SILVA FENNICA

Silva Fennica 45(3) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

The Cost-Efficiency of Seedling Packaging Specifically Designed for Tree Planting Machines

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Ersson, B.T., Bergsten, U. & Lindroos, O. 2011. The cost-efficiency of seedling packaging specifically designed for tree planting machines. Silva Fennica 45(3): 379–394.

Today's crane-mounted planting heads plant seedlings with biologically similar or better results than operational manual planting. However, the total cost of mechanized tree planting in southern Sweden must decrease at least 25% to compete economically with manual planting. Although seedlings packed in machine-specific packaging increase the productivity of planting machines by reducing seedling reloading time, they also increase logistics and investment costs. In this study, we analyzed the total cost of outplanting seedlings with an excavator-mounted Bracke Planter and seedlings packed according to four different concepts: cultivation trays, cardboard boxes, band-mounted seedlings in cardboard boxes and linked pots in container modules. The total cost per planted seedling was calculated for each packaging system as the sum of all costs from nursery to the recovery of empty packaging. The results showed that today's system of transporting seedlings in cultivation trays is the most cost-efficient of the four alternatives. Machine-specific seedling packaging was 16–23% costlier per planted seedling than cultivation trays when trucking distances were 100 km. Sensitivity analyses indicated that machine-specific seedling packaging increased in cost-efficiency relative to cultivation trays primarily when more planting machines were contracted, but also as planting machine fixed costs and productivity increased. Moreover, the relative cost-efficiency of band-mounted seedlings, but not seedlings in container modules, increased with increasing trucking distance. Thus, we show that investments in machine-specific seedling packaging for today's planting machines are justified only when the fixed costs, productivity and number of contracted planting machines increase substantially.

Keywords mechanized planting, containerized seedlings, seedling transport, logistics, cost analysis, seedling feed, nursery technology
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Received 4 January 2011 **Revised** 9 May 2011 **Accepted** 1 July 2011
Available at http://www.metla.fi/silvafennica/full/sf45/sf453379.pdf

1 Introduction

In the Nordic countries, stand regeneration after clearcutting is predominantly performed using manual tree planting. As an alternative to manual tree planting, mechanized tree planting has been revived in southern Sweden in the last five years. In contrast to the high investment, highly productive, continuously operating planting machines of the 1980s–90s (Hallonborg 1997), today's machines use low investment, intermittently advancing, crane-mounted planting heads like the Bracke Planter, EcoPlanter (Hallonborg et al. 1997, Saarinen 2006) and M-Planter (Rantala et al. 2009). Currently, however, mechanized planting in southern Sweden is only performed using the Bracke Planter and at a higher cost than manual planting.

One of the key reasons why crane-mounted planting machines are still not economically competitive with manual planting in Sweden is the lack of automated seedling handling and feeding systems. The planting heads must instead be reloaded manually, and this task can occupy from 15% (Rantala et al. 2009) to more than 30% of the machine's effective working time (Halonen 2002). Manual reloading entails that the planting machine's capital costs and driver's wage are still present while the machine's production is zero. Moreover, as machine productivity increases, relatively more of the effective working time is spent manually reloading seedlings (Halonen 2002). There is, therefore, a need to automate the feeding and handling of seedlings if crane-mounted planting machines are to become cost competitive compared to manual planting (Normark and Norr 2002, Sönsteby and Kohmann 2003).

Historically, there have been few attempts to automate the seedling feeding and handling systems on tree planting machines, none of which are in operation today. For example, the Serlachius planting machine, developed in the late 1970s, used a chain-driven conveyor to feed seedlings automatically to the planting arms from either Hiko growth containers or special peat pots that were sawn apart (Stjernberg 1985, Hallonborg 1997). The latter were part of an integrated cultivation system including specially designed pallets on which 384 seedlings per pallet could be cultivated, transported and used as the basic unit for the automatic feeding system (Kohonen 1981).

In the mid 1990s, an attempt to automate the seedling feeding system on the Silva Nova planting machine was also made (Hallonborg 1997). This feeding system was called the Pot Link System (PLS) and used plastic pots linked together to form belts. The PLS-belts were loaded at the landing by a portable loading robot using standard seedlings delivered from the nursery in their growth containers, and then automatically shunted into a large container holding approximately 7000 seedlings. Finally, the large container was placed on the Silva Nova using the planting machine's crane.

A few years later, a concept called EcoBandPak (EBP) was developed for the EcoPlanter (Normark and Norr 2002). The EBP was based on the band-mounted seedling concept in which seedlings were mounted one after another between two strips of plasticized paper. Thereafter, the coils of band-mounted seedlings were packaged into cardboard boxes, transported to the planting machine and then manually inserted into a prototype automatic feeding system.

The efficiency of automated handling and feeding systems is also dependent on how seedlings are packaged and transported. For example, the planting machine loses productivity if the operator must unpack seedlings from cardboard boxes or move them from nursery trays and then load them into an automatic seedling feeding system (Sönsteby and Kohmann 2003). Considering that today's containerized seedlings in southern Sweden are delivered to the planting machine either in nursery trays or cardboard boxes designed for manual planting, machine-specific seedling packaging solutions are necessary if automatic seedling feeding systems on planting machines are to become cost-efficient.

However, machine-specific packaging solutions warrant extra labour, packaging, and investment costs at the nursery and extra investment costs for the planting machine (Normark and Norr 2002). Seedling transport costs and work methods might also be affected. In one previous study, Lawyer and Fridley (1979) modelled how seedling transport affected the total cost of mechanical planting systems under North American conditions. In their model, Lawyer and Fridley used Eq. 1 to show that the total cost per hectare of mechanized tree planting systems can be divided into three parts as follows:

$$C_{Total} = C_S + C_T + C_F \quad (1)$$

where C_S = nursery costs; C_T = cost of transporting seedlings from the nursery to the planting site; C_F = cost of planting machine.

