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Simulating differences between forwarding short and normal-length timber

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Abstract: Normal log lengths in Norway are 3–6 m (NL), but occasionally there is a demand for short timber with a 2.5 m log length (ST). There are concerns that ST could reduce the forwarders' productivity. Six type stands were created based on harvester data. Different assortment distributions, conditions, and forwarders were simulated in each type stand. It was found that an additional ST assortment almost always decreased productivity (from –15.5 to +4%). Increased forwarding distance (m), more difficult driving conditions, and increased log concentration [$m^3 \cdot (100 \text{ m strip road})^{-1}$] decreased the productivity difference between sites with ST and NL and sites with only NL. Increased forwarder size increased the productivity difference between sites with ST and NL and sites with only NL. It is possible to load two stacks of ST on some forwarders. Such loading was more productive than loading one stack on longer forwarding distances, while the opposite was the case on short distances. However, loading two stacks of ST can lead to overloading.

Keywords: analysis of covariance (ANCOVA); clear cutting; comparative study; computer simulations; relative difference; terrain transportation

Logging in Norway is mostly mechanised with a widespread use of harvesters and forwarders. The harvester fells and bucks the trees while the forwarder transports logs to the roadside landing. The value of each tree is optimised during bucking, depending on tree characteristics and current demand for different assortments. Normally, assortments in Norway are 3–6 m long (NL) and consist of three main assortments, saw timber (3.5–6 m length), pulp wood (3–6 m length), and energy wood (3–6 m length). Depending on market conditions, there is sometimes a demand for short saw logs with a length of 2.5 m (ST), which is practically a fourth main assortment. There is generally adequate knowledge about the productivity of both harvesters and forwarders under common conditions with NL (e.g. Suadicani, Fjeld 2001; Nurminen et al. 2006; Eriksson, Lindroos 2014). However, there is limited knowledge about ST in Norwegian forest conditions. In theory, forwarding would be particularly affected by ST, as ST reduces load size and increases the number of crane cycles needed to load the same volume. Thus, there is a lack of knowledge about the effect of ST on productivity that needs to be addressed.

There are three main options for investigating the effect of ST on forwarding productivity: in-field time studies (e.g. Nurminen et al. 2006; Manner et al. 2013; Berg et al. 2017), automatically recorded machine data (e.g. Berg et al. 2019; Manner et al. 2019), and simulations (e.g. Eliasson 1999; Wang et al. 2005; Bergström et al. 2007). Time studies can give detailed information about work ele-

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ments. However, those studies are time-consuming when investigating several machines and conditions. Together with a varying demand for ST, it is difficult to conduct time studies. Automatic data collection can gather large-scale data covering most conditions. However, detailed records of forwarding are rarely kept in Norway. This leaves simulations as the best option for investigating the addition of ST as an added assortment. The benefit of simulation is that conditions can be adjusted and kept equal for all treatments. The drawback is that there always must be simplifications in a simulation. However, the benefits generally outweigh the drawback.

The objective of this study was to estimate the relative difference in forwarding productivity between sites with only NL assortments and sites with both NL and ST assortments. The hypothesis in the study was that an additional ST assortment would reduce the productivity for the forwarders.

MATERIAL AND METHODS

To investigate how an additional ST assortment affects forwarding productivity, forwarding with and without ST was computer-simulated (Figure 1). Six type stands with set locations and volumes for the forwarder's working points (FWP) were created with data from six logging sites with different log concentrations. In each type stand, assortment distributions with only NL, and with

