Productivity and Costs of Harwarder Systems in Industrial Roundwood Thinnings

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Abstract

In several studies, the harwarder has proven to be a more cost-effective wood harvesting system than the traditional two-machine (harvester-forwarder) system, especially when the average stem size of the marked stand is relatively small, the removals per hectare/stand low (i.e. the harvesting site small), and the forwarding distance short. One of the strengths of a harwarder is considered to be the lower relocation costs compared to the two-machine system. The time consumption of harwarder relocations have not, however, been reported in the previous harwarder studies. Metsäteho Oy conducted a follow-up study of harwarders in industrial roundwood harvesting, and also investigated the relocations of harwarders. A total of five – three Ponsse Wisent Dual and two Valmet 801 Combi – harwarders were examined in the follow-up study. The amount of harvested industrial roundwood in the study totalled nearly 30,000 m^3. The cost calculations showed that the harwarder system is more competitive than the two-machine system when the average stem size of the marked stand is relatively low, i.e. less than 110–170 dm^3. Furthermore, harwarders were the most competitive at low-removal harvesting sites. The proportion of the total working time of harwarders used in relocations between harvesting sites was 2.5%, and the effective relocation time was, on the average, 1.3 hours/relocation. The study results underlined that it makes sense to harvest relatively small-removal and small-diameter thinning stands marked for harvesting with a harwarder while, conversely, it is more worthwhile to harvest sites with larger removals and trees using a two-machine harvester-forwarder system, thereby raising the profitability of forest machine business.

Keywords: harwarder, harvester-forwarder system, wood harvesting, cost-efficiency, machine relocation, follow-up study

1. Introduction

In the 2010s, total roundwood removals amounted to 59.7–70.3 million m^3 (over bark) in Finland (Hakkuukertymä metsäkeskusalueittain 2017). Two mechanized harvesting systems are used for industrial roundwood and energy wood:

⇒ traditional two-machine (harvester and forwarder) system

⇒ harwarder system (i.e. the same machine can perform both cutting and forest haulage).

During the last few years, annually, there has been an average of between 1870–1990 harvesters and 1930–2020 forwarders in use in Finland (Mäki-Simola 2017). At the same time, there have been less than 100 harwarders in wood harvesting operations in Finland.

The active development of harwarders in Finland started in the late 1990s after Lilleberg (1997) demonstrated that the harwarder was a more cost-effective wood harvesting system than a two-machine harvesting system, when the average industrial roundwood stem size in the marked stand was less than 150 dm^3. Since then, the productivity and profitability of harwarders in industrial roundwood harvesting, as well as in energy wood harvesting, have been investigated in several studies. These trials have been almost exclusively time studies (e.g. Cederlöf 1997, Hallonborg et al. 1999, 2005, Strömgren 1999, Eriksson and Rytter 2000, Hallonborg and Nordén 2000, Rieppo and Pekkola 2001, Andersson 2002, Bergkvist et al. 2002, 2003, Andersson 2003, Rieppo 2003, Wester and Eliasson 2003, Ljungdahl 2004, Nordén et al. 2005, Laitila and

Asikainen 2006, Bergkvist 2007, 2008, Johansson 2010, Nordin 2011, Di Fulvio et al. 2012, Zinkevicius and Vitunskas 2013, Spinelli et al. 2014, Jonsson et al. 2016a, 2016b, Manner et al. 2016). Comprehensive, long-term follow-up study data on harwarders has been produced in only two studies: Sirén and Aaltio (2003) in industrial roundwood harvesting, and Kärhä (2006) in energy wood harvesting. In the studies of Strömgren (1999), Hallonborg and Nordén (2000), Rieppo and Pekkola (2001), Bergkvist et al. (2003), Rieppo (2003), Sirén and Aaltio (2003), Talbot et al. (2003), Nordén et al. (2005), Jylhä et al. (2006), Kärhä (2006), Bergkvist (2007), Väätäinen et al. (2007), Johansson (2010), Jonsson et al. (2016a), and (2016b) the harwarder has proven to be a more cost-effective wood harvesting system than the traditional two-machine system, especially when the average stem size of the marked stand is relatively small, the removals per hectare/stand low (i.e. the harvesting site small), and the forwarding distance short. These kind of harvesting conditions are common in Finnish stands, and the share of cuttings from them (e.g. peatland cuttings) for industrial roundwood volume will be increasing in the near future (Palander and Kärhä 2016).