Using Eq. 1 as a starting point, this present study investigates if specifically designed seedling packaging systems which raise C_T can lower C_F enough to reduce the total cost of mechanized planting (C_{Total}). Accordingly, the aims of this article are twofold: 1) to describe two seedling packaging concepts specifically designed for planting machines; and 2) to compare the total cost of these two packaging concepts with today's two most common containerized seedling packaging systems used during manual planting in southern Sweden.

2 Materials and Methods

This comparative cost analysis is based on data (costs and time requirements) collected from nurseries, contractors and relevant companies during winter 2010. To correct for inflation biases, all costs were adjusted to December 2009 values according to Statistics Sweden's (SCB) Consumer Price Index. The average exchange rate for Swedish kronor (SEK) to Euros (€) from January 2009 to December 2010 was SEK 10.08/€ (Sveriges Riksbank 2010).

Most time consumption data were acquired by interviewing machine operators and nursery personnel; however, time studies of some crucial tasks in the transportation chain were used to complement the interview-data. When calculating depreciation costs, the reducing balance method was used (Rantala et al. 2009).

2.1 System Delimitations and Models

The four seedling packaging systems (s1–s4) used in this cost analysis are described below. Seedlings in Hiko cultivation trays are the starting point for all systems, but with additional seedling packaging in s2–s4.

Existing systems developed for manual planting:

- s1) *Hiko trays*: cultivation trays in which seedlings are also transported to the planting machine. From the nursery, trays are handled individually by hand and distributed to the contractor's depot by light (3 ton) courier trucks. Trays are returned to the nursery for reuse.
- s2) *Cardboard boxes*: single-use boxes packed by a packing line at the nursery. Boxes are stacked onto Euro pallets and distributed to the contractor's depot as standard shipping units by general groupage delivery trucks (e.g. DHL or Schenker trucks). From the depot, individual boxes are handled manually and transported by the contractor. Boxes are recycled after use.

Systems adapted for mechanized planting:

- s3) *Band-mounted seedlings*: seedlings are lifted from the cultivation trays, mounted between strips of paper, rolled into a vertically-standing coil, and then packed into cardboard boxes at the nursery. Handling, transportation, and recycling of boxes is otherwise equal to s2.
- s4) *Container modules:* seedlings are transplanted from cultivation trays into PLS pots, 1500–2100 of which are then packed in a container the size of a Euro pallet. Containers are distributed to the contractor's depot by general groupage delivery trucks. From the depot, the containers are handled individually by the contractor using a small truck-mounted crane and a hydraulic lift on the planting machine. The containers are returned to the nursery for reuse.

The packaging systems were expressed as models based on the activities of the generic transportation chain shown in Fig. 1. The chain starts at the nursery with the seedlings still being in their cultivation trays while aggregated on large frames after having been sorted and sprayed with insecticides. The chain ends after outplanting when the empty seedling packaging has either been returned to the nursery for reuse or recycled.

The cost analysis was based on Eq. 1 from Lawyer and Fridley (1979) but modified so that C_S was defined as all costs of cultivating seedlings up until packaging them for transport. This

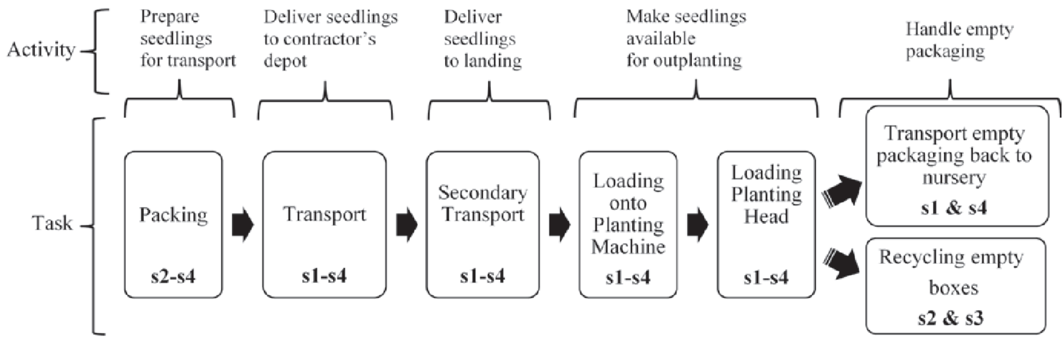

Fig. 1. Schematic activity chart of the seedling packaging systems.

kept C_S constant and was therefore not included in this study's model. Thus, the total cost per planted seedling of mechanized planting (C_{Total}, expressed as SEK per planted seedling (SEK/pl)) with s1 was calculated using Eq. 2, while s2 and s3 were calculated using Eq. 3, and s4 with Eq. 4.

$$C^1_{Total} = C^1_{Pack} + C^1_{T.Load} + C^1_{Transport} + C^1_{T.Unload} + C^1_{Water} + C^1_{V.Load} + C^1_{V.Unload} + C^1_{PM.Load} + C^1_{Outplant} + C^1_{Returns} \quad (2)$$

$$C^{2,3}_{Total} = C^{2,3}_{Pack} + C^{2,3}_{Total.Trans} + C^{2,3}_{V.Load} + C^{2,3}_{V.Unload} + C^{2,3}_{PM.Load} + C^{2,3}_{Outplant} + C^{2,3}_{Recycling} \quad (3)$$

$$C^4_{Total} = C^4_{Pack} + C^4_{Total.Trans} + C^4_{Water} + C^4_{V.Load} + C^4_{V.Unload} + C^4_{PM.Load} + C^4_{Outplant} + C^4_{Returns} \quad (4)$$

where superscript digit indicates system, and

- C_{Pack} = cost of packaging materials and extra activities at nursery including freezer storage,
- $C^1_{T.Load}$ = cost of loading seedlings onto courier truck,
- $C^1_{Transport}$ = cost of road transport with courier truck,
- $C^1_{T.Unload}$ = cost of unloading seedlings from courier truck,
- C_{Water} = cost of watering seedlings at contractor's depot,
- $C_{V.Load}$ = cost of loading seedlings onto planting machine operator's vehicle at depot,
- $C_{V.Unload}$ = cost of unloading seedlings at roadside,
- $C_{PM.Load}$ = cost of loading seedlings onto planting machine,
- $C_{Outplant}$ = total cost of outplanting seedlings including reloading planting head,
- $C_{Returns}$ = cost of returning multi-use packaging to nursery, and
- $C_{Total.Trans}$ = total cost of transporting seedlings with groupage delivery trucks including loading and unloading,
- $C_{Recycling}$ = cost of recycling single-use packaging (cardboard boxes).