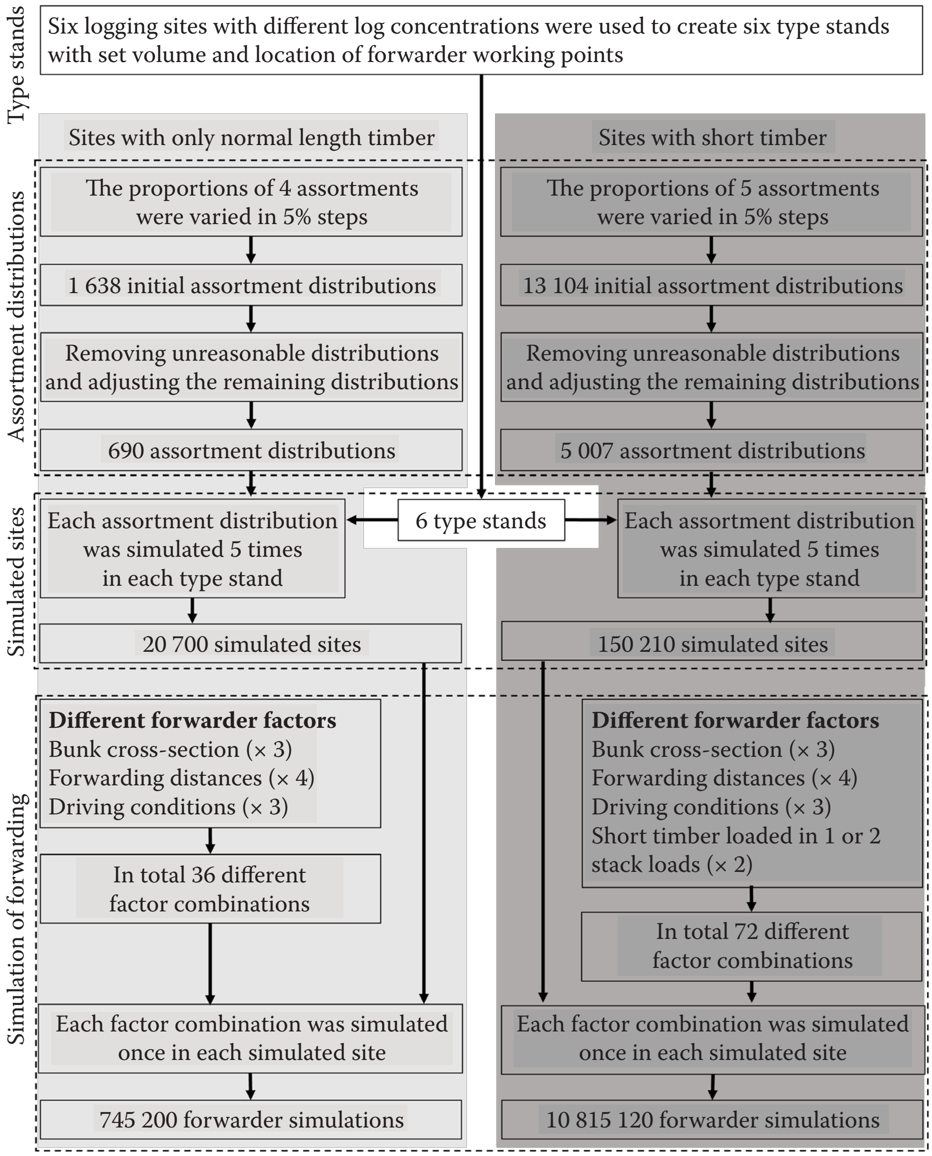

Figure 1. Simulation overview

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Table 1. Characteristics of type stands

Stand	Log concentration [m^3 sob·(100 m)$^{-1}$]	Total volume (m^3 sob)	Forwarder working point (m^3 sob)	Forwarder working point (No.)	Strip road length (m)	Distance between forwarder working points (m)
A	8.5	216	0.94 ± 0.98	230	2 523	11.0 ± 20.0
B	15.1	629	1.70 ± 1.26	370	4 166	11.2 ± 19.1
C	20.5	5 739	2.34 ± 1.88	2 450	27 988	11.4 ± 27.7
D	24.6	1 793	2.59 ± 2.10	691	7 303	10.6 ± 22.1
E	35.2	2 209	4.01 ± 4.91	551	6 275	11.4 ± 15.0
F	59.8	601	4.85 ± 3.19	124	1 005	8.1 ± 10.0

Values ± standard deviation; m^3 sob – cubic meters solid over bark

both ST and NL were simulated to create simulated sites with NL (NLS) and simulated sites with both ST and NL (STS). Forwarding was then simulated at NLS and STS. Productivity in cubic meters solid over bark per productive machine hour without delays (m^3 sob·PMh_0) was used for comparison.

Simulation of sites

Volume and location. StanforD files (Skogforsk 2007, Arlinger et al. 2012) were collected from six different logging sites with different timber stocking densities (Table 1). The harvesters' location when cutting trees and the volume of all merchantable logs were extracted from the files. Six type stands were then created, with fixed locations and volumes for FWP as the only two attributes (Figure 2). The location of each FWP was assumed to be the average of all included trees. The distance between the positions was calculated for the WGS84 ellipsoid, with an equatorial axis of 6 378 137, a polar axis of 6 356 752.3142, and an inverse flattening of 1/298.257223563 (Vincenty 1975). The type stands were assumed to contain only one single tree species.

Assortment distribution. Four assortments: pulp wood (15–45%), saw timber 1 (10–70%), saw timber 2 (0–25%), and energy wood (1–11%) were crosscut at NLS. Five assortments: pulp wood (15–40%), saw timber 1 (10–70%), saw timber 2 (0–25%), energy wood (1–11%), and short timber (10–45%) were crosscut at STS. The proportion of each assortment was varied in 5% steps, giving a total of 1 638 and 13 104 possible combinations for NLS and STS, respectively. Combinations for which the proportions' sum was from above 85% to below 115% were

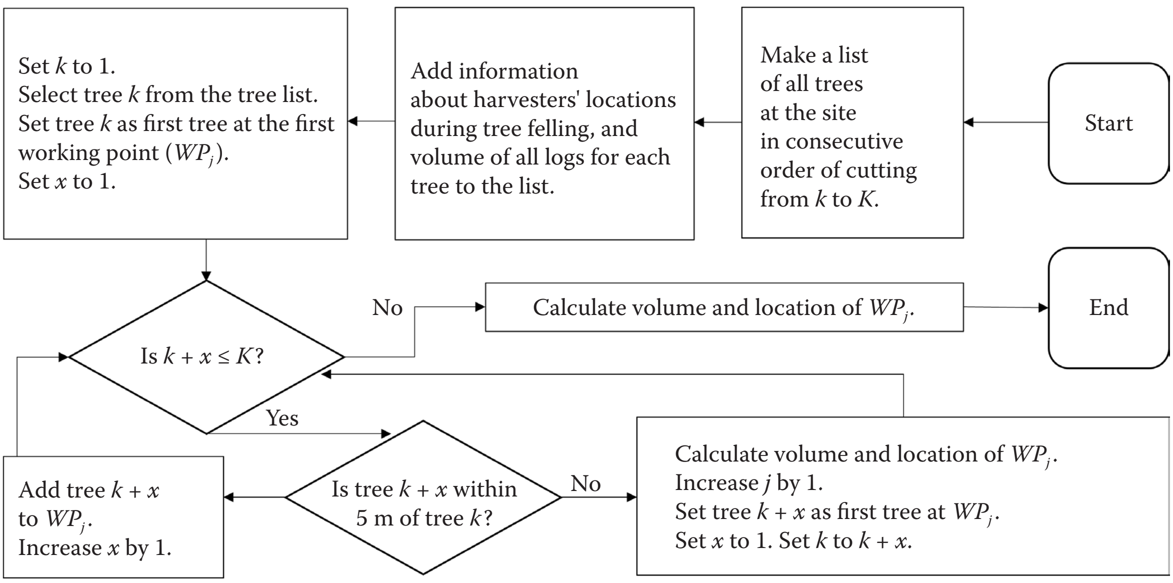

Figure 2. Process flow for how forwarder working points volume and location were estimated

j – index for working points; k – index for trees; K – total number of trees; WP_j – working point j; x – index for control inclusion of trees at working points

