Potentials of possible machine systems for directly loading logs in cut-to-length harvesting

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Abstract

In conventional mechanized cut-to-length systems a harvester fells and cuts trees into logs that are stored on the ground until a forwarder picks them up and carries them to landing sites. A proposed improvement is to place logs directly into the load spaces of transporting machines as they are cut. Such integrated loading could result in cost reductions, shorter lead times from stump to landing, and lower fuel consumption. However, it might also create waiting times for the machines involved, whereas multifunctional machines are likely to be expensive. Thus, it is important to analyze whether or not the advantages of any changes outweigh the disadvantages. The conventional system was compared with four potential systems, including two with autonomous forwarders, using discrete-event simulation with stochastic elements in which harvests of more than 1000 final felling stands (containing in total 1.6 million m^3) were simulated 35 times per system. The results indicate that harwarders have substantial potential (less expensive on ≥80% of the volume and fuel consumption decreased by ≥18%) and may become competitive if key innovations are developed. Systems with cooperating machines have considerably less potential, limited to very specific stand conditions. The results conform with expected difficulties in integrating processing and transporting machines' work in variable environments.

1 Introduction

During the last 50 years, forest operations have been subject to many steps of mechanization. The forces driving mechanization have included labor shortages, an aspiration to perform forestry operations year-round and for more hours per day, and a desire to reduce costs, the amounts of hard physical and unsafe work involved, and the lead time between logging and industrial processing (Sundberg, 1978; Silversides, 1997). As a result, highly advanced machines are available today. For instance, the harvesters and forwarders used in cut-to-length (CTL) harvesting are equipped with on board computers that facilitate the operator's work in addition to collecting and communicating data to be used in the supply chain. A logical step in ongoing developments would be automation and the removal of the operator (Hellström et al., 2009) and, indeed, ongoing efforts are being made to develop autonomous vehicles for forest harvest operations (Hellström & Ringdahl, 2009; Mettin et al., 2009; Ringdahl et al., 2011). The technological development will enable forest operations to be conducted in partly new manners. In CTL, for instance, the harvester and forwarder(s) may improve work efficiency cooperatively by reducing or removing the forwarder's work of loading logs. This mode of cooperation to enable integrated loading has recently received attention through the introduction of a prototype system called "Besten" with manned forwarders that remotely control an unmanned harvester (Eriksson, 2004; Bergkvist et al., 2006). Integrated loading could also be achieved by using one machine for both harvesting and forwarding (a *harwarder*) that places processed trees directly into its loading space. Although harwarders have been tested in commercial thinnings (Wester & Eliasson, 2003), direct loading is probably easiest to implement in final fellings where no residue trees limit the working space. In addition to its potential to improve cost efficiency, integrated loading should generally also result in shorter lead times from stump to road-side landing, cleaner logs, and lower fuel consumption due to the associated reduction in crane work. Since the effects of diverse environmental factors on the work involved in cutting trees and transporting logs differ, the productivity of these work tasks in a given stand can vary considerably. In the conventional system, a buffer (lead time) between machines is used to accommodate productivity differences. However, with the limited buffering possibilities intrinsic to directly cooperating machines, productivity differences would make it difficult to create such a system that performed optimally in all situations. Consequently, cooperating machines might create waiting times for each other. A multifunctional harwarder would not be subject to this problem, but it would probably have a higher investment cost and, thus, more expensive for work elements that would otherwise be conducted by with less expensive machinery (Asikainen, 2004).

It is important to analyze whether or not the advantages of possible new work methods outweigh their disadvantages. This should ideally be done at a very early stage to avoid resources being spent on projects that have low potential and to ensure that premature technologies or uncompetitive solutions do not become burdens for the entrepreneurs using them. This can be done by theoretical comparative studies in which an idealized suggested system is analyzed to estimate its best potential in comparison with the system it is intended to replace. Theoretical modeling enables the avoidance of confounding integration effects with other factors, for instance, variations in technological maturity, technical solutions, environmental conditions, and operator effects. Some static and deterministic (analytical) modeling of possible integrated CTL harvest systems has previously been conducted by Hallonborg & Nordén (2000), Hallonborg (2003), Bergkvist (2008), and Lindroos (2012) but with highly varying indications of systems' potentials. For example, Bergkvist (2008) found that the cooperative system Besten has considerable potential cost advantages over conventional systems for a considerable proportion (approximately 33%) of the final felling volume in Sweden, while Lindroos (2012) concluded that its potential advantages were limited to about 2% of the volume. However, since machine interactions are likely to create queuing, the analysis would benefit from dynamic and stochastic approaches to fully evaluate the potential of different systems Asikainen (2010).

The main objective of this study was to evaluate the potential of possible future systems for CTL harvests by *i*) developing a discrete event simulator to capture the dynamic and random character of interactions between machines used for integrated loading of logs and *ii*) comparing the economic performance of four potential systems for integrated CTL harvesting and a conventional harvester–forwarder system in final felling. Additionally, an evaluation of atmospheric pollution and energy efficiency was addressed in a limited comparison of the investigated systems' fuel consumption, whereas other qualitative parameters were excluded because they were assumed to be similar for all systems (e.g. approximately the same impact on soils) or they were deemed unlikely to influence the systems' potential for implementation in practical forestry strongly due to the current absence of economic values for, or restrictions related to, qualitative benefits (cf. Lindroos 2012).

2 Materials and Methods

2.1 Harvesting systems

Based on previous suggestions on possible concepts for direct loading in CTL harvesting (e.g. Hallonborg, 2003), four potential machine systems for future CTL harvesting are considered in this paper and presented graphically in Figure 1.

1. **Harwarder.** This manned machine does the work of both harvester and forwarder: felling, processing and

transporting.

2. **Autonomous load-changing (ALC) system.** Comprises a harwarder that cuts, processes, and places processed trees directly into its own bunk. When fully loaded, the harwarder switches loads with an autonomous forwarder, which then moves to the landing and unloads. Since this system has a buffer in the form of the harwarder's bunk, harvesting can be conducted, without waiting time, with one forwarder under certain conditions. If not otherwise stated, the ALC system considered in this study is assumed to contain one forwarder.

3. **Autonomous direct-loading *(ADL)* system.** In this system, a conventional harvester cuts, processes, and places processed trees directly into the bunk of an autonomous forwarder. When the forwarder is full, it moves to the landing to unload. Both driving and unloading are done automatically with no human intervention. Since the system does not involve use of a harvesting buffer, two or more forwarders have to be used to avoid the harvester waiting. If not otherwise stated, the ADL system considered in this study is assumed to contain two forwarders.

4. **Remote-controlled direct-loading (*RDL*) system.** In principle, the same as the ADL system outlined above but with manned forwarders taking turns to remotely control one unmanned harvester (as in the Besten system (Bergkvist et al., 2006)). If not otherwise stated, the RDL system considered in this study is assumed to contain two forwarders.

The ADL and RDL systems are essentially the same conceptually but with different unmanned machines and different solutions for the unmanning. Thus, when referring to methodology in which harvesters load directly into forwarder bunks, these two systems will here be called *Integrated Forwarder Loading (IFL)* (cf. Lindroos 2012).

2.2 Simulator characteristics

To fully evaluate the impact of the analyzed work methods, a discrete-event simulator was implemented in Matlab to simulate the time consumptions of the involved machines, as described in Section 2.4.