Unless otherwise stated, all activity costs were expressed in SEK per seedling (SEK/pl) and calculated according to Eq. 5 where c is the hourly cost for activity i and t is the time consumed for the performed work (h/pl).

$$C_i = c_i \times t_i \quad (5)$$

2.2 Assumptions and Inputs of the Basic Scenario

2.2.1 Nursery Investments and Packaging

The seedlings in the analysis were 1.5 year old *Picea abies* (L.) Karst grown in copper-painted Hiko v93 trays for circa 20 months at a mid-sized nursery (annual production of ten million seedlings) in southern Sweden. These seedlings were assumed to be sorted into a standard height class of 20–30 cm stem length and sprayed with insecticide against *Hylobius abietis* (L.) while in

Hiko trays three days before being packed and shipped. s1 and s4 assumed hot-lifted seedlings which require daily watering while s2 and s3 assumed frozen-stored seedlings which do not require watering the initial three days after thawing. The outplanting window, altogether 190 days, was assumed to be April 1 to November 15 but with no planting during July.

The costs of the four systems' packaging materials are shown in Table 1. The cost of s1 reflected the extra damage and wear inflicted on the Hiko cultivation trays by using the trays as seedling packaging. The interest rate was 10% for all investments by the nursery company.

Besides the material costs, C_{Pack} included the extra costs of all machinery and nursery activities needed to package the seedlings. These extra costs were absent from s1. For s2, these extra costs included the use of a small forwarder to shuttle multiple frames of seedlings from the pesticide quarantine/spraying area to a packing line; the investment and operative costs of a fully automatic packing line (including box erector, packing machine, palletizer, and stretch wrap machine) housed within an insulated production hall; and the use of a small front-end loader to move loaded pallets to a covered storage area. s2 was assumed to pack the nursery's entire yearly production due to cardboard boxes also being used for manual tree planting.

For s3, the extra costs included the use of a small front-end loader rather than a forwarder; the investment and operative costs of a manually operated band-mounting line (in which seedlings were manually band-mounted and boxes were manually erected, packed, sealed, and stacked); an automatic stretch wrap machine (all machines housed within a insulated production hall); and the use of a small front-end loader to move loaded pallets to a covered storage area. However, when the yearly number of seedlings packed in s3 surpassed 1.2 million, it was assumed that s3 entailed further investments in an automatic box erector, one additional band-mounting station and a plant-gripping robot (for automatic band-mounting of seedlings).

For s4, the extra costs included the use of a small front-end loader to shuttle multiple frames of seedlings from the pesticide quarantine/spraying area to the packing line; the investment and operative costs of a transplanting machine (for moving seedlings from Hiko trays to PLS pots,

Table 1. Cost factors for packaging materials.

Cost factor	Unit	s1 Hiko trays	s2 Cardboard boxes	s3 Band-mounted	s4 Container Modules
Capacity per handling unit	pl [a)]	40	160	200	1770
Dimensions per handling unit	cm	22×35×40	40×60×28	40×60×55	80×120×165
Mass per loaded handling unit	kg	4.5	16	20 [b)]	290
Capacity per shipping unit	pl [a)]	40	2560	2400	1770
Dimensions per shipping unit	cm	22×35×40	80×120×130	80×120×180	80×120×165 [c)]
Initial investment cost per shipping unit	SEK	17.50	242	400 [d)]	6465
Economic life	years	12	1	1	10
Mean number of shipments per unit lifetime	n	4	1	1	83
Total material cost per seedling	SEK/pl [a)]	0.12	0.10	0.17	0.07

a) = seedling
b) Maximum weight of regularly manually handled units according to workplace ordinances (Lumsden 2006)
c) According to space requirements for upright-standing seedlings in Österström et al. (1974)
d) Includes cost of paper band

and loading PLS trays into the containers) housed within an insulated production hall; and the use of a small front-end loader to move containers to and from the packing line.

Table 2 summarizes the cost data for the s2, s3, and s4 packaging costs. The depreciation period of the packing machines and production halls were 10 and 25 years respectively, the salvage values were 10% of the purchase price, and the yearly insurance costs were 0.15% of the assets' value. At the nursery, the hourly cost of labour including administration and taxes was 210 SEK, of a small front-end loader including driver was 270 SEK, and of a small forwarder including driver was 435 SEK. The total construction cost of a new production hall was 3500 SEK per m^2.

2.2.2 Seedling Transport

For s1, seedling trays were assumed to be manually loaded at the nursery by the courier truck's driver, two nursery workers, and one small front-end loader. The Hiko trays were placed lying sideways, facing each other, with the seedlings' stems intertwined so that the distance between the two trays equalled 1.5 times the average length of one seedling's stem (Österström et al. 1974). 500 cultivation trays was the space limit of the 3 ton courier truck, and this limit also meant that no seedlings were stored at the contractor's depot for longer than two weeks. At the contractor's depot, s1 entailed the manual unloading by both the courier truck's driver and the planting machine operator. Because the courier truck was assumed to be solely commissioned for seedling transport, transport costs for s1 also included the cost of the courier truck's return trip.

For the other systems, pallets and containers were loaded by the nursery's small front-end loader onto general groupage delivery trucks. For s2 and s3, unloading at the contractor's depot was handled by the delivery truck driver alone using the truck's tail lift and hand pallet truck. For s4, the delivery truck driver used a truck-mounted forklift during unloading. Because of their excess

Table 2. Cost factors for packaging machinery and extra nursery activities (based on expert assessments unless otherwise stated).