One of the main benefits in the use of harwarders is the fact that with harwarder operations one of the normal work elements of wood harvesting with two-machine system (i.e. loading of timber from ground) can be eliminated when direct loading is used in harwarder work (e.g. Di Fulvio and Bergström 2013, Jonsson et al. 2016a). Besides, one of the strengths of a harwarder is considered to be the lower relocation costs compared to the two-machine harvesting system (e.g. Talbot et al. 2003, Asikainen 2004). The time consumption of harwarder relocations has not, however, been reported in the previous harwarder studies. Hence, the aims of this study were to:

⇒ evaluate the productivity of two harwarder systems by using data on follow-up study
⇒ estimate the relocation and utilization of harwarder systems by follow-up study data
⇒ compare the profitability of harwarder systems to a two-machine system also including the relocation and machine utilization effects.

2. Material and methods

2.1 Follow-up study

A total of five – three Ponsse Wisent Dual (also in this article *Ponsse Dual*) and two Valmet 801 Combi (also *Valmet Combi*) – harwarders were examined in the follow-up study. Ponsse Dual harwarders were equipped with a separate harvester head for wood cutting and a separate timber grapple for forest haulage. Correspondingly, the Valmet 801 Combi harwarders were fitted with a fixed load space and an integrated harvesting grapple for both cutting and forwarding.

Eleven different harwarder operators participated in the follow-up study. The operators' work experience with harwarder work varied from some months to two years and with forest machine work between 1–23 years. The follow-up period started in September, 2004, and continued until May, 2005. The follow-up data was collected by Telmu 100 dataloggers. The duration and reason for each time element was recorded by the dataloggers. The accuracy of data collection was one second (s). The following time elements in the study were used:

⇒ Effective harwarder work:
  ⇒ cutting
  ⇒ forwarding.
⇒ Delays:
  ⇒ delays caused by harwarder (e.g. repairs and maintenance in the forest, changing the configuration from harvester to forwarder and vice versa with the Ponsse Dual harwarders)
  ⇒ delays due to operator (i.e. eating and personal breaks)
  ⇒ delays coming from communication (e.g. telephone calls)
  ⇒ harwarder relocations
  ⇒ other delays (e.g. larger repairs and maintenance at the workshop).

A total of 707 follow-up study days were required to collect the data. The harvesting conditions were obtained from the enterprise resource planning (ERP) systems of the wood procurement organizations for which each harwarder was contracted. The total industrial roundwood harvested with the Ponsse Dual harwarders was close to 25,000 m^3 (Table 1). The study material with the Valmet Combi harwarders was smaller, around 5000 m^3. The amount of harvested industrial roundwood in the follow-up study totalled nearly 30,000 m^3 (Table 1).

There were 92 harvesting stands, and data concerning the harvesting conditions was obtained from 70 stands (Table 1). The average size of harvesting stands was 4.0 ha in the follow-up study. The harwarders were primarily used for thinnings in the follow-up study: 14% of the total volume of industrial roundwood harvested came from first thinnings and 43% from later thinnings. Less than one-third of the wood quantity came from final cuttings. The proportion of other/combined cuttings was 11%. Furthermore, harwarders were used principally for real harwarder work, i.e. both cutting and forwarding were done by

Table 1 Number of stands in follow-up study and data for harvesting by harwarder and on average

	Ponsse Wisent Dual	Valmet 801 Combi	Total / Average
Stands (with condition data[1]), No.	64 (55)	28 (15)	92 (70)
Harvesting sites by mode of operation[2] (with condition data[1]), No.			
Real harwarder work[3]	35 (33)	20 (15)	55 (48)
Cutting only[4]	33 (26)	10 (1)	43 (27)
Forest haulage only[5]	4 (2)	0 (0)	4 (2)
Harvesting sites by cutting method[2] (with condition data[1]), No.			
First thinnings	18 (13)	9 (6)	27 (19)
Later thinnings	31 (24)	8 (8)	39 (32)
Final cuttings	27 (26)	1 (0)	28 (26)
Other/combined cuttings[6]	11 (8)	12 (2)	33 (10)
Total roundwood removal, m^3	24,935	5023	29,958
Tree species, %			
Norway spruce	50	10	44
Scots pine	35	69	40
Broadleaf	15	21	16
Total harvesting area, ha	233	132	366
Industrial roundwood removal			
m^3/stand	453	335	428
m^3/ha	107	38	82
Number of timber assortments, No.	9.0	3.7	8.4
Average stem size in stand, dm^3	247	128	226
Density of removal, trees/ha	488	532	440
Forwarding distance, m	248	229	245
Thickness of snow, %			
No snow	31	40	32
<20 cm	36	40	37
21–40 cm	28	20	27
41–60 cm	5	0	4
>60 cm	0	0	0
Undergrowth situation, %			
Pre-cleared	8	0	7
Non-obstructive	88	90	89
Moderate	3	10	3
High degree of obstructive	1	0	1
Terrain, %			
Normal	87	100	89
More difficult than normal	10	0	9
Difficult	3	0	2