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Table 2. Values used in the simulation

Variable	Pulp wood	Saw timber 1	Saw timber 2	Energy wood	Short timber one stack[A]/two stacks[B]
Log size (m^3 sob)					
Minimum	0.015	0.077	0.191	0.021	0.032
Mean	0.060	0.164	0.335	0.125	0.076
Mean diameter over bark (mm)					
Mid-log	127	211	278	217	161
Butt end	150	229	297	231	168
Load size (m^3 sob)					
4 m^2 cross-section	11.46	13.12	15.41	9.63	11.40/20.52
5 m^2 cross-section	14.52	16.40	19.10	12.38	14.44/25.99
6 m^2 cross-section	17.34	19.84	23.12	15.00	17.33/31.19
Grapple size (m^3 sob)					
Loading	1.144	1.152	1.005	0.627	0.833
Unloading	1.802	1.481	1.675	1.128	1.439

[A] loading one stack of short timber; [B] loading two stacks of short timber in tandem; m^3 sob – cubic meters solid over bark

kept for analysis, resulting in 690 and 5 007 combinations for NLS and STS, respectively. These proportion combinations were then adjusted to sum up to 100% to create the assortment distributions [Equation (1)].

$$ShareS_i = \frac{ShareSr_i}{\sum_{i=1}^{I} ShareSr_i} \quad (1)$$

where:
ShareSr – proportion of an assortment before adjustment;
ShareS – proportion of an assortment after adjustment;
i – individual assortment;
I – total number of assortments.

Simulated sites. Each assortment distribution was used five times in each type stand to create different simulated sites. The assortments at each FWP were simulated based on *ShareS* and a deviation of 5 around $ShareS_i$ [Table 2; Figure 3; Equation (2)].

$$ShareV_{ij} = unif\left[\left(ShareS_i - v_i\right), \left(ShareS_i + v_i\right)\right] \quad (2)$$

where:
$ShareV_{ij}$ – share of assortment *i* at FWP *j*;
v_i – variation for assortment *i*;
unif – uniform distribution.

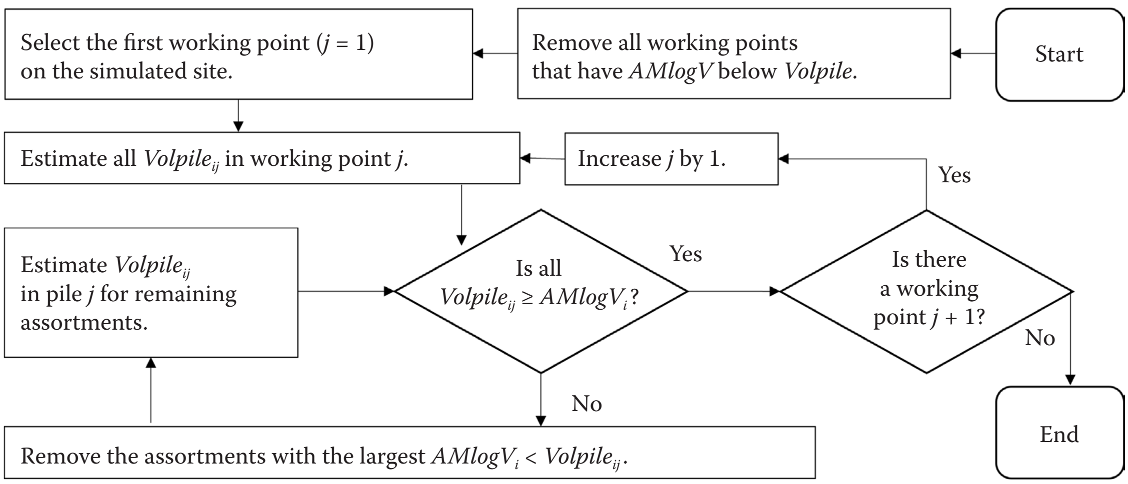

Figure 3. Process flow for simulating assortment volumes at forwarder working points

AMlogV – minimum assortment volume; *i* – assortment; *j* – index for working points; *Volpile* – volume at working point

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The share was set to 0 if the simulated value was negative. *ShareV* was then adjusted, to sum up to 100%, and their volume was calculated [Equation (3); Figure 3].

$$VolPile_{ij} = \frac{ShareV_{ij}}{\sum_{i=1}^{I} ShareV_{ij}} \times VolWP_j \qquad (3)$$

where:

$VolPile_{ij}$ – volume of assortment i at FWP j;

$VolWP_j$ – total volume at FWP j.

Simulation of forwarding

Time consumption of the following work elements was included in the study: driving unloaded, loading, driving while loading, driving loaded, unloading, and driving while unloading. These elements were either simulated or calculated (Figure 4). Only productive time (PMh_0) was estimated, and the forwarder was assumed to be standing still while the crane was moving. Unloaded and loaded forwarding distance was fixed at 50 m, 100 m, 250 m, or 400 m for each simulation. Forwarding size was fixed as small, normal, or large for each simulation. Driving conditions for loaded and unloaded driving were fixed as easy, normal or difficult for each simulation. This resulted in 36 different combinations of factors for simulated NLS. At STS, forwarding with one stack ST loads (1STL) and forwarding two stack ST loads (2STL) was simulated separately, resulting in 72 different combinations of factors. Each one of these combinations was simulated once for each simulated site.

