Whole-tree harvesting in young stands in Finland

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Abstract. In Finland, two mechanized harvesting systems are used for small-diameter \( d_{1.3} < 10 \text{ cm} \) thinning wood: 1) the traditional two-machine (harvester and forwarder) system, and 2) the harwarder system (i.e. the same machine performs both cutting and forest haulage to the roadside). There are currently more than 20 energy wood harwarders in use in Finland. However, there have been no comprehensive studies carried out on energy wood harwarders. Metsäteho Oy undertook a study on the two mechanized harvesting systems for small-sized thinning wood. Time study and follow-up study material was collected for the study from whole-tree harvesting using energy wood harwarders and two-machine harvesting systems. The productivity and cost levels of the two main harvesting systems were determined, and the whole-tree harvesting costs for harwarders were compared with those of the conventional two-machine system.

The results gave a clear indication of what kind of machine resources can be most profitably allocated to different whole-tree harvesting sites. The energy wood harwarders should be directed towards harvesting sites where the forwarding distances are short (<150 m), the whole trees to be harvested are relatively small (<20 dm\(^3\)), and the total volume of whole trees removed is relatively low (<55 solid m\(^3\)/ha, <100 solid m\(^3\)/stand). Respectively, when the stem size removed in young stands is relatively large (>20 dm\(^3\)), the whole-tree removal is higher than average (>55 solid m\(^3\)/ha), the stand size is over 2 hectares, and the forwarding distance is more than 150 m, then the traditional two-machine system is more competitive.

Key words: whole-tree chips, small-sized thinning wood, energy wood, harwarders, young stands, Finland

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Introduction

In Finland, 3.0 million solid m\(^3\) (6.0 TWh) of forest chips were used in 2005 (Ylitalo, 2006). Of this amount, 2.6 million solid m\(^3\) (5.2 TWh) were used in heating and power plants. Less than one-quarter (0.6 million solid m\(^3\)) (about 1.1 TWh) of the total amount of commercial forest chips used for energy production was produced from small-sized trees in young stands (Ylitalo, 2006). When harvesting small-sized thinning wood in young stands, the stem size harvested typically has a breast height diameter \( d_{1.3} \) of less than 10 cm, and the stems are harvested as whole trees (stem with branches). It has been estimated that the stock of technically harvestable small-sized thinning wood in young stands is 5 million solid m\(^3\) (10 TWh) annually (Hakkila, 2004). In Finland there is a target to increase the annual use of forest chips for energy production by 5 million solid m\(^3\) (10 TWh) per year by 2010 (Anon., 1999a; Anon., 1999b). This presupposes that the harvesting of small-diameter thinning wood is doubled from the current harvesting volume.
In young stands, productivity remains low and felling-bunching costs become higher when the trees are small, the energy wood removal per hectare is small, and the number of remaining trees is high (e.g. Kärhä et al., 2005). When producing whole-tree chips in young stands, the total supply chain costs are approximately 15–20 €/MWh. In 2005, the mean price of forest chips at the plant was 11.1 €/MWh in Finland (Ylitalo, 2006). In order to speed up the production of small-sized wood chips in young stands, the Finnish state pays production subsidies for small-sized wood chips according to the Sustainable Silviculture Foundation Law (KEMERA). The KEMERA subsidy for small-sized wood chips is typically about 6–9 €/MWh.

However, neither the state’s production subsidies nor their levels are continuous. Hence, in order to improve the productivity of harvesting small-diameter trees, active research and development work needs to be carried out on harvesting methods and technology. During the last few years, the harvesting of small-diameter trees has undergone considerable development and become highly mechanized in Finland. Two mechanized harvesting systems are used for small-diameter energy wood: 1) the traditional two-machine (harvester and forwarder) system, and 2) the harwarder system (i.e. the same machine performs both cutting and forest haulage to the roadside).