Two general assumptions are made concerning the similarity of the five investigated systems. First, the outcomes of all systems' work are assumed to be equal, in terms of both output quality and impact on the stand environment (e.g. rutting). Second, it is assumed that the same type of work is done equally rapidly by all systems. Hence, the potential of integrated loading as a work method is addressed without considering possible differences in specific technical implementations between systems. This is justified by the fact that if technical advances make one system

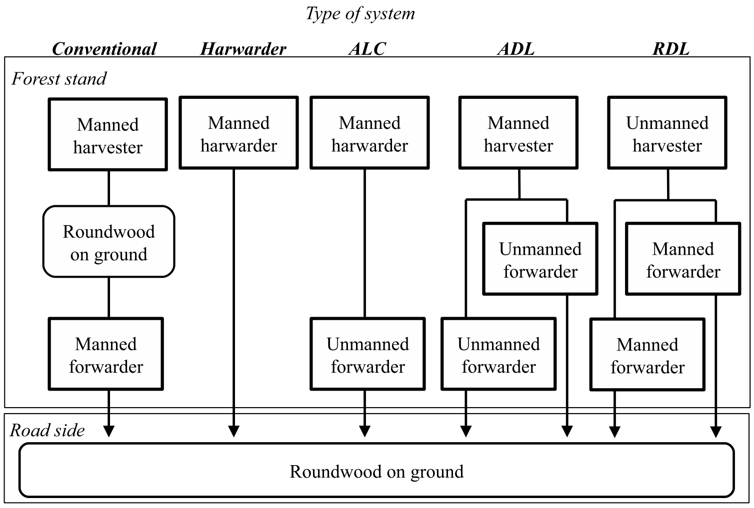


Figure 1: Graphical overview of the workflow in the four investigated systems compared with a conventional system.

faster than another (e.g. by use of a more powerful crane), those advances could also be applied to other systems, unless there are fundamental restrictions (e.g. being enabled due to the lack of an operator). Given the similarities in basic technical details, it was assumed that the trafficability of the terrain affected all machine systems similarly. The following factors were considered crucial to implement in a dynamic manner to make the simulations realistic and relevant:

1. Random delays during work, due to, e.g., machine breakdowns and operator needs.

2. Variation in forwarding distance within stands, since the distance depends on where in a stand a load is collected, which affects the occurrence of queuing and waiting times.

3. Queuing due to random delays and mismatches between the work of interdependent machines; for instance, a harvester may have to wait for a forwarder to be available before loading or switching of loads can commence in the IFL and ALC systems, respectively.

To avoid the simulator being too complex, other aspects of the operation were applied in a static and deterministic manner. The simulator was applied to stand data (Section 2.11), and each simulation was repeated 35 times to allow for random delay effects. The number was empirically determined such that the simulation results were stable. More simulation runs were tested on a subset of the data but did not change the results in any significant way. The computations for time consumptions, costs, and fuel consumptions were partly based on Nurminen et al. (2006, 2009) and Lindroos (2012). Aggregated machine time consumption functions were used for calculation of the productive machine time required for the completion of the intended work task (cf. Björheden 1991). The simulator ran in scheduled machine time, which is the productive machine time plus all nonproductive machine time (e.g. delays and waiting time). The time units used are productive machine minutes or hours (PMmin and PMh, respectively) and the corresponding scheduled time units (SMmin and SMh). The simulator was validated by comparison with previous analytical work (Hallonborg, 2003; Lindroos, 2012).

2.3 Work elements

A certain amount of productive machine time is required to complete a given work task, irrespective of the amount of non-productive time that elapses. For the simulations, harvesting work was regarded as a single work element t^h_{ld}, and direct loading was assumed to not affect the harvesting efficiency. Forwarding work t^f_{fh} in the conventional system was divided into five work elements according to Nurminen et al. (2006):

$$t^f_{fh} = t^f_e + t^f_l + t^f_{dl} + t^f_{ld} + t^f_{ul} \tag{1}$$

where

t^f_{fh}: total effective time consumption for forest haulage [PMmin/m^3]

t^f_e: time consumption for driving empty [PMmin/m^3]

t^f_l: time consumption for driving loaded [PMmin/m^3]

t^f_{dl}: time consumption for driving while loading [PMmin/m^3]

t^f_{ld}: time consumption for loading [PMmin/m^3]

t^f_{ul}: time consumption for unloading and driving while unloading [PMmin/m^3].

In the integrated systems, logs are not picked up from the ground, so t^f_{dl} and t^f_{ld} are not relevant for these systems. However, the work elements are replaced by the time it takes for the harvester to load a forwarder in the IFL systems and by the time it takes to switch loads in the ALC system. In the simulator, the elements required for a forwarder (or harwarder) to go to the landing, unload, and return to the harvesting site were pooled into the time t^f_{tu} because the work is conducted in sequence without interactions with other machines:.

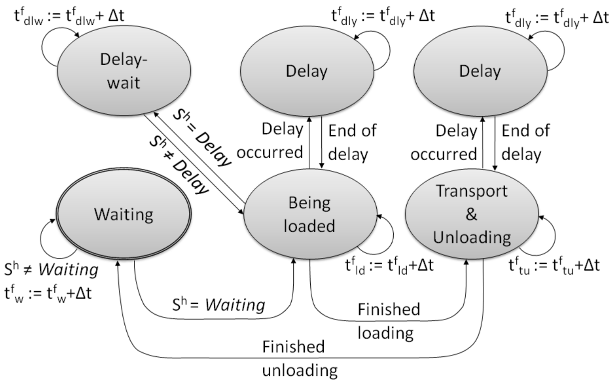
$$t^f_{tu} = t^f_e + t^f_l + t^f_{ul}. \tag{2}$$

The time required to switch between forwarders (T_{fc}) in the IFL systems and to switch loads (T_{sw}) in the ALC system was added for both interacting machines as constant time consumptions per switch.

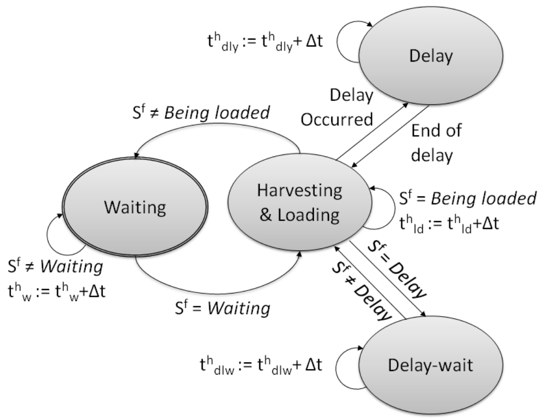
2.4 Simulation of interdependent machine work

To evaluate the performance of several interdependent machines affected by random delays, a discrete-event simulator was developed for the ALC and IFL systems. The simulator was implemented with one finite state machine for each forest machine, with slight differences between IFL and ALC systems, as illustrated in Figures 2 and 3. A forwarder is in the state *Transport & Unloading* while driving loaded towards the landing, unloading at the landing, and driving unloaded back to the harvesting site. The *Harvesting & Loading* state includes harvesting work and loading of logs into the load space, and *Waiting* is done while a machine is waiting for another machine to be able to continue its work. The times required for *Harvesting & Loading* and *Transport & Unloading* are determined by Equations 6 and 2, respectively. The state *Switching loads* in ALC includes the interaction of harwarder and forwarder switching loads with each other, with the constant time requirement T_{sw} per load. The IFL machines interact during the *Harvesting & Loading* state. Thus, the constant time requirement to switch between forwarders being loaded by the harvester T_{fc} is included in the *Harvesting & Loading* state instead of introducing a new state. When a machine is not waiting for another machine (represented by the states *Waiting* and *Delay-wait*), it may be affected by a delay (represented by the state *Delay*). The computations for probability and length of a delay are described in Section 2.6. If a delay occurs while interacting with another machine, the machine that is not delayed must wait until the delayed machine resumes production. This is represented by the state *Delay-wait.* The reason for not letting delays occur during the states *Wait and Delay-wait* is that the risk for certain types of delays is very low when the machine is not in operation. Furthermore, some delays, e.g., the operator taking a short break or replacement of the saw chain, could be dealt with while the machine is waiting. Several machines may be delayed at the same time, but a machine cannot have a new delay while in the state *Delay.* The interaction between machines and the state changes resulting from delays are exemplified for parts of a simulation for the IFL and ALC systems in Figure 4.