ST was assumed to always be forwarded in single assortment loads. Forwarding 1STL and forwarding 2STL were simulated separately, as forwarders with four or more stakes could load ST in tandem stacks. All assortment combinations of NL were simulated in fixed mixes at each simulated site. The combination that gave minimum time consumption at each simulated site was used in the analysis. Different assortments were assumed to be loaded and unloaded in separate crane cycles. For each simulation, driving loaded and unloaded was set to a fixed distance for all loads.

Rabie (2015) estimated that crane cycle time when loading is lognormal distributed. Manner et al. (2019) reported that the 5th and 95th quantile for crane cycle time is 19.2 and 32.2 $s \cdot cycle^{-1}$, respectively. Rabie's (2015) estimation was transformed into the range of Manner et al. (2019) [Equation (4)].

$$xt_i = \frac{\left[x_i - \min(x)\right](b - a)}{\max(x) - \min(x)} + a \qquad (4)$$

where:

x – crane cycle time when loading;

i – individual cycle;

xt – transposed time;

a – minimum desired time;

b – maximum desired time.

The mean and standard deviation of the distribution on the logarithmic scale for the transposed values were calculated to be 3.18616893 and 0.10403948, re-

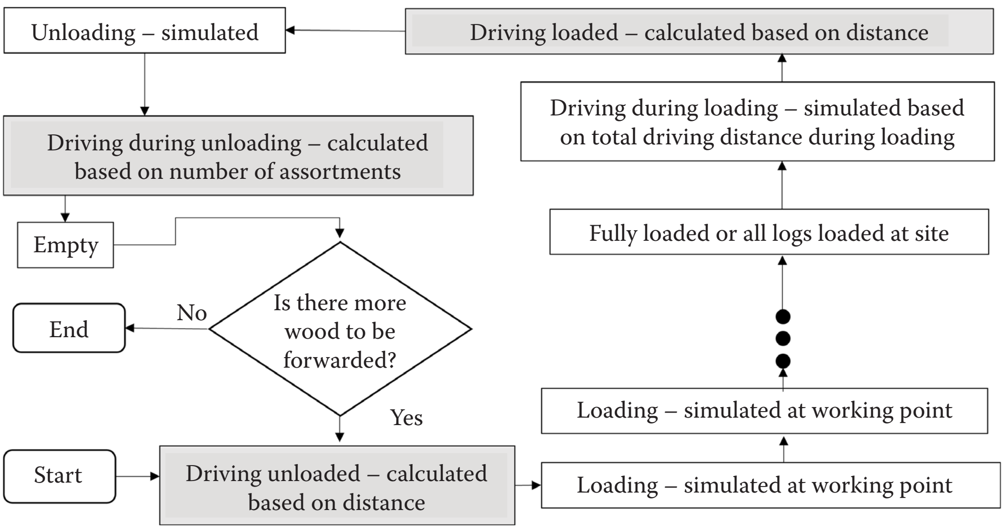

Figure 4. Process flow for forwarder simulations

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spectively (Venables, Ripley 2004). These values were used to simulate the crane cycle time when loading. Crane cycle time when loading 2STL was increased by 20–40%, with a uniform distribution. The increase was based on that it takes 44% longer to load a forwarder trailer than it took to load the main bunk when the load capacity is expanded by adding a forwarder trailer (Lindroos, Wästerlund 2013), and 27% longer to load the rear bunk than it took to unload the closest bunk of a tracked forwarder with three platforms two bunks and a cab (Brunberg, Lundström 2011).

Crane cycle time for unloading varied between 18.5 $s\cdot cycle^{-1}$ and 32.6 $s\cdot cycle^{-1}$ (Manner et al. 2019), with a uniform distribution (Rabie 2015). The crane cycle time when unloading 2STL was increased by 35% to 85%, with a uniform distribution, based on observations by Lindroos and Wästerlund (2013), and Brunberg and Lundström (2011). When unloading mixed NL loads, cycle time increased by 25.93%, 88.89%, and 105.56% for 2, 3, and 4 assortment loads, respectively (Manner et al. 2013).

The maximum volume per crane cycle was estimated with an assumed maximum grapple area of 0.32 m^2 and 0.5 m^2 when loading and unloading, respectively. The number of logs that could fit inside the grapple area was estimated with circle packing inside a circle (Specht 2014), assuming a circular grapple area and using the mean mid-log diameter of each assortment (Table 2).

Three bunk cross-section areas: 4 m^2 (small), 5 m^2 (normal), and 6 m^2 (large) were used to estimate the loaded volume for different forwarder sizes (Table 2). These sizes were then simulated separately. The number of logs that could fit inside the bunk was estimated with circle packing within a square (Specht 2012), assuming a square representation of the cross-section area and using the mean butt end diameter of each assortment (Table 2). When 2STL was loaded, the volume was increased by 80%. The volume in mixed NL loads was continually estimated based on already loaded volume and the maximum volume for different single assortment loads. The loading was stopped when loading the next FWP would exceed the capacity of the bunk [Equation (5)].

$$totvol > \sum_{i}^{I} \frac{loadv_i}{totvol} \times maxvol_i \qquad (5)$$

where:

totvol – total loaded volume in a mixed load;

$loadv_i$ – loaded volume of assortment *i*;

$maxvol_i$ – maximum volume for assortment *i*.

The driving speed while loading was simulated based on the total driving distance while loading for each load. Five different quantile regressions for driving speed were used (Berg et al. 2019) in combination with a uniform distribution (0 to 1). 0 gave the value of the quantile regression 5th percentile, 0.11 the value of the 15th percentile, 0.5 the value of the 50th percentile, 0.89 the value of the 85th percentile, and 1 the value of the 95th percentile. Other values from the distribution were interpolated.