Cost factor	Unit	s2 Cardboard boxes	s3 Band-mounted manual pack line	s3 Band-mounted automatic pack line	s4 Container modules
Annual packaging production	pl/year	10 000 000	447 000	1 342 000	442 000
Purchase price of packing line machinery	SEK	6 400 000	323 000	2 213 000	800 000
Variable operating costs including maintenance and electricity	SEK/h	1353	335	396	326
Line productivity	pl/h	25 000 [a)]	1000 [b)]	5000	5000 [a)]
Labour	Fulltime operators	2	1.25	1	1
Small front-end loader occupancy rate	%	50	13	25	25
Small forwarder occupancy rate	%	100	-	-	-
Floor space required	m^2	400	150	150	150
Production hall cost including insurance and variable costs	SEK/h	413	155	212	701
Total packing cost per seedling	SEK/pl	0.18	0.59	0.38	0.49
Total freezer storage cost	SEK/pl	0.15	0.15	0.15	-

a) Based on empirical data from nurseries and a first-generation packaging machine
b) Based on empirical data from the prototype EcoBandPak packaging machine

height, shipping units in s3 and s4 were assumed to not be stacked double within the delivery truck as was done with s2's pallets. Because of desiccation concerns, frozen-stored seedlings could not be stored at the contractor's depot for longer than three days. This rule limited each truck load for s2 and s3 to three days worth of seedlings. Meanwhile, for s4, balancing container module investment costs against scale economies during primary transport meant that five shipping units per truck load was the most cost-efficient.

At the contractor's depot, s1 and s4 included the cost of daily watering of stored seedlings by the planting machine operator. For s2 and s3, this cost was instead replaced by the cost of freezer storage (Table 2).

Seedling transport from the contractor's depot to the landing was assumed to coincide with the planting machine operator's daily travels to and from the clearcut. Therefore, the cost of secondary transport referred only to the time needed for the planting machine operator to load and unload seedlings from his personal vehicle. Since this workplace time would otherwise be effective planting machine work time, all tasks performed by the planting machine operator were assumed equal to the planting machine's fixed costs including operator wage. For s4, however, secondary transport entailed an investment in a pickup truck equipped with a small manually-operated hydraulic crane allowing for loading and unloading containers. Nevertheless, the variable costs (e.g. fuel and maintenance costs) of s4's secondary transport were assumed to equal the other three systems' variable costs. The depreciation period of secondary transport vehicles was five years for all systems. The interest rate was 6% for all investments by the contractor. Table 3 summarizes the transport costs of the four packaging systems.

2.2.3 Outplanting

The cost analysis assumed seedling supply to two planting machines, and that these were both Bracke Planters mounted on a used 16 ton Kobelco 135BSR excavator; that the yearly use of the planting heads and the base machines was 1000 hours and 1100 hours respectively (where the base machine works 100 hours per year with other duties); and that 200 000 seedlings per year per machine were planted using a single-shift work system. However, when productivity rose, more seedlings were assumed to be planted per year instead of the machine only working fewer hours per year (and vice-versa for lower productivity). Moreover, in this analysis, the planting machine's annual relocation costs were considered constant regardless of machine productivity. Table 4 lists the main factors assumed when calculating the cost of the planting machine.

For s1, s2, and s3, seedlings were assumed to be loaded from the operator's vehicle directly into the planting machine's storage box. Thereafter, the planting head was reloaded using two handling units for s1 and one handling unit for s2 and s3. For s3, reloading included removing the seedling coil from the cardboard box and positioning the band into the feed rollers. For s4, containers were assumed to be offloaded from the pickup truck before being lifted onto the side of the base machine by a hydraulic lift. Thereafter, the planting head was reloaded with 200 seedlings using the PLS pots formed into two separate trays of 100 seedlings each. These trays were removed one at a time from the container and then hooked together on the planting head to form one long chain of pots. During planting, seedlings were automatically extracted from this chain and fed into the planting tube.

Empty packaging was assumed to be organized and placed back into the storage box during each reloading occasion. The time required for these tasks was included in the reloading cost. For s4, the empty PLS chain was assumed to be broken up into two separate trays by the operator before being placed back into the container.

As can be seen in Table 5, the packaging systems other than s1 also required modifications to the seedling storage box or planting head. These investments were assumed to have no salvage value and a depreciation period of 5 years.

2.2.4 Returns and Recycling

All empty packaging was returned to the contractor's depot after each shift. From there, empty Hiko trays in s1 were returned two times per year to the

Table 3. Cost factors for primary (from nursery to contractor's depot) and secondary (from depot to landing) seedling transport and watering.

Cost factor	Unit	s1 Hiko trays	s2 Cardboard boxes	s3 Band-mounted	s4 Container modules
Primary transport					
Shipping units per truck load	n	500 [a)]	2 [b)]	3 [b)]	5 [b)]
Seedlings per truck load	pl	20000	4640	5400	8830
Loading time per truck load	min	30	5	5	10
Loading cost of nursery resources	SEK/h	690	270	270	270
Loading cost of transport truck	SEK/h	295	- [c)]	- [c)]	- [c)]
Unloading time per truck load	min	45	15	15	20
Unloading cost	SEK/h	707	- [c)]	- [c)]	- [c)]
Trucking cost per load	SEK/km	10.87	6.87	9.88	12.45
Total primary transport cost	SEK/pl	0.16	0.16	0.20	0.17
Secondary transport					
Handling units per load	n	40	10	9	1
Loading time per load	min	10	5	5	5
Unloading time per load	min	- [d)]	- [d)]	- [d)]	5
Purchase price of secondary transport vehicle	SEK	100000	100000	100000	291000
Loading and unloading cost	SEK/h	412	414	426	482
Total secondary transport costs	SEK/pl	0.04	0.02	0.02	0.04
Seedling watering					
Watering time	min /1000 pl	1	-	-	2
Watering cost	SEK/h	412	-	-	482

[a)] Using a light courier truck
[b)] Using general groupage delivery trucks
-[c)] Loading and unloading costs of the groupage delivery truck is included within the total primary transport cost
-[d)] Unloading trays and boxes during secondary transport is assumed to coincide directly with loading seedlings into the planting machine's storage box

nursery by the returning courier truck. Unloading empty Hiko trays at the nursery assumed the help of one nursery worker and a small front-end loader. For s2 and s3, flattened boxes were stacked and tied onto empty Euro pallets that were picked up once a year by a recycling company. For s4, empty containers were transported back to the nursery by the general groupage delivery trucks in conjunction with each delivery of loaded containers to the contractor's depot. Unloading empty containers at the nursery assumed the help of a small front-end loader.