[1] Harvesting stands with obtained harvesting conditions, e.g. average stem size in stand, roundwood removal, area of stand, forwarding distance
[2] As the same harvesting stand may consist of several modes of operation and cutting methods, there may be more harvesting sites than study stands
[3] Both cutting and forest haulage with harwarder
[4] Only cutting with harwarder
[5] Only forwarding with harwarder
[6] Other cutting methods or different harvesting sites of study stands had to be combined

a harwarder at the harvesting site (69% of the total volume of industrial roundwood harvested in the follow-up study). Harwarders were also used to balance two-machine (harvester-forwarder) harvesting systems, with the cutting carried out by a harwarder and the forwarding later performed by a forwarder (30% of the total volume of roundwood harvested). There were only a few harvesting sites where the harwarders carried out only forest haulage at the harvesting site (Table 1).

Follow-up study data for the Valmet Combi harwarders was focused on thinnings, which was reflected in markedly smaller hectare and stand-specific roundwood removals, average stem sizes, and number of timber assortments compared to the Ponsse Dual harwarders (Table 1). Out of the total harvested timber volume, 44% was Norway spruce (*Picea abies* (L.) Karst.), 40% Scots pine (*Pinus sylvestris* L.), and 16% broadleaf (i.e. *Betula verrucosa* Ehrh., *Betula pubescens* Ehrh. and *Populus tremula* L.). Final cuttings were spruce-dominated and first thinnings pine-dominated. With the Ponsse Dual harwarders, half of the harvested volume was spruce, and with the Valmet Combi harwarders, more than two-thirds was pine. The average number of timber assortments per harvesting site was 8.4, ranging from 2–15 between harvesting sites. With the Ponsse Dual harwarders, the number of assortments ranged from 4–15, and with the Valmet Combi harwarders from 2–5.

The cutting was initially primarily performed by the Ponsse Dual harwarders included in the follow-up study and, afterwards, the machines were outfitted for forwarding and used to haul the felled timber to roadside landings. In thinnings, the following working method was mainly applied using the Valmet Combi harwarders: The harwarder was driven forward into the stand while, at the same time, the trees along the strip road were cut and both sides of the strip road were thinned. The felled timber was bunched mainly into piles along the strip road. At the end of the strip road, the harwarder turned around and drove back along the harvested strip road while, at the same time, the bunched logs and poles were loaded. In final cuttings, the Valmet Combi harwarders were driven forward parallel with the edge of the stand, while cutting along one side. Direct loading was not carried out with the Valmet Combi harwarders in the follow-up study in either final cuttings or thinnings.

2.2 Cost calculations and system analysis

The operating costs were calculated using the Forest Machine Calculation Program of Metsäteho Oy. Operating costs include both time-dependent costs (capital depreciation, interest expenses, labor costs, insurance fees, administration expenses) and variable operating costs (fuel, repair and service, machine relocations). Cost calculations were prepared for two harwarders, of which the purchase price of the Harwarder system II (Valmet 801 Combi) was 130,000 € (VAT 0%) higher than that of Harwarder system I (Ponsse Wisent Dual), and for the two-machine harvesting system, which consisted of a harvester for thinnings (weight: 16–18 tonnes; e.g. John Deere 1070, Komatsu 901, Ponsse Beaver) and a medium-duty forwarder (carrying capacity: 12 tonnes; e.g. John Deere 1110, Komatsu 845, Ponsse Wisent) (Table 2). For all the machines, the annual operating (E_{15}, including short (<15 min) delays) hours were standardized at 2511 operating hours in the calculations. In the cost calculations, the proportion of thinnings was 40% of the total volume of industrial roundwood harvested. The operating hour costs for the harvester for thinnings were 101 €/E_{15} hour and for the medium-duty forwarder 72 €/E_{15} hour (Table 2). The operating hour costs of the Harwarder system I (Ponsse Dual) was 94 €/E_{15}