To complete the simulator, a framework capable of administrating the interaction between the finite state machines and to perform all necessary computations was designed and implemented. Initially, all current and previous states are set to *Waiting*, except in the ALC case where the harwarder's current state is set to *Harvesting & Loading.* The simulator is run for a number of loads delivered to the landing, determined by the total volume in each stand and the loading capacity of the simulated forwarder. A load is considered to be completed when the state of a forwarder



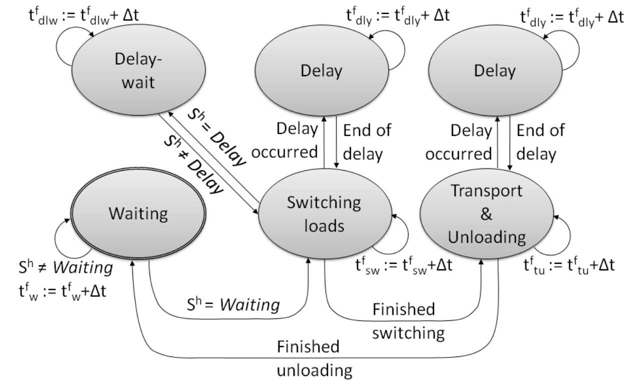
(a) Direct-loading forwarder (autonomous or manned)



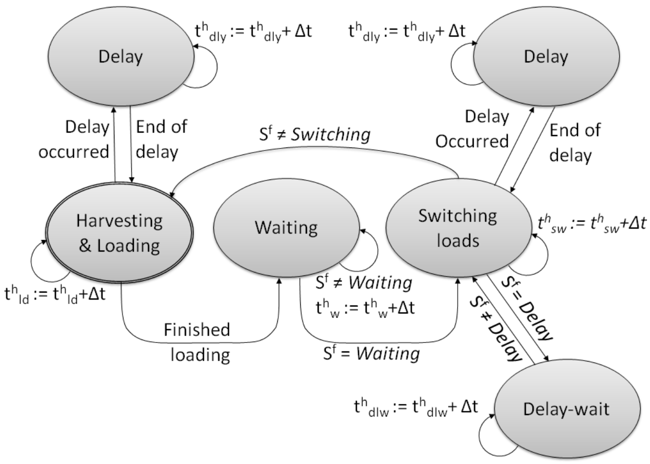
(b) Direct-loading harvester (remote-controlled or manned)

Figure 2: State diagrams for a harvester directly loading one or more forwarders (IFL systems). S^h and S^f are the current states of the harvester and forwarder, respectively. *Harvesting & Loading* includes the time required for changing forwarders. Time t is incremented by Δt in each simulator step. At the start of each simulation, both harvester and forwarder are initialized to the state *Waiting*.

changes from *Transport & Unloading* to *Waiting*. This means that the forwarder has successfully unloaded at the landing and returned to the harvester, waiting for it to be ready for the next load. The global time t is incremented by Δt in each step in the simulator and is used to check the conditions for state changes. $\Delta t = 0.1$ SMmin was used in all simulations presented in this paper. Algorithm 1 (Appendix A) describes how the total machine time is computed for interdependent machine systems.

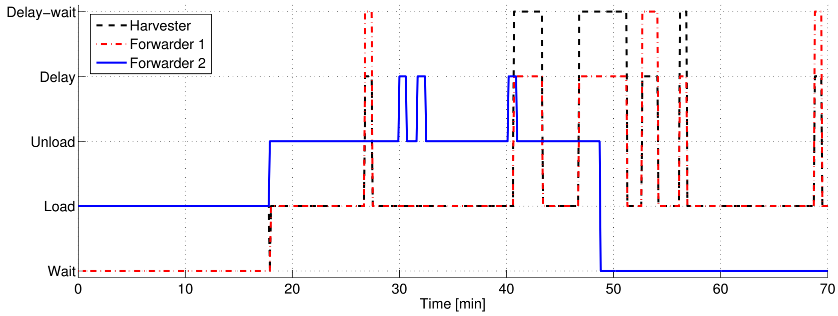


(a) Load-changing forwarder

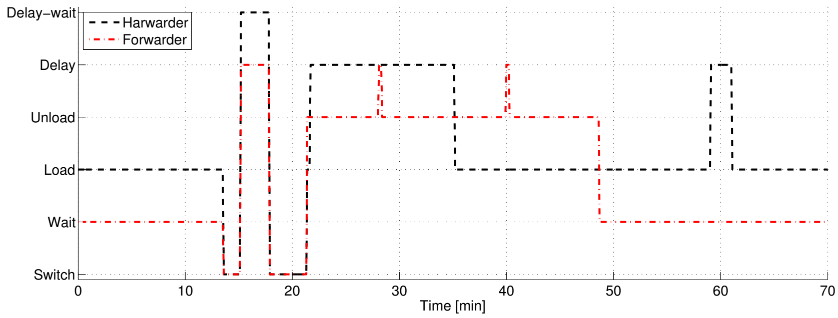


(b) Load-changing harwarder

Figure 3: State diagram for one or more autonomous forwarders changing loads with a harwarder (ALC system). S^h and S^f are the current states of the harwarder and forwarder, respectively. Time t is incremented by Δt in each simulator step. At the start of each simulation, the harwarder is initialized to state *Harvesting* & *Loading* and the forwarder to state *Waiting*.



(a) IFL system



(b) ALC system

Figure 4: Interactions between machines and the resulting state changes for parts of a simulation.

2.5 Simulation of independent machine work

Since there is no dependence between the harvesting and forwarding phases when using harwarders or conventional systems, computations of scheduled machine time consumption are less complex for these systems. The productive machine time required to harvest and forward a stand's total volume is calculated for each stand's specific conditions according to Sections 2.3 and 2.8. During the time period required, occurrence and length of delay time are calculated for each time step according to Section 2.6, as described in Algorithm 2 (Appendix A). The total scheduled machine time is computed as the sum of all delay times added to the required (delay-free) productive machine time.

2.6 Simulation of delay occurrence

At each time step in the simulator, a delay with a length between 0.4 and 50 SMmin, can occur for each machine with certain probabilities (Spinelli & Visser, 2008). This may force other machines to wait for the delayed machine, depending on the length of the delay and the work phase in which the delay occurs.

According to Spinelli & Visser (2008), there are three categories of delays:

1. *Mechanical delays* - break-downs, saw-chain derailings, and saw-chain replacements
2. *Operator delays* - rests, breaks, physiological, smoking, and phone calls
3. *Other delay* - waiting, interference, reconnaissance, refuel, and maintenance.

To determine if a delay occurs and, if so, its type and length, the procedure described below was used. The calculations are based on data from a meta-analysis of the delay components in 34 harvester time study data sets, resulting in statistics for 2151 delays in the categories described above and with a total duration (d_{tot}) of 8725 minutes (Spinelli & Visser, 2008).

Given a simulator time step Δt, the probability for a delay occurring between time t and $t + \Delta t$ is

$$p(delay) = 0.072\,\Delta t \tag{3}$$

where the constant 0.072 is computed as the total number of delays divided by total productive machine time PM_{tot} (29894.4 min) in the study by Spinelli & Visser (2008). This corresponds to an approximately exponential distribution.

At each time step, delay occurrence is determined by drawing a (uniformly distributed) random number r in the interval [0 1], with a delay occurring if $r \leq p(delay)$.

If a delay occurs, the following procedure gives the type and length:

1. Draw a random number r in the interval [0 1]. Following Spinelli & Visser (2008), the three types of delays occur with the following probabilities: *Mechanical* ($p = 0.154$), *Operator* ($p = 0.341$), and *Other* ($p = 0.505$). Hence, the type of delay is *Mechanical* if $r \leq 0.154$, *Operator* if $0.154 < r \leq 0.495$ and *Other* if $r > 0.495$.

2. The length of delays is divided into six delay periods with increasing durations. Figure 5 shows the probability for a delay belonging to a certain duration period given a delay type. From this, the duration period of a delay is determined by drawing a random number in the interval [0 1].

3. In Spinelli and Visser's (2008) work, total delay time d_{tot} for each delay type and duration period was presented as well as the number of delays N for each delay type. In the simulator, the length of a single delay d_{len} in a given duration period is determined by

$$d_{len} = d_{tot}/N. \tag{4}$$

4. In Spinelli & Visser (2008) d_{tot} (and thereby d_{len}) was based on a total productive machine time PM_{tot} corresponding to a machine utilization rate U of 77.4% of the total observed machine time (and hence 22.6% delay time). In the simulator, the productive machine time required for a given work task is constant, but different values for U are used for different machine types. Thus, different delay times had to be added to result in different levels of U. Therefore, the delay times in Spinelli & Visser (2008) were modified to the U-dependent delay time d_{len}^U according to Eq.5 in which the left-hand fraction gives the productive work time required for d_{len} with the U in the original study, whereas the right-hand fraction provides the relationship between delay time and productive machine time required to achieve the wanted level of U:

$$d_{len}^U = \frac{d_{len}}{d_{tot}/PM_{tot}} \frac{100 - U}{U}. \tag{5}$$

For example, a delay that originally (i.e. with $d_{tot}/PM_{tot} = 0.29$, which corresponds to a U of 77.4%) was 5.0 minutes becomes 1.9 minutes with 90% U and 5.7 minutes with 75% U. In Figure 6 the length of delays for the different delay types and durations periods is exemplified for $U = 75\,\%$ (harwarder).