For s4, containers were rinsed out by a nursery worker using a water hose after each delivery. This task was assumed to take 25 minutes. Moreover, the PLS pots were washed once a year at the end of the season in the nursery's standard tray washing machine to avoid peat residue build up. This washing task was assumed to cost 0.05 SEK/pl plus require an additional 30 minutes of labour per container module. For s1, however, the cost of washing Hiko trays was not included because trays were washed before being used for cultivation regardless of the tray having left the nursery

Table 4. Baseline cost factors for the Bracke planting head and base machine.

Factor	Unit	Value
Productivity per productive hour [a)]	pl/E_{15}h	200 [b)]
Fixed costs	SEK/h	412
Full labour costs including operator travel costs	SEK/h	290
Capital costs including insurance and administration	SEK/h	122
Variable costs	SEK/h	138
Maintenance costs	SEK/h	41
Fuel and oil costs	SEK/h	97

[a)] Including delays shorter than 15 minutes
[b)] Based on contractor's mean productivity in 2009

of not. In Table 6, handling time per shift includes all necessary tasks when handling empty packaging from the planting machine to the depot.

2.3 Sensitivity Analysis

The basic scenario assumed used base machines, relatively short primary transport distances, relatively high interest rates and few contracted planting machines (Table 7). Therefore, the sensitivity analysis focused mainly on investigating the impact of higher fixed costs (e.g. through new base machines), longer primary transport distances, lower interest rates and more contracted planting machines on the cost analysis. Table 7 gives the sensitivity analysis' factor variation range. Mean planting time excluding seedling handling is a measure of the planting machine's overall productivity where –40% reaches the theoretical limit of the Bracke Planter.

Planting machine-specific seedling packaging is also relevant for the M-Planter, a two-headed, crane-mounted planting head. According to Rantala et al. (2009), this type of planting machine increases planting productivity per productive hour (E_{15}, delays shorter than 15 minutes included) by 36% while only increasing total costs by 4.1% compared to the Bracke Planter. Therefore, a supplemental analysis was done using the M-Planter instead of the Bracke planting machine in which reloading the M-Planter planting head for s1, s2, s3 and s4 was assumed to take 366, 492, 420 and 460 s respectively.

Table 5. Cost factors for storing seedlings on planting machine and reloading planting head.

Cost factor	Unit	s1 Hiko trays	s2 Cardboard boxes	s3 Band-mounted	s4 Container modules
Planting machine investments					
Modified storage box	SEK	-	10 000	10 000	-
Hydraulic lift	SEK	-	-	-	25 000
Modified planting head	SEK	-	-	47 770	87 380
New fixed costs after investments	SEK/h	412	414	426	482
Seedling handling					
Storage box loading time per shift	min	10	8	8	10
Time per planting head reload	s	223	279	240	280
Seedlings per reload	pl	72	72	200	200
Total reloading time per shift	s	4960	5944	2147	2474
Total cost of handling seedlings on planting machine	SEK/pl	0.40	0.48	0.17	0.23

Table 6. Cost factors for handling empty seedling packaging.

Cost factor	Unit	s1 Hiko trays	s2 Cardboard boxes	s3 Band-mounted	s4 Container modules
Contractor costs					
Handling time per shift	min	15	20	20	20
Total contractor cost for handling empty packaging	SEK/pl	0.06	0.09	0.08	0.09
Transport from depot to nursery					
Trips per year	n	2	-	-	25
Loading time at depot	min	90	-	-	20
Loading cost at depot	SEK/h	295	-	-	-[a)]
Unloading time at nursery	min	60	-	-	20
Unloading cost at nursery	SEK/h	774	-	-	270
Total transport costs for returns	SEK/pl	0.02	-	-	0.17
Container washing and servicing cost	SEK/pl	-	-	-	0.07
Recycling costs					
Total cardboard recycling cost	SEK/pl	-	0.01	0.01	-

-[a)] Loading cost of the groupage delivery truck is included within the total transport cost for returns

Table 7. Change in factors from the basic scenario.

Factor	Unit	Basic scenario	Sensitivity analysis	
			Minimum	Maximum
Planting head reloading time	s	223, 279, 240, 280[a)]	–50%	+30%
Planting machine fixed costs	SEK	412	–10%	+50%
Interest rate	%	6 and 10[b)]	3%	12%
Primary transport distance	km	100	0	600
Mean planting time excluding seedling handling	s/pl	14.9	–40%	+30%
Mechanical availability of planting head's seedling feeding system (MA)	%	100	80	100
Contracted planting machines	n	2	2	20

[a)] For s1, s2, s3, s4 respectively
[b)] For contractor and nursery respectively

Table 8. Cost factors for the M-Planter planting machine.

Factor	Unit	Value
Productivity per productive hour[a)]	pl/ E_{15}h	269
Fixed costs	SEK/h	433
Variable costs	SEK/h	140
Seedlings per reload		
s1 & s2	pl	162
s3 & s4		400

[a)] Including delays shorter than 15 minutes

3 Results

3.1 Basic Scenario and Sensitivity Analysis

Under the basic assumptions, s1 (the reference system) was the most cost-efficient packaging system; it was 12.0%, 16.4% and 23.1% less costly than s2, s3 and s4 respectively (Table 9). Both s3 and s4 were burdened by high nursery investment costs when only two planting machines were contracted. Consequently, the

Table 9. Aggregated costs in the basic scenario for the four seedling packaging systems.

