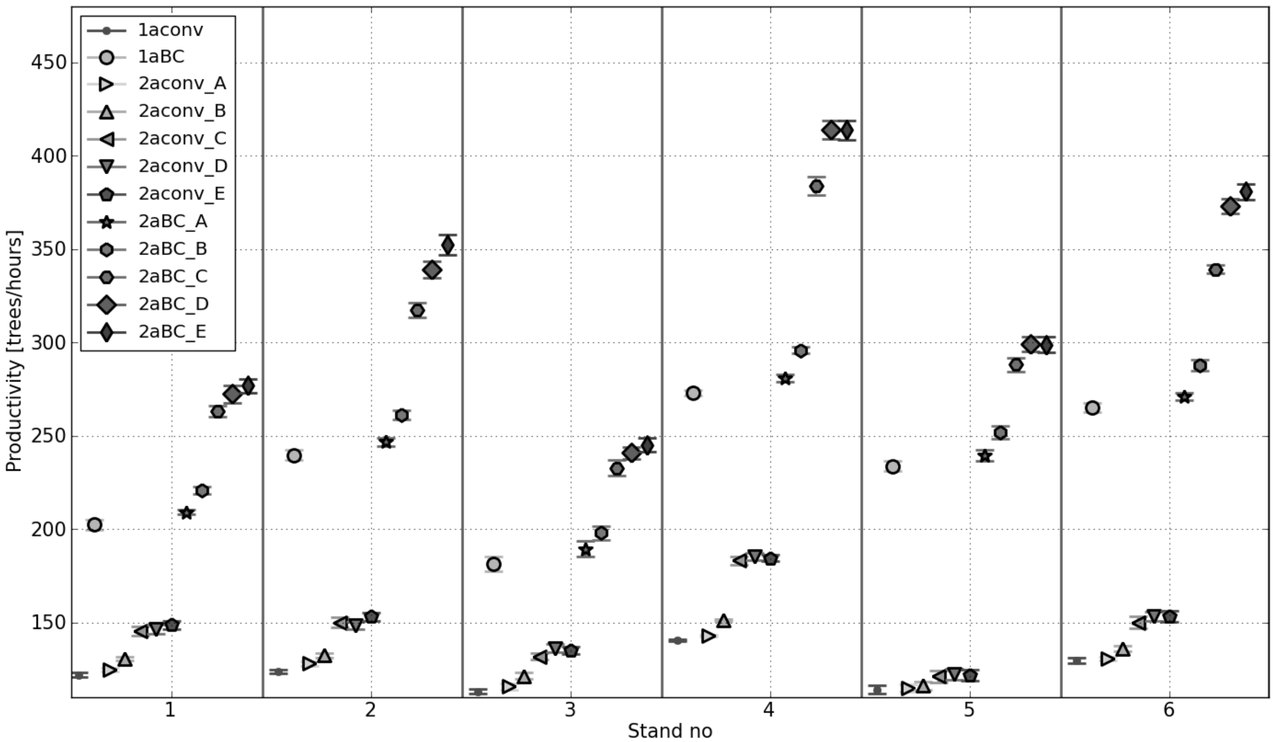

Figure 2. Simulated productivity for the different machine types and automation configurations (A - E) (see Table 2) and six different stands (1 - 6) with 95% confidence intervals. 1a/2a means one or two arms, BC is boom-corridor head and Conv is the conventional crane head.

The results from each simulation are data sets of the elapsed times for the different tasks and of the number of harvested trees for the given stands. Productivity, defined as cut trees per hour, was computed from these data sets. The biggest increase of productivity was due to addition of automatic release of the trees (configuration C) (Figures 2 and 3). For the BC head, the productivity was increased by about 40% with full automation and two cranes compared to the standard case of one crane and no automation.