Time for driving during unloading was set to 0.008 $min\cdot m^{-3}$ for single assortment loads and 0.027 $min\cdot m^{-3}$ for mixed-assortment loads (Nurminen et al. 2006). Loaded driving speed and unloaded driving speed was estimated for easy, normal, and difficult driving conditions. Easy conditions were represented with the quantile regression for the 5th percentile from Berg et al. (2019). Normal conditions were represented with the quantile regression for the 50th percentile from Berg et al. (2019). Hard conditions were represented with the quantile regression for the 95th percentile from Berg et al. (2019).

Statistics

Analysis of covariance (ANCOVA) was used to investigate the effect of an additional ST assortment on forwarders' productivity. The relative shares (percentage points) of short timber, pulp wood, saw timber 1 and saw timber 2 were used as covariates. Forwarder sizes (3 levels), forwarding distances (4 levels), forwarding conditions (3 levels), log concentrations (type stands; 6 levels), and type of short timber site (NL, STS with 1STL, and STS with 2STL; 3 levels), were used as factors. Productivity (m^3 $sob\cdot PMh_0^{-1}$) was used as the dependent variable. All interactions between factors were tested for.

Type 3 sum of squares was used in the ANCOVA. Intra-level differences were tested with Tukey's method. All comparisons were tested in one test to avoid problems with multiple testing. However, not all interactions were analysed. Between different types of short timber sites, only interactions with equal log concentration, driving conditions, forwarding distance, and forwarder size were analysed. Between different log concentrations, only interactions with equal forwarder size, type of short timber site, driving conditions, and forwarding distance were analysed. Between different forwarder sizes, only interactions with equal log concentration, type of short timber site, driving conditions, and forwarding distance were analysed. Between different driving

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conditions, only interactions with equal log concentration, type of short site, forwarding distance, and forwarder were size analysed.

All statistical tests were conducted with a 1% significance level. All simulations and statistical tests were conducted in R using RStudio (Version 1.1.463, 2018).

RESULTS

Simulated productivities were 16.2–59.9 m^3 sob·PMh_0^{-1}, 13.4–54.5 m^3 sob·PMh_0^{-1}, and 14.1–52.9 m^3 sob·PMh_0^{-1} for NLS, STS with 1STL, and STS with 2STL, respectively. All factors and covariates were significantly different (Table 3). The intra-level difference was

Table 3. Results of type III ANCOVA

Factor	*Df*	Sum of square	Mean square	*F* value	*P*-value*
rST	1	7 727 306	7 727 306	15 193 426	0
rP	1	222 203	222 203	436 895	0
rS1	1	1 641 635	1 641 635	3 227 782	0
rS2	1	2 929 496	2 929 496	5 759 974	0
LS	2	27 303 431	13 651 715	26 841 996	0
DC	2	55 794 547	27 897 274	54 851 606	0
ShS	2	4 049 808	2 024 904	3 981 365	0
LC	5	186 601 804	37 320 361	73 379 276	0
D	3	247 235 320	82 411 773	162 037 990	0
LS × DC	4	159 778	39 944	78 539	0
LS × ShS	4	101 868	25 467	50 073	0
DC × ShS	4	508 886	127 221	250 143	0
LS × LC	10	363 151	36 315	71 403	0
DC × LC	10	3 726 564	372 656	732 717	0
ShS × LC	10	329 516	32 952	64 789	0
LS × D	6	855 345	142 557	280 296	0
DC × D	6	2 761 285	460 214	904 873	0
ShS × D	6	2 404 653	400 776	788 005	0
LC × D	15	17 177 591	1 145 173	2 251 638	0
LS × DC × ShS	8	234	29	57	3.66×10^{-94}
LS × DC × LC	20	22 638	1 132	2 226	0
LS × ShS × LC	20	24 496	1 225	2 408	0
DC × ShS × LC	20	41 160	2 058	4 046	0
LS × DC × D	12	39 344	3 279	6 447	0
LS × ShS × D	12	2 561	213	420	0
DC × ShS × D	12	11 020	918	1 806	0
LS × LC × D	30	120 932	4 031	7 926	0
DC × LC × D	30	70 391	2 346	4 613	0
ShS × LC × D	30	201 792	6 726	13 225	0
LS × DC × ShS × LC	40	178	4	9	4.52×10^{-51}
LS × DC × ShS × D	24	2 429	101	199	0
LS × DC × LC × D	60	10 567	176	346	0
LS × ShS × LC × D	60	1 125	19	37	0
DC × ShS × LC × D	60	4 449	74	146	0
LS × DC × ShS × LC × D	120	446.99	3.72	7.32	1.03×10^{-115}

* *P*-value < 1.03×10^{-115} is shown as 0 in R studio; ANCOVA – analysis of covariance; *D* – forwarding distance (m); *DC* – driving conditions; *Df* – degrees of freedom; *LC* – log concentration (m^3 sob·$100m^{-1}$); *LS* – bunk cross-section (m^2); m^3 sob – cubic meters solid over bark; *rP* – pulp wood (%); *rST* – short timber (%); *rS1* – saw timber assortment 1 (%); *rS2* – saw timber assortment 2 (%); *ShS* – short timber (No., 1 stack loads, 2 stack loads)

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Table 4. Non-significant intra-level contrasts for small (4), normal (5), and large (6) bunk cross-sections; in easy (E), normal (N), and difficult (D) driving conditions; for different log concentrations (*LC*) (Table 1) at different forwarding distances for sites (Sites) where short timber was not present (0) and sites where it was and forwarded in one (1) or two (2) stack loads