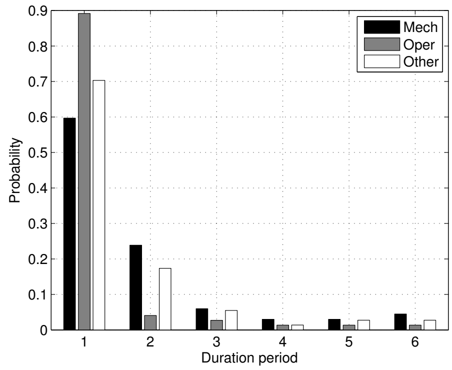


Figure 5: Probability of delay for three delay types and six duration periods.

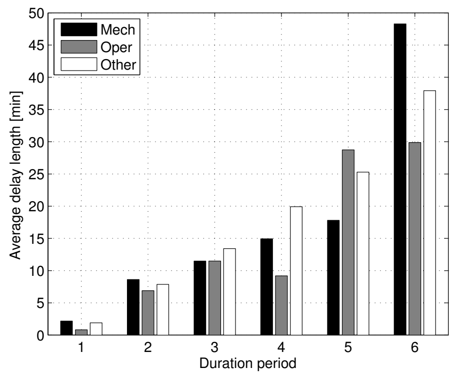


Figure 6: Length of delays given the type of delay and duration period for a harwarder with 75% machine utilization rate (U).

2.7 Variation in forwarding distance

For ALC and IFL systems, the total number of loads that would be produced by harvesting a stand was calculated based on total stand volume harvested and load volume. Thereafter, the average one-way forwarding distance $\bar{d_m}$ (metres) was used to generate distances for each load to meet the assumption that $\bar{d_m}$ is normally distributed with a standard deviation of 20% ($d_m \in N(\bar{d_m}, 0.2\,\bar{d_m})$). Forwarding distances were regenerated for each simulation run. For the conventional and harwarder systems, which lack machine interdependence, a stand's average forwarding distance was used as a static variable and thus was identical across loads and simulations.

2.8 Estimations of time consumptions

Given a stem size V_S, the time consumption for final harvesting of spruce t^h_{ld} (min/m^3) can be calculated according to Nurminen et al. (2006):

$$t^h_{ld} = 60/(4.067 + 78.623\,V_S - 18.507\,(V_S)^2). \tag{6}$$

Time consumption for the work elements of forwarding presented in Section 2.3 were based on equations provided by Nurminen et al. (2006) for loads with several assortments:

$$
\begin{aligned}
t^f_e &= \frac{\max(0,\, \bar{d_m} - \frac{V_F\,l_r}{2\,V_R})}{v_e\,V_F} && (7)\\
t^f_l &= \frac{\max(0,\, \bar{d_m} - \frac{V_F\,l_r}{2\,V_R})}{v_f\,V_F} && (8)\\
t^f_{dl} &= \frac{l_r}{V_R\,v_l} && (9)\\
t^f_{ld} &= 1 + \frac{0.155}{\exp(-0.447 + 0.3\ln(\frac{100\,V_R}{l_r}))} && (10)\\
t^f_{ul} &= 0.657 && (11)
\end{aligned}
$$

where

V_R: Timber density in the stand [m^3/ha]

l_r: Total length of the strip road network (= 769 m/ha)

V_F: Timber volume per load (= 18 m^3)

$\bar{d_m}$: Average forwarding distance one way [m]

v_e: Average speed when driving empty (= 56 m/min)

v_f: Average speed when driving fully loaded (= 43.9 m/min)

v_l: Average speed when driving during loading (= 27 m/min)

It was assumed that forwarders and harwarders could each load 18 m^3 of roundwood and the total strip road length was based on the assumption that there would be 13 m between roads (cf. Nurminen et al. 2006). The time required to change loads, T_{sw}, in the ALC system was set to 5 PMmin (approximately 0.28 PMmin/m^3) and the time to switch between forwarders T_{fc} in the IFL systems was set to 2 PMmin (approximately 0.11 PMmin/m^3). Irrespective of whether machines were manned or not, their utilization rates (U) were assumed to be 80% for harvesters, 90% for forwarders, and 75% for harwarders (cf. Lindroos 2012).

2.9 Cost calculation

The total cost (c_t) for a machine system is the sum of the costs for forwarding (c^f) and harvesting (c^h). These costs are computed as the costs per scheduled hour, divided into work and idle costs, multiplied by the corresponding simulation time consumption output (Eq. 12). Hence, the times spent in different states are grouped into normal work (e.g. *Transport* & *Unloading* for a forwarder) and work time when the machine's hourly cost is reduced due to idle time (e.g. *Being loaded*, see Section 2.10). Algorithms 1 and 2 (Appendix A) describe in detail how work and idle time is computed for integrated and conventional systems, respectively.

$$\begin{aligned} c^h &:= t^h_W\, c^h_{h,W} + t^h_i\, c^h_{h,I} \\ c^f &:= t^f_W\, c^f_{h,W} + t^f_i\, c^f_{h,I} \\ c_t &:= c^h + c^f \end{aligned} \tag{12}$$

where

c^h, c^f: Cost per m^3 for harvesting and forwarding, respectively

$c^h_{h,W}$, $c^h_{h,I}$: Hourly cost for harvesting during normal work and idling, respectively

$c^f_{h,W}$, $c^f_{h,I}$: Hourly cost for forwarding during normal work and idling, respectively

t^h_W, t^h_I: Total time consumption for harvesting work and idling, respectively

t^f_W, t^f_I: Total time consumption for forwarding work and idling, respectively

Irrespective of whether harvesting or forwarding is being performed, and irrespective of whether machines are working or idling, the hourly cost c_h consists of three different components:

$$c_h = c_f + c_o + c_l \tag{13}$$

where

c_f: Fixed costs (investment cost, expenses for insurance, interest, etc.) per scheduled machine hour

c_o: Operating costs (e.g. fuel consumption, maintenance, spare parts, etc.) per scheduled machine hour

c_l: Labor costs (operator salary) per scheduled machine hour

It was here assumed that all machines were scheduled for 2600 hours per year. Since harvesting and forwarding were conducted by separate machines in all systems but the harwarder, c_h for those systems was equal to the hourly machine costs during the performance of normal work and idling, respectively (cf. Table 1).

2.10 Assumptions on hourly costs and fuel consumptions

Hourly costs for the involved machines are listed in Table 1, with all times referring to scheduled time and costs converted from Swedish krona to euro (10 SEK = 1 €). The underlying cost-related assumptions are:

- The fixed cost is 29.74 and 19.63 €/SMh for a conventional harvester and forwarder, respectively, based on estimated prices from manufacturers in fall 2009.
- The operating cost is 40.0 and 22.8 €/SMh for a conventional harvester and forwarder, respectively, based on author estimations.
- The operator cost is 35.28 €/SMh for all manned machines based on estimations from union representatives.
- The fixed cost for a RDL harvester is 20% lower than for a conventional harvester (no need for a cabin), based on estimated prices from manufacturers in fall 2009.

- The fixed cost for a RDL forwarder is 17% higher than for a conventional forwarder (requires remote control gear and rotatable bunk) based on estimated prices from manufacturers in fall 2009.
- The fixed cost for an autonomous forwarder is 5% higher than for a conventional forwarder (requires rotatable or switchable bunk but no cabin) based on author estimations.
- The fixed cost for a harwarder is 17% higher than for a conventional harvester (requires harvester head-grapple and rotatable bunk) based on estimated prices from manufacturers in fall 2009.
- The fixed cost for a ALC harwarder is 20% higher than for a conventional harvester (requires harvester head-grapple and rotatable and switchable bunk) based on author estimations.
- The fuel consumption when idling is 21% of the consumption in normal operation (Nordfjell et al., 2003).
- The fuel cost when working is 35% of the total operating costs for a harvester, and 51% for a forwarder, based on the cost levels in 2005 (Nurminen et al., 2009).

Further, a relocation cost of 200 € per machine and stand was added to the total cost. Irrespective of system, fuel consumption per PMh for forwarder work was assumed to be identical for all work elements (Nordfjell et al., 2003) based on the assumption of a constant optimal engine load, which is possible by use of the machines' hydrostatic–mechanical transmission system. The harvesting work was assumed to have 23% higher fuel consumption per PMh than forwarding work, due to a larger engine, and working with higher engine revolutions (Brunberg, 2006; Klvac & Skoupy, 2009). Thus, relative differences could be addressed without having to assume specific fuel consumption rates for specific machines. In the fuel consumption calculations machines were considered to be idling during the states *Delay, Waiting*, and *Delay-waiting*. Additionally, the IFL forwarders were considered to be idling when being loaded. However, during cost calculations machines were not considered to have reductions in operational costs during *Delay*, because such idling time is normally included in operating cost estimations for scheduled machine time. Hence, the fuel consumption was directly dependent on the total time expenditure and its proportion of working and idling time. As mentioned above, fuel consumption during idling was assumed to be 21% of the consumption during normal work.