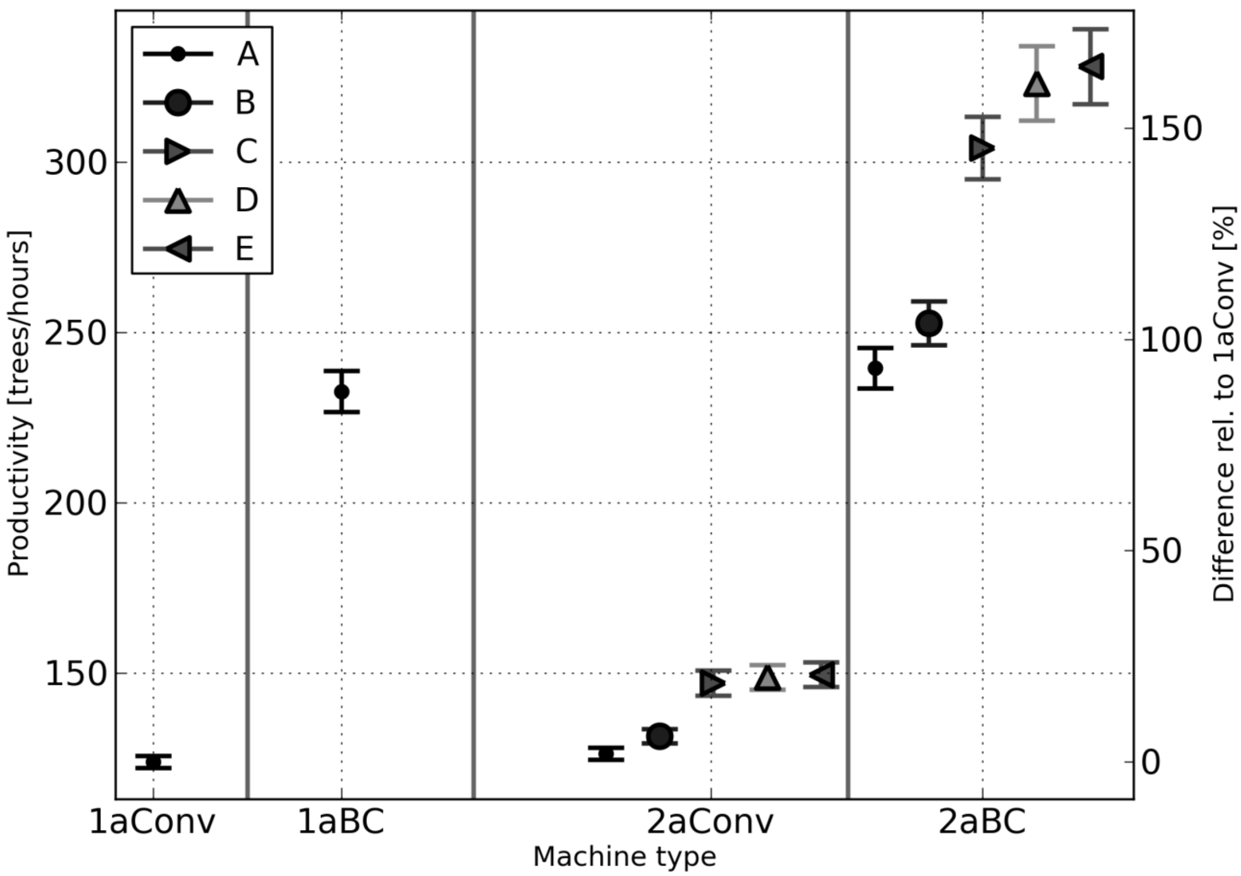

Figure 3. Simulated productivity for the different machine types and automation configurations (A - E) (see Table 2) with a 95% confidence interval. Mean absolute value and productivity relative to the 1aConv head, over the six stands are shown.

The operator is either idle or actively working. As expected, the activity ratio (working time in relation to total time) decreased as the level of automation increased (A - E, Figure 4) and in configuration E, the driver was practically idle except when the vehicle was moving.