Site		Bunk cross-section (m^2)	Driving conditions	Forwarding distance (m)	*LC*	Estimate	SE	*P*-value*
0	2	4	D	250	F	−0.0891	0.0130	1
1	2	5	N	250	E	0.0477	0.0064	1
1	2	6	E	400	C	0.0495	0.0064	1
0	2	4	N	400	D	0.1039	0.0130	1
0	2	4	D	400	B	−0.1049	0.0130	1
0	2	5	D	400	D	−0.1199	0.0130	1
1	2	5	N	250	D	−0.0684	0.0064	1
0	2	6	D	400	F	−0.1328	0.0130	1
0	2	5	D	400	C	−0.0021	0.0130	1
0	2	4	N	400	E	−0.0092	0.0130	1
1	2	5	E	400	E	0.0133	0.0064	1
1	2	6	N	50	A	0.0111	0.0064	1
1	2	4	D	100	B	−0.0048	0.0064	1
1	2	5	E	100	A	−0.0187	0.0064	1
1	2	4	E	250	B	0.0278	0.0064	0.514
1	2	4	E	100	A	0.0302	0.0064	0.169
1	2	5	N	50	A	0.0342	0.0064	0.012

* *P*-values > 0.999 are shown as 1 in R studio; degrees of freedom were 11 559 668; SE – standard error

therefore tested with the interaction effect of all factors. Seventeen of the relevant interactions were not significant (Table 4). Ten of these interactions were between forwarding 1STL and 2STL at STS, and seven were between forwarding NLS and forwarding 2STL at STS.

In most conditions, the addition of ST reduced productivity (Figure 5), meaning that NLS were more productive than STS. The difference in productivity between NLS and STS decreased with increasing forwarder size at low log concentrations. The difference in productivity between NLS and STS increased with increasing forwarder size in all other conditions [Table 5; Figure S1–S6 in the Electronic Supplementary Material (ESM)]. The productivity difference between NLS and STS decreased

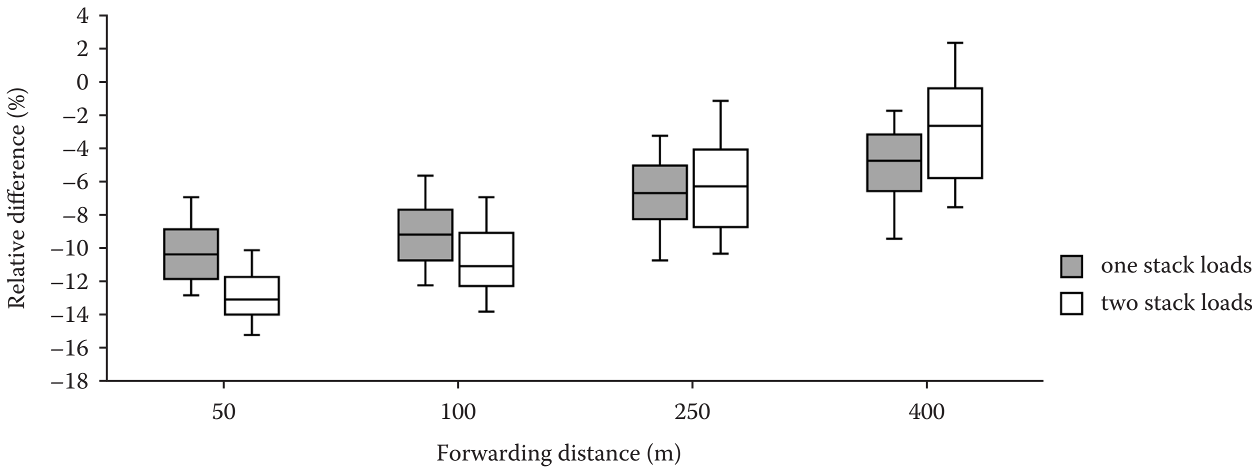

Figure 5. Boxplot for the mean relative difference in forwarders' productivity between sites with only normal-length assortments and sites with normal-length assortment and short timber, including all log concentrations, driving conditions and bunk cross-sections. Differences between loading one stack and two short timber stacks are shown.

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Table 5. Relative difference (%) between least square means for simulated productivity (m³ sob·PMh_0^{-1}) at sites with short timber (STS) and sites without short timber (NLS) for forwarders with a small, normal, or large cross-section in easy, normal, or difficult driving conditions at six log concentrations (*LC*), (see Table 1)