Table 2 Purchase prices, operating hour productivities and annual outputs used in cost calculations, as well as calculated operating hour costs of machines

Machine	Purchase price, € (VAT 0%)	Productivity, m^3/E_{15} hour		Industrial roundwood, m^3/a	Operating hour costs, €/E_{15} hour
		Thinnings	Final cuttings		
Harwarder system					
I (Ponsse Wisent Dual)	370,000	6.1	7.7	17,499	105
II (Valmet 801 Combi)	500,000	6.1	7.7	17,499	94
Two-machine system					
Harvester	380,000	9.0	18.0	32,300	101
Forwarder	260,000	11.0	15.0	32,840	72

hour and of the Harwarder system II (Valmet Combi) 105 €/E_{15} hour.

The wood harvesting costs in thinnings with Harwarder systems I and II were compared to the harvesting costs with the two-machine harvesting system. The effective (E_0, excluding delays) hour productivities in thinnings with the two-machine harvesting system in cutting and forest haulage was determined by the time consumption models presented by Kärhä et al. (2006). It was assumed that, when the average stem size in the stand increased from 50 dm^3 to 250 dm^3, the industrial roundwood removal increased from 38 m^3/ha to 84 m^3/ha in thinnings (cf. Kärhä and Keskinen 2011). There were 500 Norway spruce undergrowth trees per hectare in the thinning stand, and the average height of the spruce undergrowth trees was 2 m. The average load size was 11.0 m^3 in forest haulage with a forwarder (cf. Eriksson and Lindroos 2014). The effective hour (E_0) productivities of cutting and forest haulage of two-machine system were converted to operating hour (E_{15}) productivities by coefficients of 1.393 and 1.302, respectively, in the cost calculations.

2.3 Data analysis

The variables were analyzed using percentage shares and mean values. The differences between harwarder systems (Ponsse Dual and Valmet Combi) and cutting methods (first thinning, later thinning and final cutting) were analyzed using the Mann-Whitney *U*-test and Kruskal-Wallis one-way ANOVA test.

The operating (E_{15}) hour productivity in real harwarder work was modeled by applying regression analysis with the average stem size in the stand, industrial roundwood removal per hectare, density of removal, share of tree species volume, average forwarding distance, and number of timber assortments as independent variables. The suitability of the models with respect to the data was numerically assessed on the basis of the degree of explanation and statistical significance ($p<0.05$).

3. Results

3.1 Total time consumption and productivity

In the follow-up study, the technical utilization rate of the harwarders was, on the average, 88.1%, and the operational utilization rate 82.6%. In the real harwarder work, the share of the effective working time was 78.2% of the total working time. Correspondingly, the proportion of machine delays (i.e. repairs and maintenance) was 12.4% of the total working time. The proportion of operator delays (i.e. eating and personal breaks) was 5.2%, the proportion of harwarder relocations 2.5%, and the proportion of communication (i.e. telephone calls, forest visits by forest machine entrepreneur, wood procurement officer, or forest owner) was 1.5% of the total working time.

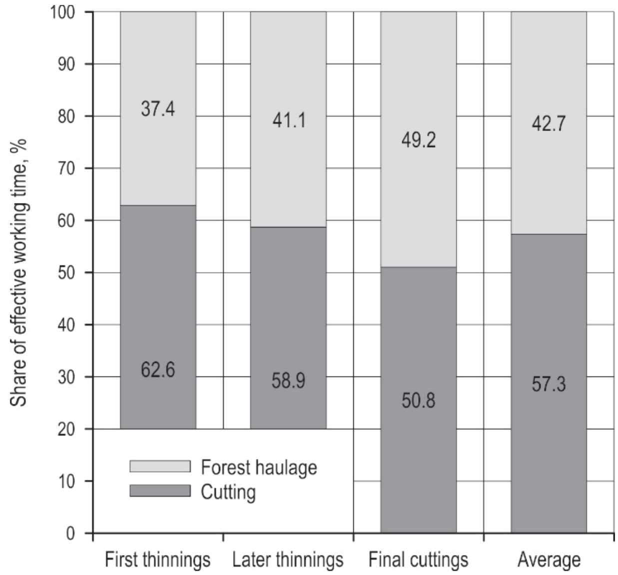

Fig. 1 Distribution of effective working time in real harwarder work by cutting method, and on the average in the follow-up study

In real harwarder work, based on the entire follow-up study material (average stem size in marked stand 198 dm^3 and average forest haulage distance 239 m), an average of 57% of the effective working time was used for cutting and 43% for forest haulage (Fig. 1).