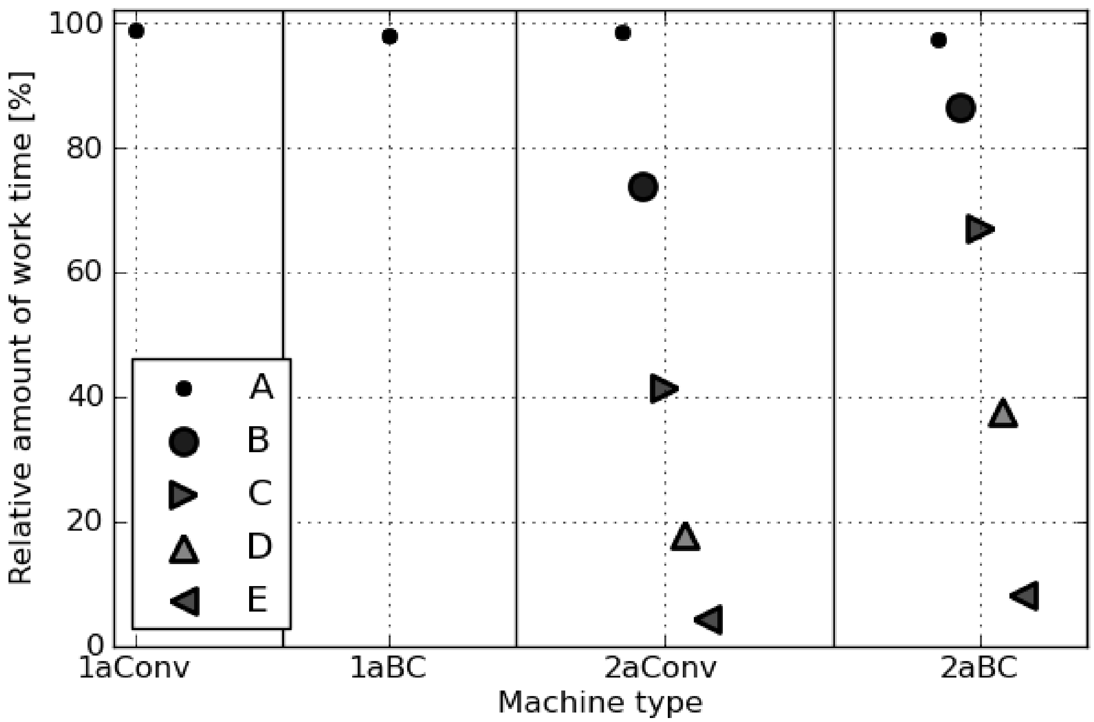

Figure 4. Work time of the machine "operator" in relation to total machine work time (operator activity ratio).

DISCUSSION

As the level of automation of forest machines increases, the double-crane model will clearly be beneficial for thinning operations. For the maximum automation level E, the simulation shows a productivity increase of 40% for the double-crane with a BC head compared to a single-crane fitted with a BC head. This should be compared with the theoretical maximum of 100% increase, which would be the case if the cranes worked completely independent and the machine movements between stop points where infinitely fast. The single-crane Conv head harvester showed a corresponding productivity increase of up to 20% with two arms compared to one arm, which is lower than for the BC-head. The reason for this is the number of corridors per side. If the head on one side finishes before the other it has to wait until the other side is finished and the machine has moved to the next stop point, then the crane work can start again. With the given stands and limits for the heads, one side had fewer corridors than the other quite often.

Thus, waiting times have a larger impact on productivity for the conventional head than for the BC head due to the difference in speed between the heads.

The double-crane has 160% higher productivity with a BC head than with the single-crane Conv head. Comparing Conv and BC heads is not completely relevant, however, as multi-tree handling heads are currently available and thus the simulated Conv head does not represent state of the art in today's technology.

One observation is that as automation increases, the gain from it decreases. The activity ratio for the different configurations (Figure 4) gives a hint as to the reasons for this behavior. Steps D and E do not increase productivity that much since automation does not increase the speed of the processes, it just gives the driver a rest. Since the driver is already often resting in configuration C, automating more processes only increases productivity in the cases that the driver is busy when the task "arrives". This phenomenon can be studied in more detail by considering more than the five automation configurations considered in this study. In the most automated configuration, when the driver rarely works at all, the step from that machine to a robot is not a big one and, because of this, configuration E will probably never be implemented. It should, of course, also be remembered that for many years to come, a driver will be needed to move the machine between different harvesting positions. The positive results of different automation steps also indicate that automation development does not have to occur for all tasks at once. Single steps will increase productivity and it will be up to producers and customers to decide what concepts that will be economically viable to develop.

The operator model should be the most uncertain part of the study. The time constants in Table 8 have been derived with no assumptions based on automation (cf. Sängstuvall et al. 2012). Automation can change the time required for resting and making decisions, either positively or negatively, which has not been considered in this study. The time constants used in the simulations should thus be verified in some way, such as using a training simulator environment (cf. Brander et al. 2004). Capturing the exact behavior of a human being is difficult but since the simulations were quite simple, e.g. we used just a straight strip road, we believe that our model mimics relevant choices that a human operator would have under the simulated conditions.

Another flaw with the used model is that in reality increased crane loads somewhat slows down the crane movements, which is not captured by our simplified crane model. However, the loads considered in these simulations are small, so the model should be accurate enough.

This study is a step towards rigorous sustainability analysis of early thinning to motivate investments in the technology and to help determine what solutions to aim for. The automation techniques assumed in this study are technically feasible but might be costly to adapt and use for forestry applications. The study is limited to an isolated part of the early thinning process. A full analysis should also include different harvesting systems with e.g., different degrees of on-site refining included such as bundling processes integrated with the work of the harvesters.

Conclusions

The study shows that introducing boom-corridor thinning with a semi-automatic double-crane system results in substantial increases in productivity when compared to conventional thinning and harvesting operations. For the specific harvester model used here, the single largest productivity increase enabled by the automation of a work task was as a result of the automatic release of trees. In the double-crane simulations, two reasons for queuing were identified. One case was the operator’s attention for manual tasks and the other queuing situation was when one side of the strip road was finished before the other and one crane head had to wait. If a double crane system is to be constructed, these waiting times will be crucial for the productivity.

The productivity yields from automation diminish as the level of automation increases, which indicates that the operator model is a close representation of reality. Studies on the effects of implementing automation for other forest machine operations could be analyzed using a similar approach.