Variable	s1 Hiko trays	s2 Cardboard boxes	s3 Band-mounted	s4 Container modules
C_{Pack}	0.12	0.43	0.91	0.56
$C^1_{T.Load}$	0.02	-	-	-
$C^1_{Transport}$	0.11	-	-	-
$C^1_{T.Unload}$	0.03	-	-	-
C_{Water}	0.05	-	-	0.03
$C_{V.Load}$	0.04	0.02	0.02	0.02
$C_{V.Unload}$	-	-	-	0.02
$C_{PM.Load}$	0.04	0.04	0.03	0.05
$C_{Outplant}$	2.75	2.88	2.52	2.81
$C_{Returns}$	0.08	-	-	0.33
$C_{Total.Trans}$	-	0.16	0.20	0.17
$C_{Recycling}$	-	0.10	0.09	-
C_{Total}	3.24	3.63	3.77	3.99

higher cost of s3 compared to s2 was mostly attributed to the low capacity utilization rate of the nursery's band-mounting machine. Similarly, s4 suffered from the low capacity utilization rate of the nursery's transplanting machine as well as high costs for handling, transporting and washing empty container modules.

As revealed by Fig. 2A, s1 was most cost-efficient even when planting head reload time was decreased by 50%. Halving the reload time increased total planting machine productivity the least for s3 (3.9%) because its baseline reloading time was relatively low to begin with. In contrast, s3 benefitted the most from increased planting machine fixed costs (Fig. 2B); increasing the fixed costs by 50% made s3 slightly more cost-efficient than s2 (0.6%). Primary transport distances longer than 100 km affected s1 most negatively (Fig. 2C) because the cost benefit of the other systems' groupage trucks were first realized over these longer distances. Shorter distances, on the other hand, affected s4 the most which reflected s4's added cost for a truck-mounted forklift. Likewise, s4 was the most sensitive to changes in the mean planting time excluding seedling handling (Fig. 2D). s3 was slightly more cost-efficient than s2 when mean planting time decreased by 30%, and s4 was more cost-efficient than both of them when the planting time was 40% lower. Neither the mechanical availability (MA) of the planting head's seedling feeding system (Fig. 2E) nor interest rate affected the relative cost-efficiency of the packaging systems to a large extent although s4 benefitted relatively most from a lower interest rate (Fig. 2F).

Although the values of C_{Total} all decreased, the packaging systems' relative order of cost-efficiency did not change when using the M-Planter compared to the Bracke Planter in the cost analysis. s1 was still ca 10% to 18% more cost-efficient than the other packaging systems. As can be seen in Fig. 3, varying the relative planting head reloading time had little effect on this result.

3.2 System Investment Costs

The total supplementary investment cost of s1, s2, s3 and s4 in the basic scenario was 0.12, 0.29, 0.82 and 0.88 SEK/pl respectively. s1 entailed no additional investments for the contractor, while 4%, 8% and 36% of the total investment cost was borne by the contractor for s2, s3 and s4 respectively. s4 resulted in the largest total investment cost per seedling except when there were precisely five contracted planting machines. Five planting machines lead to sufficient demand for band-mounted seedlings to warrant an investment in an automatic band-mounting line for s3. This additional investment momentarily raised s3's total investment cost per seedling above that of s4.