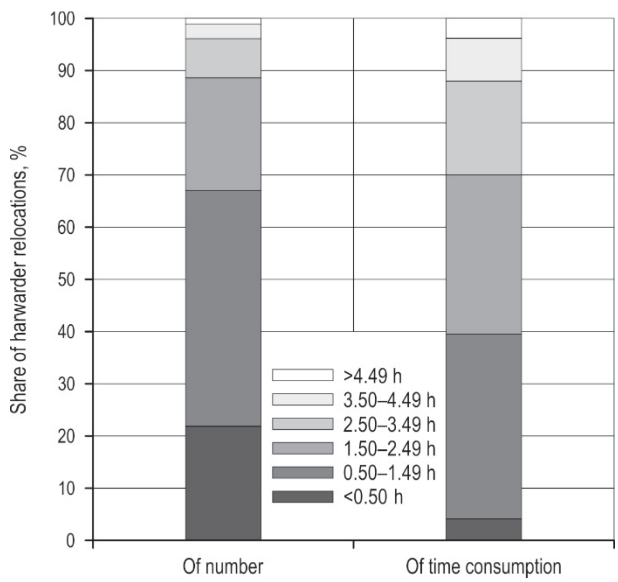

Fig. 2 Distribution of harwarder relocation times out of the number and of time consumption in the follow-up study

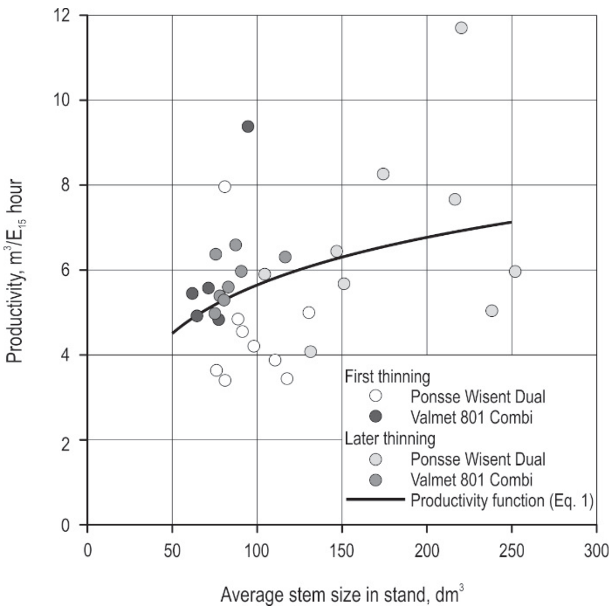

Fig. 3 Operating hour productivity in thinnings in real harwarder work by harvesting site, and productivity curve as a function of average stem size (Table 3, Eq. 1)

With first thinnings (89 dm^3 and 280 m), the cutting took an average of 63% and forwarding 37% of the effective working time. With final cuttings (326 dm^3 and 179 m), the effective working time was split almost equally between cutting and forest haulage (Fig. 1).

In the follow-up study, the effective relocation time of harwarders used in relocations between harvesting sites was, on the average, 1.3 hours/relocation. The majority of harwarder relocations took 0.5–1.0 hour/relocation (Fig. 2). The average relocation time with the Ponsse Dual harwarders was 1.29 hours and with the Valmet Combis 1.48 hours/relocation.

In real harwarder work within the follow-up study, the productivity per operating hour in first thinnings was, on the average, 5.1 m^3/E_{15} hour and in later thinnings 6.4 m^3/E_{15} hour. The operating hour productivity in real harwarder work was significantly higher in later thinnings than in first-thinning stands (p<0.05). The larger stem size in later thinnings explained the disparity in the productivity levels (Fig. 3). In the first thinnings, the productivity with the Valmet Combi harwarders was, on the average, 1.5 m^3/E_{15} hour higher than with the Ponsse Duals. Respectively, the productivity in the later thinnings with the Ponsse Dual harwarders was 0.8 m^3/E_{15} hour higher than with the Valmet Combis. There was no significant difference in productivity between the Ponsse Dual and Valmet Combi harwarders in (first and later) thinning stands (p=0.334). The productivity observations in (first and later) thinnings with the harwarders were combined and modeling was conducted based on these data.