Table 2: Characteristics of the stands included in the follow-up dataset of final fellings in three Swedish regions.

	Region		
Characteristic	North	Central	South
Total volume [m^3]	319 053	310 801	994 150
Total no. of loads (18 m^3)	17 795	17 340	55 610
Number of stands	165	162	802
Mean forwarding distance one way[1] [m]	359	425	387
Mean stand density[1] [m^3/ha]	213	302	246
Mean stem size[1] [m^3]	0.24	0.37	0.48

[1)] Volume-weighted

Table 1: Hourly cost (€/SMh) for the simulated machines.

Machine	Work time	Idle time
Conventional forwarder	77.71	68.52
Conventional harvester	105.02	93.96
Harwarder (harvesting)	110.08	99.02
Harwarder (forwarding)	92.88	83.69
Load-changing harwarder	110.97	99.91
Autonomous forwarder	43.41	34.23
RDL harvester	63.79	52.73
RDL forwarder	81.05	68.52

2.11 Stand data

Followup data for finally felled stands harvested by conventional systems were gathered from forestry companies for three regions of Sweden: northern (Norrbotten, approximately 66° N, 22° E), central (Medelpad, approximately 62° N, 16° E) and southern (Östergötland-Sörmland, approximately 58° N, 16° E) (Table 2). For each stand, these data included information on the stand volume (m^3), stand density (m^3/ha), mean harvested stem size (m^3) and mean forwarding distance one way (m). The time consumption functions used here are not adapted to stands with densities less than 100 and more than 1000 m^3/ha, and such stands were therefore excluded. This resulted in the exclusion of 7.8%, 2.4%, and 8.9% of the harvested volume in original data from northern, central and southern Sweden, respectively. Stands with more than 1000 m^3/ha only occurred in the southern dataset, and the excluded stands corresponded to 0.9% of the volume in the original data set. The data set used is identical to the one used in Lindroos (2012).

2.12 Sensitivity and data analysis

The original assumptions were relaxed to investigate the robustness of the simulation results. The following parameters were varied: productive machine time consumption (+10% for harwarders and autonomous forwarders), one forwarder in the IFL systems instead of two, two forwarders in the ALC system instead of one, fixed cost, and additional reductions in operational cost and fuel consumption when a machine is idle (consuming fuel or not). In the cost analysis, unmanned machines were assumed to turn off their engines during the states *Waiting* and *Delay-wait* (cf. Section 2.10), since cabin comfort (heating/cooling) and other operator-related needs are not necessary. In the fuel consumption analysis, unmanned machines were assumed to turn off engines during the states *Delay, Waiting,* and *Delay-wait*.

For each machine, total time consumption within regions was summarized (in SMmin) for each simulation and used for cost calculations, resulting in a total cost for one machine in a region. Time consumption and cost per cubic metre were computed by dividing their respective values by the total volume in the region. Time consumption and costs for a whole system were computed as the sums of corresponding values for all machines. Results are presented as means and standard deviations for the 35 simulation runs in the basic scenario. Due to the very low variation in time consumption and cost over several runs, the sensitivity analyzes on increased time consumption and with different number of forwarders were based on single simulation runs. Variation between runs was computed as the coefficient of variation (CV) (SD/mean $\times$ 100). Differences in system mean values within regions were analyzed by one-way ANOVA. The significance level was set to 5%.

3 Results

3.1 Time consumptions

Assuming 2600 SMh/machine and year, the simulated final felling volume of, in total, approximately 1.6 million m^3 would take approximately 29, 48, 33, and 31 years to harvest by the conventional, harwarder, ALC, and IFL systems, respectively. The large amount of simulated work reduced the effect of the random elements because even if the outcome of the 35 different simulations differed quite strongly in a given stand (e.g. CV = 70% for delay time), the variations evened out in the total harvested volume (CV $\leq$ 5% for the states *Delay, Waiting,* and *Delay-wait*, and CV $\leq$ 0.2% for total times). Similarly, the variations within stands increased as time spent in a stand decreased. Due to the extremely small variation, the total time consumption differed significantly ($p < 0.001$) between all systems in

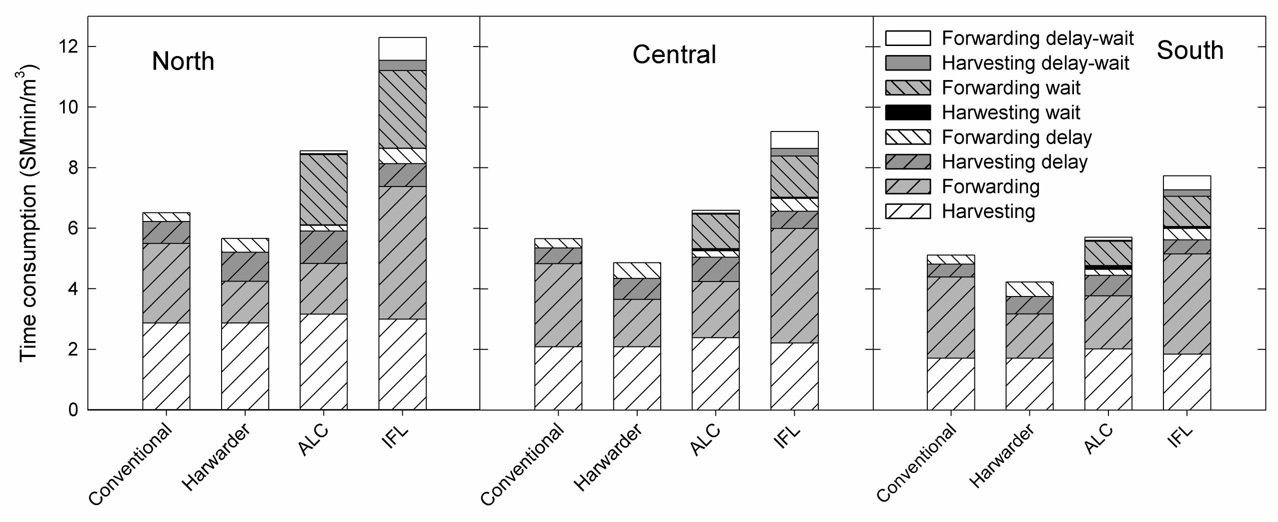


Figure 7: Average time consumption for each of the states in the four systems in the three regions. Note that for ALC, *Harvesting* includes the state *Switching loads.* For ALC and IFL, *Forwarding* includes the states *Transport* & *Unloading* and, respectively, *Switching loads* or *Being loaded.*

all regions, with the same order between systems' efficiency in all three regions. For the harwarder, the absence of loading time fully compensated for the low level of machine utilization rate (U), such that it required least machine time per cubic metre. The conventional system was the second least machine-time consuming system per cubic metre, followed by the ALC and IFL systems (Figure 7). The two least efficient systems suffered heavily from waiting time, especially for the forwarders, and especially in the north region (where it corresponded to more than 20% of the total time consumed), whereas the waiting time for harvesters was less than 0.1% of the total time consumed, irrespective of region. In the south region, the stand conditions were more favorable (i.e. the mean stem size was larger in relation to forwarding distance) such that harvesting and forwarding times offered a better match for the systems. However, the performance of all systems was better the farther south they were applied. The lower level of interaction between machines in the ALC system resulted in slightly shorter *Waiting* times and considerably shorter *Delay-waiting* times compared with the IFL systems (Figure 7). As can be seen from the differences in *Harvesting* times between the conventional system and the ALC and IFL systems, the extra time required to enable direct loading only marginally affected the productive work time per cubic metre. Hence, such arrangements for enabling direct loading only marginally influence a system's total time consumption compared with the negative effects of machine interactions. However, the weaker the negative interaction effects, the more important the arrangements are (e.g. they are more influential in the south than in the north region).

Table 3: Average total cost (€/m^3) including relocation costs for the three different regions in 35 runs with different random delays. The numbers within parentheses are the standard deviations. System averages within columns differ significantly (one-way ANOVA, $p < 0.001$).