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Tables

Table 1: Characteristics of the six different type stands from Bredberg (1972) used in simulations. Aggregation index is defined by Clark and Evans (1954) and is a measure of the clustering of the trees

Stand name in literature (Bredberg 1972)	Stand notation in present study	Arithmetic mean diameter at breast height, standard deviation in parenthesis (cm)	Species distribution (pine/spruce/birch) (% of total number of trees)	Stand density (trees/ha)	Tree aggregation index
GA-102	1	10 (2.6)	95.6 / 3.2 / 1.3	1580	1.35
GA-103	2	8.8 (2.9)	97.0 / 0 / 3.0	2320	1.02
GA-105	3	10.8 (3.4)	97.8 / 0 / 2.2	1350	1.38
GA-210	4	7.6 (2.3)	100 / 0 / 0	2440	1.21
GA-304	5	9.9 (3.2)	88.2 / 4.2 / 7.6	2370	1.22
GA-403	6	8.8 (2.7)	100 / 0 / 0	2780	1.13

Table 2. The five different automation configurations simulated with different work tasks

	Automated work task			
Configuration	**Move arm outwards**	**Move arm inwards**	**Release trees**	**Cut trees**
A	No	No	No	No
B	No	Yes	No	No
C	No	Yes	Yes	No
D	Yes	Yes	Yes	No
E	Yes	Yes	Yes	Yes

Table 3. Working algorithm for the thinning machine

Require: Information about the corridors and the strip roads, a list with the positions that will be visited along the strip road, *posList*, given from the corridor selection algorithm and access to the crane head(s).

while not end of *posList* **do**
    Assign the main road to one of the crane heads and start harvest process
    Wait until all the trees between current position and *posList.next()* have been cleared
    Update position to *posList.next()*
    Assign the corridors connected to the current position to the crane heads and start harvesting process. If machine is equipped with two cranes, assign the corridors to the left to that side's head and vice versa.
    Wait until crane heads are done with the corridors
end while

Table 4. Working algorithm for the crane heads

Require: Information about positions of machine and crane, time consumption of processes, weight and volume of surrounding trees.

Wait until corridor/strip road has been assigned

for all reachable trees in corridor / strip road **do**

if crane head will pass the capacity limit when harvesting tree **then**

Return to machine, release the harvested trees on the ground

end if

Move crane to tree and harvest tree

end for

Return to start position beside the machine, release harvested trees

Table 5.Working algorithm for the operator

Require: Task queue, *tQueue*, that is continuously filled with tasks that requires the operator's attention.

while not end of simulation **do**

if no task in *tQueue* **then**

wait until a task is queued

end if

Give access to the first process in tQueue

Wait until process is finished

end while

Table 6.Working algorithm for the operator

Require: Crane length *L*, corridor width *W*, number of corridors per side *n*, start position *pos*. *corridor(pos, side,* $\boldsymbol{\theta}$ *, L, W)* class. Map limits *xlim*, *ylim*

$\boldsymbol{\theta_{min}} \leftarrow \boldsymbol{\frac{\pi}{4}}$
$\boldsymbol{\sigma} \leftarrow \boldsymbol{\frac{\pi}{3n}}$
while *pos.y≤ylim* **do**
    for side in [-1,1] **do**
        for *i* in [0,1,2,…,*n*] **do**
            $\propto \leftarrow side \cdot \left(\theta_{min} + \frac{\pi - 2\theta_{min}}{n-1} i\right)$
            c ← *corridor(pos, side,* θ *, L, W)*for $\theta \in [\alpha - \sigma, \alpha + \sigma]$
            Save the corridor with the most chopable trees
        end for
    end for
    pos.y ←*pos.y*+ $\cos(\theta_{min})L$
end while

Table 7. Properties of the crane heads used in simulations. Some values, marked with "-", are not relevant.

Parameter	**BC**	**Conv**
Height (m)	2	-
Width (m)	1	-
Depth (m)	1.5	-
Mass (kg)	1000	-
Maximum cutting diameter d_{bh} (cm)	10	10
Maximum tree height (m)	10	10
Maximum cumulative tree mass (kg)	350	350
Tree storage capacity	-	1
Radial crane velocity, v_r (m/s)	2.5	2.5
Angular crane velocity, v_θ (Rad/s)	0.35	0.35

Table 8. Time and automation information for different parts of the simulation. The time constant is the minimum time a specific task takes. Values from (Sängstuvall et al. 2012)

Task	**Time constant (C)**	**Velocity (v)**	**Dependent quantity (x)**
Move machine	5 s	1 m/s	Distance (m)
Move arm outwards	1.5 s	Equation (2)	Crane angle or radial distance (rad or m)
Move arm inwards after harvest	1.5 s	Equation (2)	Crane angle or radial distance (rad or m)
Cut a tree	3 s	0.08 m^2/s	Cross-sectional area of tree (m^2)
Place/ harvested trees at the side of the strip-road	10s	-	-
Switch operator focus between crane arms	3s	-	-