In the case of thinnings, the productivity per operating hour of real harwarder work was best explained by the average stem size in the marked stand (Table 3, Eq. 1, Fig. 3). The other independent variables (i.e. the share of tree species volume, industrial roundwood removal per hectare, density of removal, average forwarding distance, and number of timber assortments) had no statistically significant impact on the operating hour productivity in thinnings.

Table 3 Regression model for operating hour productivity of real harwarder work in thinnings

Coefficient	Estimate of coefficient	Standard error of estimate	*t-value*
a	–1.877	3.728	–0.504
b	1.641	0.796	2.062*

F value = 3.056*; R^2 = 0.13*; * p<0.05; ** p<0.01; *** p<0.001

$$y = a + b \times LN(x) \quad (1)$$

Where:
- y operating hour productivity, m^3/E_{15} hour
- x average stem size in the stand, dm^3
- a constant
- b coefficient of variable.

When the average stem size in the stand was 100 dm^3, the productivity of real harwarder work in thinnings was 5.7 m^3/E_{15} hour (Fig. 3, Table 3). The productivity was 6.8 m^3/E_{15} hour when the average stem size was 200 dm^3. In the final cutting of the real harwarder work within the follow-up study, the average productivity was 7.7 m^3/E_{15} hour.

3.2 Profitability of harvesting systems

The harwarder systems were more competitive than the two-machine system when the average stem size of the marked stand was relatively low, i.e. less than 110–170 dm^3 (Fig. 4). In this case, the industrial roundwood removal was typically below 55–70 m^3/ha (cf. Kärhä and Keskinen 2011). Furthermore, harwarders were the most competitive in low-removal – i.e. small-sized – stands, particularly at harvesting sites that were below 50 m^3. As the stem size in the stand and roundwood removal per hectare/stand increased, the competitiveness of the two-machine harvesting system improved in comparison to that of the harwarder systems (Fig. 4).

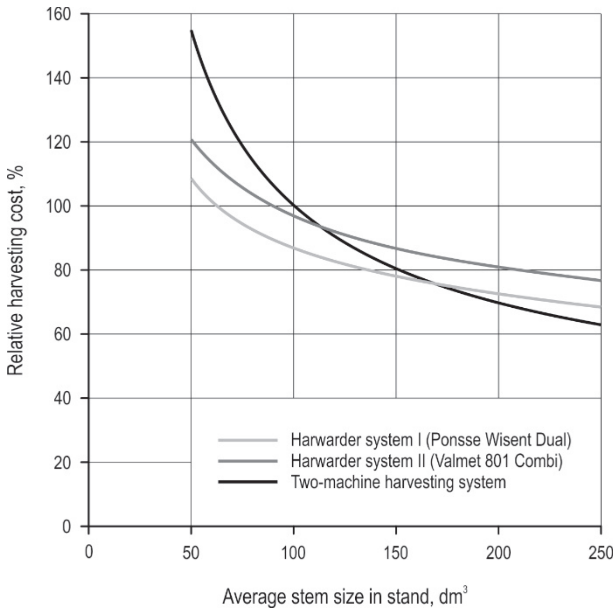

Fig. 4 Effect of average stem size on relative harvesting costs of thinning wood with harwarder systems I and II and with a two-machine harvesting system; industrial roundwood removal increased from 38 m^3/ha (average stem size 50 dm^3) to 84 m^3/ha (250 dm^3) (Kärhä and Keskinen 2011), and the forwarding distance was 250 m; harvesting costs 100 = Harvesting costs with a two-machine harvesting system at an average stem size of 100 dm^3

4. Discussion

4.1 Follow-up study

The follow-up study material totalled nearly 30,000 m^3. The amount of follow-up study material collected was extensive compared to the harwarder follow-up studies carried out earlier: The material in the study of Sirén and Aaltio (2003) was around 16,000 m^3 industrial roundwood with the Pika 828 Combi harwarders. Correspondingly, in the follow-up study by Kärhä (2006), the study material was close to 14,000 m^3 of small-diameter whole trees from young stands. The amount of study material collected from the Ponsse Wisent Dual harwarders was significantly greater than that from the Valmet 801 Combi harwarders. The reasons for that being that the Valmet Combi harwarders were only used in one work-shift, and the study stands were mostly thinnings (cf. Table 1). Nevertheless, the material of this research was quite small compared to the material of very large follow-up study by Eriksson and Lindroos (2014) with two-machine harvesting systems including around 23 million m^3 (over bark) of industrial roundwood.