	Region		
System	North	Central	South
Conventional system	10.26 (0.01)	8.72 (0.01)	7.92 (0.00)
Harwarder	9.96 (0.02)	8.42 (0.01)	7.36 (0.00)
ALC	10.83 (0.02)	8.47 (0.02)	7.49 (0.01)
ADL	12.39 (0.01)	9.42 (0.02)	8.17 (0.01)
RDL	14.36 (0.02)	10.93 (0.02)	9.45 (0.01)

3.2 Cost comparisons

Due to the very low level of variation in time consumptions, the costs were also very stable over simulation runs, as illustrated by the low standard deviations in Table 3. Consequently, there were significant differences between all systems' mean costs per m^3 within all three regions ($p < 0.001$). The harwarder was the most viable system in all three regions, and the ALC system was more viable than the conventional system in the central and south regions (Table 3). The ADL system was the second least viable system in all regions, whereas the RDL system was the least viable of the five systems in all regions.

However, although the total mean costs per cubic metre and region were stable, the costs varied considerably between stands, even within the same region. Based on the mean cost for harvesting a stand in the 35 simulation runs, Table 4 shows the proportion of the total volume for which each alternative machine system is more profitable than a conventional one. As expected, the viability patterns between systems are similar to those for average total costs in Table 3. However, it should be noted that the harwarder is viable for a remarkably high proportion of the harvested volume (≥79.7%) and the RDL system for almost no volume at all (≤0.7%). The distributions of between-stand cost differences compared with the conventional system (Figure 8) show that no system is more profitable than a conventional system in all stands, although no system is less profitable in all stands either. However, the results also indicate that the harwarder is quite consistent in terms of cost differences (mainly less expensive with low variation). The ALC system has quite stable costs compared with the conventional system in the central and south region, whereas its costs vary more in the north. For the two IFL systems, the costs (relative to those of the conventional system) differ greatly between stands, especially for the RDL system (from 0.5 € less expensive to 15 € more expensive per cubic metre). It should also be noted that the cost differences between the conventional system and the ALC and IFL systems are smaller in the south than in the north region (Figure 8).

Table 4: Proportions of total volume (%) for which the alternative systems are more profitable than a conventional one.

	Region		
System	North	Central	South
Harwarder	79.7	85.4	95.8
ALC	26.7	70.4	88.0
ADL	0.5	17.1	46.4
RDL	0.0	0.0	0.7

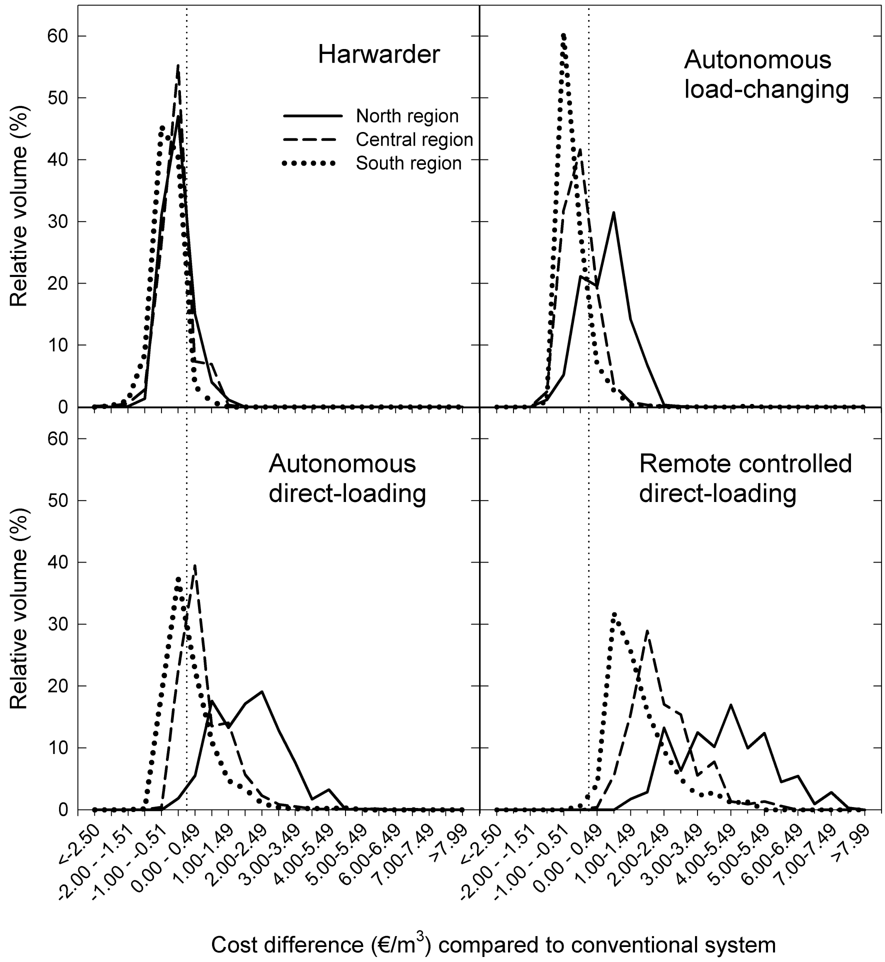


Figure 8: Relative distribution of harvest volume over grouped median differences in costs between a conventional system and four other systems for three different regions in Sweden. Negative numbers indicate that the conventional system is less profitable. Note that only every second interval value is shown on the x-axis.

3.3 Fuel consumption

The harwarder had the lowest fuel consumption of all systems; compared with the conventional system it required 18%, 20%, and 23% less fuel in the north, central and south regions, respectively. In contrast, the ALC system consumed more fuel (14-18%) than the conventional system due to the waiting times. Although the IFL systems have reduced fuel consumption for the forwarders' productive work of being loaded, the increased time for forwarder loading (i.e. harvesting) in combination with the large amount of waiting time resulted in more fuel consumption in the north region (+6%) than the conventional system. However, the decrease in both harvesting time and waiting time made the systems less fuel consuming in both the central (-2%) and south regions (-7%).

3.4 Sensitivity analysis

3.4.1 Harwarder costs

The harwarder was the most profitable system, but if the fixed costs of the machine were 30% higher than those of a conventional harvester (rather than 17%), it would be less profitable than a conventional system in the north and central regions (+0.07 and +0.01 €/m^3 respectively) but still more profitable in the south (-0.29 €/m^3). At 44% higher fixed costs, the harwarder becomes as profitable as the conventional system in the south.

3.4.2 ALC costs and number of forwarders

In the basic scenario with one forwarder, the ALC harwarder had almost no waiting time and the ALC system was more viable than the conventional system in all regions but the north. Thus, use of more forwarders would increase their waiting times without increasing productivity of the system. Using two ALC forwarders would increase costs in all three regions, by between 1.45 and 2.52 €/m^3 compared with the mean costs shown in Table 3.

To be more profitable in the north too, the ALC harwarder would have to have the same fixed costs as a conventional harvester (rather than 20% higher) and the ALC forwarder 6% lower fixed cost than a conventional forwarder (rather than 5% higher). If the ALC harwarder had 29% higher fixed fixed costs than a conventional harvester and the ALC forwarder 14% higher fixed costs than a conventional forwarder, the ALC system would be as equally profitable as a conventional system in the central region, and it would still be more profitable in the south (-0.22 €/m^3). In fact, in the south the ALC harwarder would have to have 39% higher fixed costs than a conventional harvester and the ALC forwarder 24% higher fixed costs than a conventional forwarder for the ALC system to be less viable than a conventional system (+0.01 €/m^3).

3.4.3 ADL costs and number of forwarders

The ADL system was the second least viable system, being less profitable than the conventional system in all three regions. Using only one forwarder would increase its mean cost in all three regions by between 0.44 and 3.01 €$/m^3$. If autonomous forwarders had 30% lower fixed costs than conventional forwarders (rather than 5% higher), the ADL system would be more profitable than a conventional system in the central and south regions (0.00 and -0.34 €$/m^3$ less expensive, respectively) but still less profitable in the north (1.18 €$/m^3$ more expensive). In the north, the ADL forwarders would have to have 75% lower fixed costs than a conventional forwarder to make the ADL system more viable than a conventional system (-0.02 €$/m^3$) .

3.4.4 RDL costs and number of forwarders

As can be seen in Figure 7, the IFL harvester had almost no waiting time in the simulations, while the IFL forwarders had to wait between 13% and 21% of the total time. Using more than two forwarders would thus only increase waiting times for the forwarders without increasing productivity for the harvester. Using a single forwarder instead of two reversed the roles, with almost no waiting time for the forwarder but 14%-20% waiting times for the harvester.