Cross-section		Small (4 m²)						Normal (5 m²)						Large (6 m²)					
Driving conditions		easy		normal		difficult		easy		normal		difficult		easy		normal		difficult	
Short timber stack		1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
LC	distance																		
A	50	−13.7	−14.4	−13.3	−13.6	−12.6	−12.2	−12.9	−13.3	**−12.5**[A]	**−12.6**[A]	−11.8	−11.3	−12.9	−13.2	**−12.7**[B]	**−12.7**[B]	−12.3	−11.9
	100	**−13.1**[C]	**−13.2**[C]	−12.4	−11.8	−11.5	−10.0	**−12.3**[D]	**−12.2**[D]	−11.6	−11.0	−10.7	−9.2	−12.6	−12.5	−12.3	−11.7	−11.8	−10.4
	250	−11.6	−10.2	−10.5	−8.0	−9.5	−5.8	−10.8	−9.4	−9.6	−7.2	−8.3	−4.9	−11.8	−10.6	−11.2	−9.1	−10.4	−7.4
	400	−10.5	−7.9	−9.3	−5.4	−8.3	−3.2	−9.5	−7.1	−8.0	−4.3	−6.7	−1.9	−11.1	−9.0	−10.2	−7.0	−9.3	−5.1
B	50	−13.0	−15.5	−12.3	−14.3	−11.1	−12.3	−12.9	−15.3	−12.3	−14.3	−11.3	−12.7	−12.7	−15.0	−12.2	−14.3	−11.5	−12.9
	100	−11.9	−13.7	−10.8	−11.8	**−9.2**[E]	**−9.2**[E]	−12.0	−13.9	−11.1	−12.3	−9.8	−10.1	−12.0	−13.9	−11.3	−12.6	−10.2	−10.8
	250	**−9.4**[F]	**−9.5**[F]	−7.6	−6.4	−5.8	−3.3	−9.9	−10.4	−8.4	−7.8	−6.7	−4.9	−10.3	−11.0	−9.0	−8.8	−7.6	−6.3
	400	−7.5	−6.2	−5.4	−2.6	−3.5	**0.6***	−8.3	−7.6	−6.4	−4.3	−4.7	−1.5	−8.9	−8.6	−7.3	−5.8	−5.8	−3.2
C	50	−11.1	−14.5	−10.4	−13.2	−9.2	−11.0	−11.2	−14.6	−10.6	−13.5	−9.6	−11.8	−11.2	−14.6	−10.7	−13.7	−9.8	−12.2
	100	−10.0	−12.6	−8.9	−10.5	−7.4	−7.7	−10.3	−13.0	−9.4	−11.4	−8.1	−9.0	−10.4	−13.3	−9.7	−11.9	−8.5	−9.8
	250	−7.6	−8.0	−5.8	−4.8	−4.1	−1.5	−8.3	−9.3	−6.8	−6.5	−5.2	−3.6	−8.7	−10.0	−7.4	−7.6	−6.0	−5.0
	400	−5.7	−4.6	−3.7	−0.8	−1.9	2.6	−6.6	−6.3	−4.9	−2.9	−3.3	**0.0***	**−7.3**[G]	**−7.4**[G]	−5.7	−4.5	−4.4	−1.8
D	50	−10.7	−14.5	−10.0	−13.1	−8.9	−10.9	−10.9	−14.7	−10.3	−13.6	−9.4	−11.8	−10.9	−14.7	−10.4	−13.8	−9.6	−12.2
	100	−9.7	−12.5	−8.6	−10.4	−7.2	−7.6	−10.1	−13.1	−9.1	−11.3	−7.8	−8.8	−10.2	−13.4	−9.4	−11.9	−8.3	−9.7
	250	−7.4	−7.9	−5.7	−4.6	−3.9	−1.2	−8.0	−9.1	**−6.4**[H]	**−6.2**[H]	−4.8	−3.1	−8.4	−10.0	−7.1	−7.5	−5.7	−4.8
	400	−5.5	−4.4	−3.5	**−0.5***	−1.8	2.8	−6.3	−6.0	−4.5	−2.5	−2.9	**0.6***	−7.0	−7.3	−5.4	−4.2	−4.0	−1.4
E	50	−9.2	−13.5	−8.6	−12.2	−7.5	−10.0	−9.6	−14.0	−9.1	−13.0	−8.2	−11.2	−9.8	−14.4	−9.4	−13.5	−8.7	−12.0
	100	−8.3	−11.5	−7.3	−9.5	−6.0	−6.7	−8.8	−12.5	−8.0	−10.8	−6.9	−8.4	−9.2	−13.0	−8.5	−11.6	−7.6	−9.6
	250	−6.1	−7.0	−4.6	−3.8	−3.1	−0.6	−7.1	−8.7	**−5.8**[I]	**−6.0**[I]	−4.5	−3.1	−7.7	−9.8	−6.6	−7.4	−5.4	−4.8
	400	−4.5	−3.6	−2.8	**0.0***	−1.3	3.1	**−5.7**[J]	**−5.8**[J]	−4.2	−2.5	−2.8	0.4	−6.5	−7.2	−5.1	−4.2	−3.9	−1.6
F	50	−8.3	−13.2	−7.7	−11.7	−6.7	−9.3	−8.4	−13.6	−7.8	−12.3	−7.0	−10.2	−8.4	−13.9	−8.0	−12.8	−7.2	−11.0
	100	−7.4	−11.0	−6.5	−8.7	−5.4	−5.7	−7.6	−11.7	−6.8	−9.7	−5.7	−7.0	−7.8	−12.3	−7.1	−10.6	−6.1	−8.2
	250	−5.5	−6.0	−4.2	−2.8	−3.0	**0.4***	−5.8	−7.3	−4.5	−4.3	−3.3	−1.2	−6.2	−8.5	−5.1	−5.7	−3.9	−2.9
	400	−4.1	−2.6	−2.7	1.0	−1.4	4.0	−4.4	−4.1	−3.0	−0.6	−1.8	2.3	−5.0	−5.5	−3.6	−2.3	−2.5	**0.5***

Bold – insignificantly different values; * insignificant difference from NLS; [A–J] values sharing superscript were insignificantly different; at STS, one (1) or two stacks (2) of short timber were forwarded; m³ sob – cubic meters solid over bark; PMh_0^{-1} – productive machine hour without delays

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in more difficult driving conditions (Table 5; Figure S1–S6 in the ESM). Increased log concentration decreased the productivity difference between NLS and STS (Table 5; Figure S1–S6 in the ESM). Increased forwarding distance reduced the productivity difference between NLS and STS, and the reduction was more rapid for 2STL than for 1STL. At 250 m and 400 m forwarding distances, the productivity of 2STL was sometimes equal to or higher than the productivity of NL loads. This did not occur for 1STL. However, 1STL were in most conditions more productive than 2STL on short forwarding distances. Where the switch from 1STL to 2STL being more productive occurred depended on several factors. More difficult driving conditions decreased at what forwarding distance forwarding 2STL became more productive than forwarding 1STL. Increased forwarder size and increased log concentration increased at what forwarding distance forwarding 2STL became more productive than forwarding 1STL. Large forwarders at high log concentrations could in certain instances have 1STL as the more productive option, regardless of forwarding distance. However, at low log concentrations, 2STL could be more productive than 1STL regardless of forwarding distance.