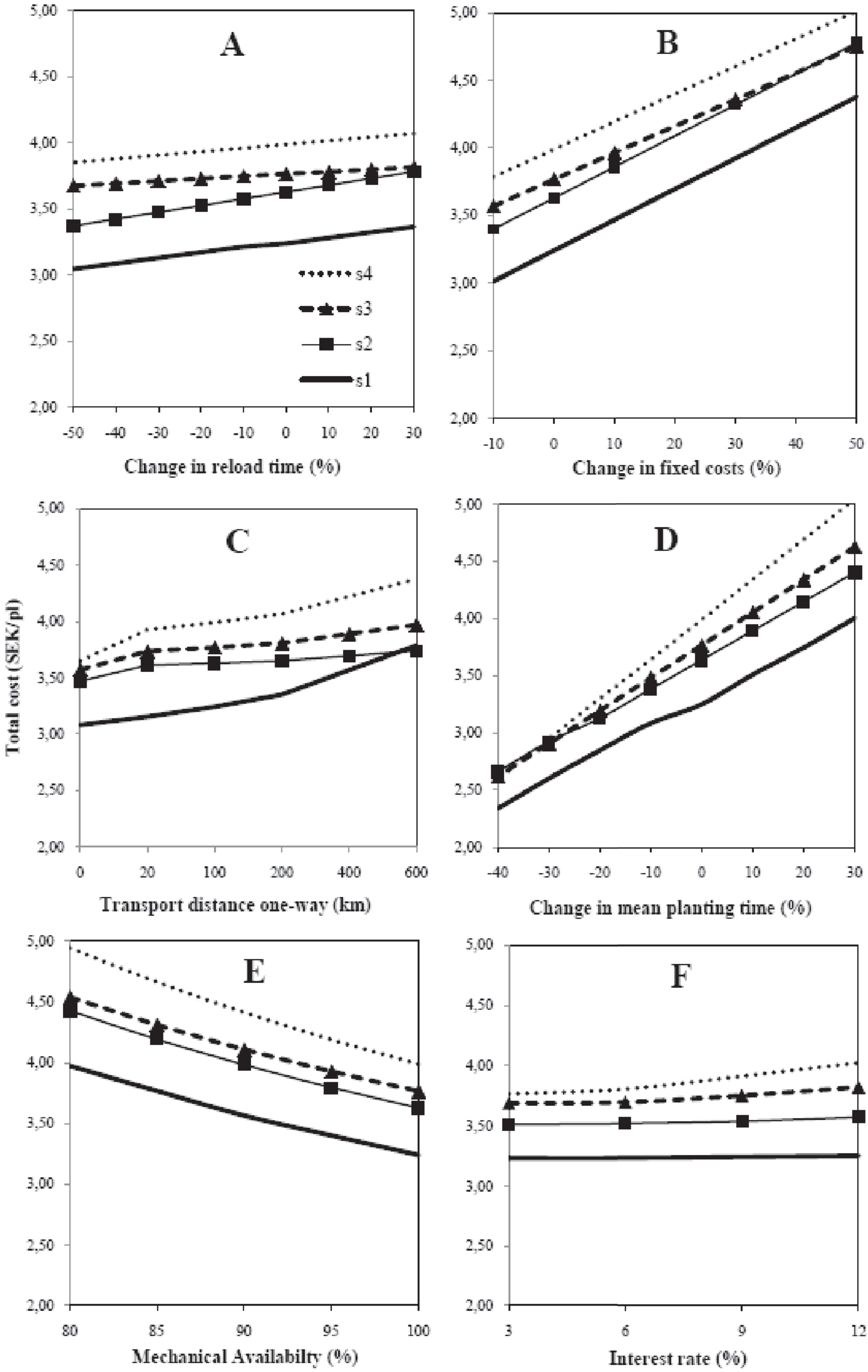

Fig. 2. The effect on the total cost of the four seedling packaging systems when varying (A–F): the relative planting head reload time; the planting machine's fixed costs; the primary transport distance; the mean planting time excluding seedling handling; the planting machine's mechanical availability; and the interest rate.

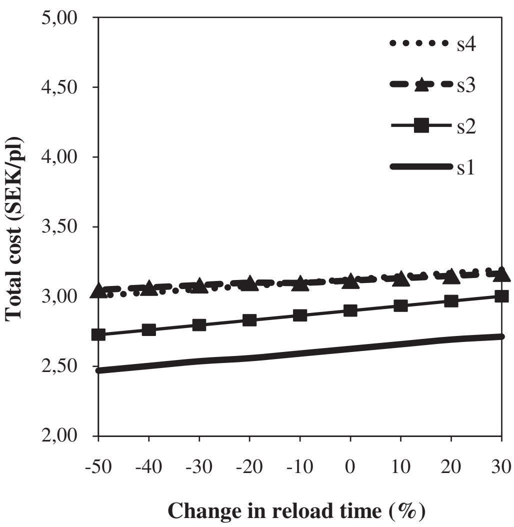

Fig. 3. Total cost of the four packaging systems with two M-Planter planting machines.

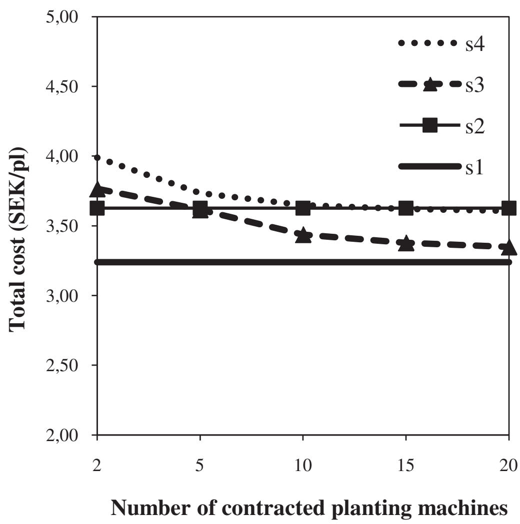

Fig. 4. Total cost of the four packaging systems when contracting more planting machines.

Because s1 and s2 entailed no planting machine-specific investments for the nursery, an increased number of contracted planting machines only reduced the total cost of s3 and s4 (Fig. 4). Therefore, s3 became more cost-efficient than s2 already with five contracted planting machines. With 20 planting machines, s3 became only 3.4% costlier than s1 while s4 became 0.6% more cost-efficient than s2. The nursery's supplementary investment cost for s3 and s4 fell from respectively 0.75 and 0.56 SEK/pl in the basic scenario to 0.34 and 0.18 SEK/pl with 20 planting machines.

3.3 Best and Worst Case Scenario

The primary transport's effect on the cost-efficiency of planting machine-specific packaging systems s3 and s4 in the best case (35% higher planting machine fixed costs, 20% lower mean planting time, 3% interest rate, and 20 contracted planting machines) and worst case scenario (same fixed costs, 10% higher mean planting time, 12% interest rate, and two contracted planting machines) is shown in Fig. 5. In these scenarios, the MA of the planting head's seedling feeding system for s1 and s2 was assumed to be 100% while it was lowered for both s3 and s4 to 97% and 85% in the best and worst case respectively.

The difference in cost-efficiency for s3 between the best case and worst case scenario at 100 km primary transport distance was 37%, whereas s1 and s2 only varied 3.2% and 2.4% respectively. Nonetheless, s3 was, despite being penalized with a lower MA compared to s1 and s2, only 0.9% more expensive than s1 in the best case scenario at 100 km primary transport distances, while more cost-efficient at primary transport distances of 200 km and longer (Fig. 5A).

4 Discussion

According to the proposed model, s1 was more cost-efficient than the other three packaging systems under southern Swedish conditions. However, decreasing the mean planting time increased s3 and s4's cost-efficiency, albeit to a small extent. As can be seen in Fig. 2D, the negative slope of s3 and s4 are steeper than s1 and s2. This difference in slope indicates that as planting machine productivity increases, the fixed costs of s3 and s4's additional investments decrease and these packaging systems become more cost-competitive relative to s1 and s2.

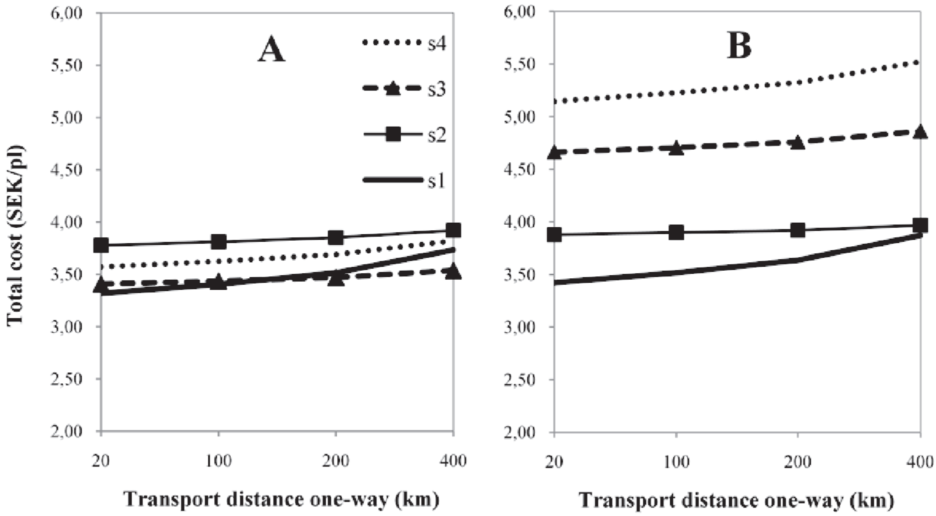

Fig. 5. Best (A) and worst (B) case scenario for the cost-efficiency of s3 and s4.