The RDL system was the least profitable of the five studied (Table 3). Using only one forwarder instead of two decreased the mean cost of the RDL system in the north and central regions (-1.79 and -0.19 €$/m^3$, respectively) but increased it slightly in the south (+0.04 €$/m^3$). Nevertheless, it was still the least profitable system of the five analyzed.

When the two RDL forwarders were assumed to have the same fixed cost as a conventional forwarder per hour (rather than 17% higher), the system still did not become more profitable than a conventional system in any of the three regions even if the RDL harvester had no fixed costs at all. Compared with the conventional system's mean costs, the RDL system had between 0.40 and 2.37 €$/m^3$ higher cost (cf. Table 3).

If one RDL forwarder was used with the same fixed cost as a conventional forwarder, the fixed cost of the RDL harvester would have to be 92% lower than that of a conventional harvester to be more profitable than a conventional system in the south (-0.01 €$/m^3$). However, it would still be less profitable in the north and central regions (+0.28 and +0.22 €$/m^3$, respectively).

Table 5: Average total costs (€/m^3) if the harwarders' and autonomous forwarders' work required 10% longer times. The numbers in parentheses are the differences in costs compared with the base scenario (cf. Table 3).

	Region		
System	North	Central	South
Harwarder	10.95 (0.99)	9.27 (0.85)	8.07 (0.71)
ALC	10.89 (0.04)	8.62 (0.15)	7.64 (0.15)
ADL	12.42 (0.03)	9.50 (0.08)	8.28 (0.11)

3.4.5 Time and fuel consumption

The assumption that it would take 10% longer for autonomous forwarders to transport and unload does not affect the order of viability of the systems. With a 10% increase in time consumption for the harwarder system (for both harvesting and forwarding), it becomes less profitable than a conventional system in all three regions (as shown by the data in Tables 3 and 5).

If the unmanned machines, i.e. autonomous forwarders and RDL harvesters, could switch off their engines while idling (and thus have zero fuel costs in this state), the costs would not be substantially affected. The effect would be largest for ADL systems, with cost reductions between 0.13 and 0.26 €/m^3, while the cost reductions for the other systems would be less than 0.10 €/m^3. This would not affect the order of viability of the systems. Similarly, assuming that their engines would be turned off does not change the order of the systems in terms of fuel consumption. The assumed engine turnoff improves the competitiveness for the IFL systems by a few percentage points, but they still consume more fuel in the north region (+1%) and less in the central (-5%) and south regions (-9%) than the conventional system. For the ALC system, the engine turn-off decreases fuel consumption but it would still consume 7-11% more fuel than the conventional system.

4 Discussion

When aiming to replace a machine system in order to reduce costs, a possible alternative system's competitiveness is dependent on its time consumption per produced unit and hourly costs relative to those of the system that it is intended to replace. Lower time consumption allows higher hourly costs (e.g. more expensive machines) and vice versa. Analyzing these relationships in forest harvest operations is generally straightforward, but with machines interacting to enable the direct loading of logs, the analysis becomes more demanding. These interactions can be addressed by the created simulator, enabling comparisons of systems including the dynamic and random characteristics lacking in previous analyses based on static modeling (Hallonborg, 2003; Bergkvist, 2008; Lindroos, 2012).

4.1 Harwarder

Among the five machine systems tested in simulations of operations in the three selected Swedish geographical regions, the harwarder was the most cost competitive and least fuel consuming system in all regions. The elimination of loading time and reduction of relocation costs are strong advantages, and thus the high potential of harwarders is in line with many previous studies based on both theoretical (e.g. Talbot et al., 2003; Väätäinen et al., 2006; Lindroos, 2012) and empirical data (Hallonborg & Nordén, 2000; Andersson & Eliasson, 2004; Bergkvist, 2007). However, this machine concept (now more than 50 years old) has had limited commercial success, despite repeated attempts to promote it. As pointed out by Lindroos (2012), the viability of this technical approach to integrate direct loading of logs is dependent on solving key technical limitations, and wider commercial success might follow the development of a combined "harvester head-grapple" and forwarder–harvester crane that does not compromise functions and can be sold at a reasonable price. The harwarder's potential is quite insensitive to stand characteristics, as indicated in Figure 8, and it can be considered a possible competitor to the conventional system in general. In contrast, the other tested systems have rather heterogeneous responses to stand characteristics and can therefore be considered to be possible competitors to the conventional systems only under very specific conditions. When operating in a variable environment, difficulties can be expected when attempting to integrate the work of machines that are influenced by different environmental variables. Hence, it is not surprising that limitations have also been previously found when attempting to integrate processing and transport (e.g. chipping directly into transportation vehicles (Asikainen, 1998; Talbot & Suadicani, 2005; Asikainen, 2010)). Thus, such difficulties are likely to be encountered when attempting to integrate work by directly cooperating machines, irrespective of harvesting method and assortment.

4.2 Load changing and direct loading of forwarders

In our analysis, the ALC system also shows high potential but cannot compete with current CTL systems in the north region because the forwarder waiting times are too long. The other two regions contain stands with larger trees (faster harvesting/loading) and similar forwarding distances, which just as for the IFL systems better fit the system constellations. The substantial potential of ALC found in our analysis is in contrast with the results of Hallonborg (2003), who found it to be the least competitive system of the five analyzed here when addressing delay-free work analytically. Although the system's high time expenditure was sufficiently compensated by lower hourly costs in the cost comparisons in our analysis, it made the system the most fuel consuming one. Hence, the potential cost reductions would be accompanied by increases in energy expenditure and emissions to the atmosphere. Thus, since it is one of the systems that requires fully autonomous forwarder work and thus much future research before implementation, further analysis of the system's potential compared with the conventional system and harwarder is warranted.

The two IFL systems, in which a harvester directly loads a forwarder, were both less profitable than all of the other systems. This shows that it would be difficult to make this concept profitable, since it induces a lot of waiting time for either the forwarder or the harvester, depending on the number of forwarders used. These results conform with previous findings by Lindroos (2012), who pointed out that the IFL direct loading methodology does not necessarily decrease productive work time consumption (in addition to creating waiting time) and that the larger number of machines involved results in higher relocation costs. Lindroos' (2012) conclusions were based on the assumption that the RDL system would be used, whereas we also tested the system under the assumption that a manned harvester with autonomous forwarders (ADL) would be used. This solution reduced costs, compared with those of the RDL system, by removing one operator and by letting unmanned (and thus inexpensive) machines have most the waiting time, but the reductions were not sufficient enough to make the system competitive in comparison with the other systems. An interesting finding is that the RDL system would benefit from using just one forwarder instead of the two used in the experimental system Besten currently being tested in actual harvesting operations, at least in the north and central regions. In our simulations, less than 1% of the volume was harvested more inexpensively with the RDL system than with the conventional one, confirming Lindroos' (2012) prediction that a dynamic and stochastic analysis would prove the RDL system to be even less viable than in his static modeling based on data for the same stands and under similar assumptions. However, the differences are only minor, since Lindroos' (2012) RDL system was more viable than a conventional system for less than 2% of the volume. This coincides with previous findings that static modeling might only slightly underestimate the influence of machine interactions (Asikainen, 2010) when applying appropriate model assumptions. However, it is important to note that the underestimation is most severe when the interdependent machines are harmonized, since there is no waiting time to buffer for the dynamic elements (e.g. delays).

The results from both Lindroos' (2012) study and the current investigation are rather inconsistent with the estimation by Bergkvist (2008) that the RDL system should be viable for a considerable proportion (approximately 33%) of the final felling volume in Sweden. However, Bergkvist's (2008) estimation was based on rough estimates of mean stand conditions in Sweden with no consideration of delays in rather simplified static modeling. The estimated reductions in the IFL systems' fuel consumption compared with a conventional system obtained in our study were also considerably smaller than the RDL system's reduction estimated by Bergkvist (2008), indicating that a substantial proportion of the possible fuel savings that can be obtained from direct loading is lost due to the large amounts of waiting times. In fact, in the north region, the IFL systems consumed more fuel than the conventional system.