DISCUSSION

The effect of adding ST on forwarding productivity was generally negative (from −15.5 to +4%). This confirmed the hypothesis for the study in most conditions. However, there were some conditions under which the hypothesis was rejected (Table 5). Eriksson and Lindroos (2014) found that going from four to five NL assortments reduces forwarders' productivity by about 3% at site level. According to Eriksson and Lindroos (2014), this productivity difference was constant for all site conditions. The present study found quite varying results depending on conditions. One explanation for the difference between Eriksson and Lindroos (2014) and the present study is probably the difference between adding an ST and an NL assortment, and another is the difference between regression analysis that should provide functions valid in all conditions and performing ANCOVA between groups.

The relative difference between STS and NLS decreased with increased forwarding distance in this study. This decrease could in part be explained by the fact that driving speed was unaffected by assortment while loading time, unloading time, and load size were affected. Previous studies have found that the share of driving loaded and unloaded generally increased from 10% at 100 m to 30% at 400 m forwarding distance (Manner et al. 2013). Longer distances, therefore, meant that the share of time spent in work elements that were unaffected by assortment increased. Similarly, the productivity difference between STS and NLS decreased in more difficult driving conditions when relatively more time was spent travelling. The productivity difference between STS and NLS increased with forwarder size. Driving speed was the same for all forwarder sizes in this study, as recent studies have indicated that larger forwarders can drive faster than smaller ones (Gagliardi et al. 2020). The transportation from site to landing takes less time per m^3 sob for larger forwarders. Larger forwarders, therefore, spent relatively less time travelling, which probably explains part of the increased difference in productivity between STS and NLS for larger forwarders. These differences in relative productivity indicate that when relative travelling time is increased, regardless of reason, the difference in productivity between STS and NLS decreases.

Forwarding 2STL could however lead to overloading. The moisture content is 40–60% in recently cut Norway spruce, and the basic density is around 400 $kg \cdot m^{-3}$ (Lehtikangas 1999). Thus, 2STL should weigh 13.7–20.5 tonnes, 17.3–26.0 tonnes, and 20.8–31.2 tonnes for small, normal, and large-sized forwarders, respectively. If the wood has a medium to high moisture content, overloading occurs. Therefore, the benefits of 2STL at STS can be overestimated. Overloading does sometimes occur in practice, even though it is not recommended by the machine manufacturers, so depending on the situation these volumes can still be realistic.

The optimal assortment mix for forwarding NL can vary over a NLS, while a static assortment mix was applied in this study. However, the assortment mix that minimised the time consumption at each simulated site was used. Selecting the optimal assortment mix is difficult in practical operations. There is often a lack of knowledge about volume and locations, and the forwarder and harvester are also often working simultaneously at sites, making optimising the assortment mix even more difficult. Therefore, dose probably static assortment mixes of NL yield a relatively realistic result in the end. Circle packing was used in this study to estimate load and grapple

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volumes. Variations in log size, and the possibility to alternate the top ends and bottom ends of logs could increase load volumes. However, in practical work is it difficult to place each log perfectly to reach the theoretical maximum when alternating top ends and bottom ends, so circle packing probably gives a good estimate.

Productivity assessments were not relevant in this study, only the relative difference. However, productivity can be used to see if the simulation was realistic. The average productivity in this study was 33.0 m^3 sob·PMh_0^{-1}, ranging from 16.2 to 59.9 m^3 sob·PMh_0^{-1}. Eriksson and Lindroos (2014) found an average of 21.4 m^3 sob·PMh_0^{-1}, ranging from 0.01 to 122 m^3 sob·PMh_0^{-1}. However, at similar log concentrations (sites B to C), the average productivity was more similar to that reported by Eriksson and Lindroos (2014). It is therefore likely that the simulation gave reasonable results. Due to the number of simulations in the study, it could be argued that statistical tests are meaningless, as even small differences between treatments can be significant. However, even small differences in productivity are important for the contractors in the long run and therefore ANCOVA was conducted.

Only the relative productivity difference between NLS and STS was investigated. Therefore, no regression analysis was performed in this study. However, future studies could be expanded to include regression functions. Also, the effect of ST on the productivity of harvesters was excluded from the study. Harvesters' productivity should be negatively affected by ST, as Nurmi et al. (2006) found that additional assortments bucked in a tree increased processing time. However, harvesters were outside the scope of the current study but could be considered for further studies as it is possible that also the number of cross-cuts increases with the addition of ST. The results of this study were the expected relative differences in forwarding productivity caused by the introduction of ST. To apply the results in real-life conditions, it is necessary to first estimate forwarding productivity for only NL and then apply the percentages in Table 5 to estimate the effect of adding ST.

CONCLUSION

Simulation of forwarding at simulated sites showed that sites with both normal length logs (NL) and short timber logs (ST) in general were less productive than forwarding at sites with only NL. Sites with increased forwarding distance, larger forwarder size, and more difficult driving conditions had a relatively smaller reduction in productivity due to the introduction of ST. Sites with higher log concentrations had a relatively larger reduction in productivity when adding ST. Loading one stack ST loads mostly reduced productivity less than loading two stack ST loads (2STL) on short forwarding distances, while the opposite was the case on longer distances. However, loading 2STL can lead to overloading.

The results of this study were the expected relative differences in forwarding productivity caused by the introduction of ST. To apply the results in real-life conditions, knowledge of forwarding productivity in sites with only normal NL assortments is required. The effect of ST on harvesters was not assessed in this study, but should be estimated to judge the overall productivity and economy at a site. Harvester productivity could be investigated in further research.

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