Similarly, Fig. 2B illustrates the connection between higher planting machine fixed costs and increased cost-efficiency of the planting machine-specific packaging systems. Because s1 and s2's slopes are steeper in this graph, their cost-efficiency decreases more rapidly than s3 and s4 when fixed costs increase. Thus, increasing planting machine fixed costs in the basic scenario by 35% to reflect the cost of a new Kobelco 135BSR excavator and Bracke Planter made s3 10.5% and 0.6% costlier than s1 and s2 respectively.

The model assumed that seedlings in s3 were band-mounted by custom-built nursery machines based on a prototype developed in the 1990s. There is probably improvement potential for such prototype machinery. If the productivity of the manual band-mounting station could double from 1000 to 2000 seedlings per hour, C_{Total} of s3 in the basic scenario would decrease by 0.15 SEK/pl, or 3.9 %. This adjustment in productivity would be enough to make s3 0.3% more cost-efficient than s2.

According to time studies, s3 and s4 could decrease planting head reloading time compared to s1 by 61% and 55% respectively. At the same time, s3 and s4 invariably make the planting head more complex by adding parts and creating series-parts reliability dilemmas (Bowen 1981). The basic scenario assumed no difference in the planting head's mechanical availability (MA) between the four packaging systems. This might be unrealistic, however, since the added complexity of s3 and s4 would probably lower the MA of planting heads using these packaging concepts (cf. Mellgren 1989). This added complexity is the reason why only s3 and s4's MA was reduced in the best and worst case scenarios.

The proposed model is a comprehensive theoretical cost-analysis without the effects of operators, site characteristics and different technical maturity levels which are otherwise present in empirical studies. The absence of such disturbances makes the model robust. However, since the input values are time-and-place specific, the total costs presented here might be less relevant than the systems' relative cost-efficiency and the factors which influence this correlation. Nonetheless, by changing the input values, this model should be widely applicable in the boreal context and not just limited to southern Sweden.

Because seedlings in s1 and s4 must be hot-lifted, they have actively growing shoots in May and June (Luoranen and Viiri 2005). Actively growing shoots are fragile and cannot be graded by an automatic grading line. Thus, s1 and s4 must in reality include the additional cost of manual grading at the nursery. For s2 and s3, however, seedlings can be graded and packed during winter months when the seedlings are dormant. Packaging in winter also has the advantages of handling seedlings when they are most stress resistant (Ritchie and Landis 2010) and spreading out nursery work over the whole year rather than concentrating all tasks to the growing season.

Moreover, dormant seedlings respire less and thus dry out more slowly than hot-lifted seedlings. This means that despite watering, seedlings in s1 and s4 are more likely to be planted in a less vital state compared to s2 and s3. Similarly, seedlings in s1 and s2 are exposed to detrimental abrasion after being loaded onto the carousel on today's Bracke planting head. This abrasion can cause the root plugs of seedlings grown in copper-painted cultivation trays to fall apart, thereby causing root damage and deformation during planting. Seedlings mounted in paper bands (s3) or carried in PLS pots (s4) would be protected from this abrasion. Even if these potential differences in seedling vitality were not accounted for in the proposed model, it is important to identify the packaging systems' nonmonetary benefits.

C_{Total} of s3 decreased relatively less than the other packaging systems when using the M-Planter compared to the Bracke Planter in the cost analysis (Fig. 3). s3 and s4's lack of cost-efficiency with the M-Planter can be attributed to this planting head's faster reload time. Rantala et al. (2009) measured 25.8% less time per seedling when reloading the M-Planter planting head with seedlings from cultivation trays compared to the Bracke Planter, and this lower time consumption limits s3 and s4's window of opportunity for productivity improvement.

Compared to the planting machines available today, even greater productivity improvements during outplanting could be expected if an intermittently working machine could use more planting heads, for instance four. This concept would entail a much more expensive and productive machine because it is probable that it would need two cranes. This base machine would have to be custom-built which would vastly increase the planting machine's fixed costs. These higher fixed costs would allow more economical leverage for planting machine-specific packaging concepts like s3 and s4.

Today, the Bracke planting machine plants seedlings with biologically similar (von Hofsten 1997, Saarinen 2006) or better (Ersson and Petersson 2009) results than operational manual planting. However, the total cost of today's Bracke Planter must decrease by at least 25% if it is to be economically competitive compared to manual planting in southern Sweden. As mentioned above, a two-craned planting machine using four planting heads and machine-specific seedling packaging would probably increase productivity enough to lower the total cost of mechanized planting by 25%. Nevertheless, such a machine would require some degree of semi-automation (shared control) to enable the operator to control two cranes simultaneously. Simulation studies are needed to verify the potential productivity increase of such a two-craned planting machine.

5 Conclusion

Under the circumstance of only contracting two relatively inexpensive and unproductive planting machines, no investment in machine-specific packaging systems is justified. However, an increase in the fixed cost, the productivity or especially the number of contracted planting machines increases the cost-efficiency of such packaging systems.

Acknowledgements

This cost analysis was funded by Södra Skog, Sveaskog and SLU's Faculty of Forest Sciences through the FIRST research school. We thank all contributors who provided data for this study, especially Södra Odlarna and Gransås Skogs & Lantbruks AB. We also thank Dag Fjeld for giving initial guidance, and Juho Rantala and one anonymous reviewer for their valuable comments on the manuscript.

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