4.3 Robustness of the results

In the analyses, we assumed that the systems are equally fast when conducting the same work, which enabled us to address the theoretical maximal potentials of machine concepts without influence of variation in their technical maturity. The strengths and weaknesses of this methodology are further discussed in Lindroos (2012). As for all analyses, the results of the theoretical analysis presented here depend on the input data used and the constructed models in the simulator. However, our thorough sensitivity analysis indicated that the results were not strongly affected by different assumptions. The sensitivity analysis shows that the results are quite stable under the tested variations in assumptions, in terms of the relative competitiveness of the examined systems. The harwarder and ALC systems would have to employ considerably more expensive machines ($\geq$24%) or be substantially less productive to be less profitable than the conventional systems. Correspondingly, the RDL and the ADL systems would have to employ considerably less expensive machines to be more profitable than the conventional system.

One of the limitations of the study is the limited knowledge of delays in harvest operations. We based our simulation of delays on data from a meta-analysis of delays in harvester operations presented by Spinelli & Visser (2008). Information on delays with similar level of detail is lacking for forwarders, harwarders, and (inevitably) the futuristic machines. Therefore, it was assumed that patterns of delays are similar between different machine types but with differences in duration. However, the distribution of delays probably differs somewhat among machine types. On the other hand, due to the abundance of data (corresponding to several years of harvesting operations), this will have a minor effect on the results. Another limitation in the simulator design is that the forwarder always returns to the harvester even after the last load has been delivered. On the other hand, the harvester does not incur any costs for driving into and out of the forest. This could have some effect for operations in small stands with few loads but not on the final outcome.

In the analysis we have chosen to exclude the number of assortments harvested, since integrated loading requires that all assortments are loaded together. However, the conventional system can choose to take fewer number of assortments per load and aspire to save time due to less sorting work when unloading, on the expense of increased loading time (i.e. decreased log density along striproads). Hence, with many assortments in a final felling with high stand density, it is likely that the integrated loading systems will have less competitiveness than found in this study. However, the inclusion of assortments is unlikely to affect the order of integrated loading systems in terms of their potentials compared with a conventional system.

In this theoretical analysis, some details of the systems that would be encountered if implemented in reality have been excluded. For instance, startup and take-down would be costly for ALC and IFL if the machines had to be relocated and thus were starting/stopping, simultaneously. When using two forwarders in the IFL systems, one of the forwarders would have to wait for the first one to be loaded during the first time before it could start working. Hence, the system would consume more time when operating in small stands with few loads. Accounting for this by differentiating starting/stopping times for the forwarders would be problematic because of the large variations in forwarding distances within and between stands. Another drawback for the IFL systems concerns the work conditions of the operator(s). For instance, operators would probably not appreciate standing idle for long periods due to waiting time, especially when trying to balance the system under unfavorable conditions. The systems with autonomous forwarders, on the other hand, have higher potential, but there is a large step from theory to implementation. Although some promising advances have been made towards autonomizing forwarders, it has been estimated that the forestry industry will not see a machine that can successfully navigate and unload logs autonomously for at least 10-20 years (Hellström et al., 2009). Most likely, a first step will be to produce unmanned machines that can operate under some kind of human supervision. Moreover, as for most technical innovations, the initial purchase cost of such machines is likely to be high. Hence, during at least an introductory phase, the costs of autonomous machines are likely to be higher than our analysis suggests.

4.4 Fully autonomous forwarders

As two of the systems analyzed include autonomous forwarders, it is also of interest to consider the effects of using such an unmanned machine in the conventional system (i.e. without direct loading of logs). This could easily be addressed in this analysis by changing the hourly cost of the conventional forwarder (while assuming the same production rate), which results in approximately 1.7 €/m^3 lower costs than those of the conventional system for operations in all three regions. Hence, it would be even more profitable than a harwarder. However, more detailed analysis of this kind of system, which is beyond the scope of this paper, is required to obtain more robust results.

4.5 Conclusions

The main conclusion of this work is that harwarders have considerable theoretical potential to compete with the conventional system under most of the tested stand conditions, and quite minor technical innovations appear to be required to realize the system's potential. The other tested systems had, if any, potentials under very specific stand conditions, making them viable only as complements to the conventional system. For the ADL system, the situation is the opposite of that of the harwarder, having low potential due to a combination of limitations in its work organization and the technical challenges associated with autonomizing machines. A prototype RDL system (Besten) is already available, but it suffers from the limitations in its work organization and high system costs. The ALC system represents a compromise between the harwarder and IFL systems, in terms of being less limited by the work organization but requiring autonomous forwarders to be viable.

This study indicates that when aspiring to implement direct loading in CTL, future focus should be on developing harwarders, and if or when autonomous forwarders become available, they should be used either in the conventional system or with a load-changing harwarder but not with a direct-loading harvester.

As possible integrated loading systems emerge, future analysis could focus on mimicking the specific characteristics and limitations of the suggested innovations. Hence, expected potentials when they are introduced could be estimated instead of the theoretical potentials addressed here.

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A Algorithms

Algorithm 1 Calculating total work time of interdependent machine systems.

Let S^f and S_p^f be the current and previous state of the forwarder, respectively, S^h the harvester's current state, *nLoads* the number of loads hauled so far, and *limit* the number of loads required for each stand. $V(j)$ is the initial stand volume for stand j and V_F the maximum load volume of the forwarder. Refer to Figures 2 and 3.

for each stand j **do**
  $nLoads, t_w^f, t_{ld}^f, t_{tu}^f, t_{sw}^f, t_{dly}^f, t_{dlw}^f := 0$ { t^f:s are, respectively, time spent in forwarding states *Waiting*, *Being loaded*, *Transport & Unloading*, *Switching*, *Delay*, and *Delay-wait* }
  $t_w^h, t_{sw}^h, t_{ld}^h\, t_{dly}^h, t_{dlw}^h := 0$ { t^h:s are, respectively, time spent in harvesting states *Waiting*, *Switching*, *Harvesting & Loading*, *Delay*, and *Delay-wait* }
  $limit = \left\lceil \frac{V(j)}{V_F} \right\rceil$
  $S^f, S_p^f, S^h := Waiting$
  if load-changing system **then**
    $S^h := Loading$
  end if
  while $nLoads < limit$ **do**
    Update states according to the state diagrams in Figures 2 and 3
    for each forwarder i **do**
      if $S^f(i) = Waiting$ and $S_p^f(i) = Unloading$ **then**
        $nLoads := nLoads + 1$ {we just unloaded one more load}
      end if
    end for
  end while
  {Total time consumption for forwarders t^f and harvester t^h:}
  if IFL system **then**
    $t_W^f(j) := t_{tu}^f + t_{dly}^f$ {total work time for forwarding}
    $t_I^f(j) := t_w^f + t_{ld}^f + t_{dlw}^f$ {total idle time for forwarding}
    $t_W^h(j) := t_{ld}^h + t_{dly}^h$ {total work time for harvesting}
    $t_I^h(j) := t_w^h + t_{dlw}^h$ {total idle time for harvesting}
  else {ALC system}
    $t_W^f(j) := t_{tu}^f + t_{sw}^f + t_{dly}^f$ {total work time for forwarding}
    $t_I^f(j) := t_w^f + t_{dlw}^f$ {total idle time for forwarding}
    $t_W^h(j) := t_{ld}^h + t_{sw}^f + t_{dly}^f$ {total work time for harvesting}
    $t_I^h(j) := t_w^h + t_{dlw}^f$ {total idle time for harvesting}
  end if
end for

Algorithm 2 Calculating total work time for conventional systems and harwarders.

calcDelay() is the simulated occurrence and length of a delay as described in Section 2.6. Given a current time t and a timestep Δt in the simulator:

Calculate delay-free work time for harvesting t^h_{ld} for all stands (Eq. 6)
Calculate delay-free work time for forwarding t^f_{fh} for all stands (Eqs. 1 & 2 for conventional system and harwarder, respectively)
$t := 0,\ t^h_{dly} := 0$
while $t \leq t^h_{ld}$ **do**
    $t^h_{dly} := t^h_{dly} + calcDelay()$ {delay time for harvesting }
    $t := t + \Delta t$
end while
$t := 0,\ t^f_{dly} := 0$
while $t \leq t^f$ **do**
    $t^f_{dly} := t^f_{dly} + calcDelay()$ {delay time for forwarding}
    $t := t + \Delta t$
end while
$t^f_W = t^f_{fh} + t^f_{dly}$ {total work time for forwarding}
$t^h_W = t^h_{ld} + t^h_{dly}$ {total work time for harvesting}
$t^h_I = 0,\ t^f_I = 0$ {no waiting time for these systems}