In this follow-up study, there were 92 harvesting stands in total, and data concerning harvesting conditions was obtained from 70 stands. The effect of harvesting conditions on the productivity of real harwarder work could be researched with around 50 harvesting sites. For modeling, it would have been useful if there had been more harvesting sites with harvesting condition data. The following issues restricted the amount of material for examination of real harwarder work:

⇒ harvesting condition data could not be obtained from all study stands

⇒ real harwarder work was not conducted in all study stands, but harwarders balanced the two-machine harvesting systems in several stands (Table 1)

⇒ some follow-up study stands had to be deleted from the final material used for modeling productivity, because there were problems collecting time consumption data in some study stands.

Eleven different harwarder operators took part in the study. Their work experience in harwarder work varied from several months to two years. This caused a large amount of variation for operating productivity in thinnings (Fig. 3). Earlier wood harvesting studies have pointed out that there is a significant correlation between the operator's working experience and his/her productivity in forest machine work, especially when operating in dense thinning stands. For instance, Sirén (1998), Kärhä et al. (2004) and Ovaskainen (2009) have shown that the differences between operators using the same machines are as high as 35–40%.

In thinnings, the operating hour productivity of real harwarder work was, statistically, most significantly explained by the average stem size. The coefficient of determination (R^2) of the productivity model (Table 3, Eq. 1) was left relatively low, because of the large variation of productivities by harvesting site (cf. Fig. 3). The productivity of real harwarder work in final cuttings cannot be significantly explained in the study.

In the follow-up study by Sirén and Aaltio (2003), the operating hour productivity in thinnings was explained by the average stem size in the stand, roundwood removal, and number of timber assortments. In this study, the number of timber assortments had no significant impact on the productivity of real harwarder work in thinnings. When comparing the productivity models of Sirén and Aaltio (2003) with the productivity models of this study, it is noted that in this study the productivity was 1.2–1.9 m^3/E_{15} hour higher than that of Sirén and Aaltio, when the average stem size in the stand was 50–200 dm^3. Development of harwarder technology partly explains the higher productivity in this research. Besides, the operators and their working skills may account for the disparity in productivities.

According to the results obtained, the harwarder is a more cost-effective wood harvesting system than the traditional two-machine system, when the average stem size in the stand is relatively small and the removals per hectare/stand are low. Hence, the findings are in line with earlier studies (e.g. Lilleberg 1997, Strömgren 1999, Hallonborg and Nordén 2000, Rieppo and Pekkola 2001, Bergkvist et al. 2003, Rieppo 2003, Sirén and Aaltio 2003, Talbot et al. 2003, Nordén et al. 2005, Jylhä et al. 2006, Kärhä 2006, Bergkvist 2007, Väätäinen et al. 2007, Johansson 2010, Jonsson et al. 2016a, 2016b) concerning most suited harvesting conditions for the harwarder system.

The study results also emphasized that the Ponsse Dual concept is a more cost-efficient system than the Valmet Combi (cf. Fig. 4). The reason for this being is that the Ponsse Wisent Dual, as well as the Ponsse Buffalo Dual, are clearly inexpensive machines when compared to the Valmet 801 Combi harwarder. Väätäinen et al. (2007) have also underlined the superior competitiveness of Ponsse Dual harwarders when compared to the Valmet 801 Combi with a fixed load space. Correspondingly, Talbot et al. (2003) have found that the Valmet Combi is a more cost-efficient wood harvesting system than the Ponsse Dual concept.

In the study, all harwarders were equipped with fixed load space, and therefore the working method of direct loading was not used. Many research reports, for instance by Hallonborg and Nordén (2000), Andersson (2002), Bergkvist et al. (2003), Wester and Eliasson (2003), and Jonsson et al. (2016a), have illustrated that direct loading is more productive working method with the harwarder system in final fellings when separate timber loading from the ground can be avoided. According to the studies, direct loading could improve further the cost-competiveness of harwarders. By developing harwarders and their working methods (e.g. direct loading in thinnings and final cuttings) and organization, it will be possible to enhance further the competitiveness of harwarders (Lindroos 2012, Ringdahl et al. 2012).

In the follow-up study, the share of the total working time of harwarders in relocations was 2.5%, and the effective relocation time was, on the average, 1.3 hours/relocation. These findings are new because there is no earlier information on the harwarder relocation. In Finland, the latest comprehensive study on the relocations of harvesters and forwarders was conducted more than 20 years ago (Kuitto et al. 1994). In the beginning of the 1990s, the relocation distance with the harvesters was, on the average, 28 km, and the relocation time consumption 1.7 hours/relocation (Kuitto et al. 1994). Respectively, with the forwarders, the average relocation time from one harvesting site to another was 1.2 hours and the average relocation distance was 21 km. It can be noticed that the figures of this research are very close to the values of Kuitto and his colleagues (1994). In this study the relocation distances of harwarders were not reported. Kärhä et al. (2007) interviewed 13 harwarder contractors, who mostly owned both harwarders and harvesters and forwarders. Kärhä et al. (2007) reported that harwarder contractors estimated that the average relocation distance is 28 km with their harwarders and 32 km with their two-machine harvesting systems.

In the follow-up study by Eriksson and Lindroos (2014), the average share of relocations with harvesters and forwarders were 1.4–1.5% and 0.9–1.1% of the total machine computer uptime, respectively. The bigger size of harvesting sites in Sweden explains probably the smaller proportions of machine relocations.

4.2 Future prospects

Currently, the total number of harwarders in use in Finnish forests is less than one hundred, of which more than half are mainly engaged in energy wood harvesting and the remainder in industrial roundwood harvesting. Harwarders have not been as widely adopted as it would be expected in the light of the positive results of harwarder studies. Possible reasons include resistance and prejudice towards harwarders, together with entrenched preferences for traditional harvesting technology. These factors came to light in Metsäteho's investigation on the increasing use of tracked excavators in harvesting operations in Finland (Bergroth et al. 2006).

It is estimated that the number of harwarders will increase in the near future in Finland. This development forecast is based on the following factors:

⇒ cost effectiveness in wood harvesting is being sought at the level of the stand marked for harvesting. A harwarder has a clear competitive advantage in small-removal thinnings and final cuttings, forest fellings in the archipelago, harvesting of wind-felled trees, and in seed tree and shelterwood fellings (Kärhä et al. 2001, Jylhä et al. 2006). It makes sense to harvest relatively small-removal and small-diameter stands marked for harvesting with a harwarder while, conversely, it is more worthwhile to harvest sites with larger removals and trees using a two-machine harvesting system, thereby raising the profitability of forest machine business

⇒ the structural change in cuttings is setting new demands on the harvesting fleet. Wood harvesting volumes of thinnings and on peatlands will grow during the next years (e.g. Nuutinen et al. 2000, Korhonen et al. 2007). The harvesting conditions described above (small stem size and low removals) are ideally suited for the harwarder. The use of harwarders also means less driving in stand, which is needed during harvesting operations, thus minimizing strip road rutting (e.g. Palander and Kärhä 2016). In peatland harvesting, however, long forwarding distances may reduce the profitability of harvesting based on a harwarder

⇒ as a result of changes in the forest machine business field, the size of forest machine contracting businesses is growing and large regional responsibilities in contracting are increasing (e.g. Rekilä and Räsänen 2008). These changes are creating a potential for the use of specialized harvesting fleet. In this respect, the acquisition of a harwarder alongside two-machine harvesting systems may be a profitable alternative in wood harvesting operations.

5. Conclusions

It was noted in this study that the productivity of harwarders has increased 1.2–1.9 m^3/E_{15} hour, when the average stem size in the stand was 50–200 dm^3. Development of harwarder technology partly explains the higher productivity. Furthermore, the average share of relocations with harwarders was 2.5% of the total machine time with the average relocation time of 1.3 hours/relocation. Nonetheless, harwarders have not been as widely adopted as it would have been expected in the light of the positive results. Actually, the reasons for the relatively slow growth in the use of harwarders have not been documented. Possible reasons include resistance towards harwarders. Moreover, one possible reason may be the fact that harwarder work requires higher professional skills and qualifications for operators than harvester or forwarder. The harwarder operator has to have very good skills in both cutting and forwarding work.

In forest industry, cost effectiveness in wood harvesting is being sought at the level of the stand marked for harvesting, as well as from the point of view of the forest machine business. In Finland, the size of forest machine contracting businesses is growing and large regional responsibilities in contracting are increasing. These changes are creating a potential for the use of specialized wood harvesting fleet. In this respect, the optimization of allocation and use of harwarder and two-machine harvesting systems will be a profitable solution in the future wood harvesting operations.

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