At the present time, there are more than 100 small harvesters (weight <13 tons) and harvesters for thinnings (weight 13–15 tons) cutting small-diameter thinning wood in use in Finland (Kärhä, 2006). In addition, there are over 20 energy wood harwarders. About 80 per cent of the small-sized thinning stems are chipped by truck or tractor-mounted drum or disc chippers or truck-mounted hammer or rotor crushers at roadside storage areas (Kärhä, 2006). A full trailer with a fixed platform is commonly used for the long-distance transportation of chips to the plant.

A number of studies have been carried out on the new harvesting technology, especially the cutting of small-sized whole trees with felling heads (e.g. EnHar, Naarva-Grip 1600-40, and Timberjack 720 and 730) (e.g. Gullberg et al., 1998; Eriksson & Nordén, 1999; Liss, 1999; Kärhä et al., 2002; Mäkelä et al., 2003; Laitila et al., 2004a). However, there have been no comprehensive studies carried out on energy wood harwarders (cf. Lilleberg, 1995; Eriksson & Rytter, 2000; Hämäläinen et al., 2001; Laitila et al., 2004a). For instance, time consumption functions for whole-tree harvesting with harwarders have not been determined in Finland or in any other country before the year 2006. Nevertheless, a couple of months ago Laitila and Asikainen (2006) published their time consumption models for energy wood harwarders in whole-tree harvesting. Metsäteho Oy undertook a study on the two mechanized harvesting systems for small-diameter thinning wood in 2004–2005. The productivity and cost levels of the two main harvesting systems were determined, and the whole-tree harvesting costs for harwarders were compared with those of the conventional two-machine system.

Material and methods

Time study

The time study was carried out on a total of 25 different harvesting sites in young stands (Table 1). Whole trees were also harvested with a harwarder in one stand on which clear cutting was performed (a land-clearing site: 681 whole-tree stems, 25.7 solid m³). This whole-tree harvesting site was only included in the evaluation of load sizes and driving empty, driving loaded and unloading times.

The time-study data were collected during 2004–2005. All the whole trees felled in the time study were hauled to the roadside. Each whole-tree load was weighed using grapple or axel load scales. In the harwarder time study, 35 whole-tree loads were
hauled (13 loads with Ponsse S15 Bison, 9 loads with Timberjack 1110C, 3 loads with Ponsse S16 Buffalo, and 10 loads with Valmet 801 Combi, of which 8 loads were with the A2 working method and 2 loads with the B working method) (Table 1, Figure 1). In the time study, two of the loads hauled with the Valmet 801 Combi harwarder were significantly shorter (load space over one third empty). These loads were excluded from the evaluation of the harwarders’ average load size in the time study.

In the whole-tree forwarding time study, 8 out of a total of 41 loads forwarded were classified as deficient. Of the full loads, 27 were hauled by medium-duty forwarders and 6 by small forwarders. The average load size evaluations were carried out on the basis of whole-tree loads classified as full loads.

The same researcher collected all the time-study material using a continuous time-study method (cmin) in which the work cycle was divided into the following time elements:

- Cutting: Moving, Boom-out and felling, Bunching/Transferring to processing point, Cross-cutting, Miscellaneous times (e.g. planning, moving tops and branches), and Delay (i.e. time not related to productive cutting work).
- Forest haulage: Driving empty, Loading, Driving for loading, Driving loaded, Unloading, and Delay (i.e. time not related to productive forwarding work).
- Harwarder: Driving empty, Boom-out and felling, Bunching, Cross-cutting, Moving, Loading, Driving for loading, Driving loaded, Unloading, Miscellaneous times, and Delay (i.e. time not related to productive harwarder work) (Kärhä et al., 2006).

Effective time consumption functions were prepared for each work element of the cutting, forest haulage, and harwarder work (Kärhä et al., 2006). Productivity per effective ($E_{0\nu}$ excluded delay times) hour was determined by dividing the output by the total effective time consumption.

In connection with the harvester head/harvesting grapple positioning and tree felling stage, the researcher recorded the breast height diameter and number of trees felled. Sample trees were also measured on each harvesting site. Diameter at breast

Table 1. Research material in the time study and follow-up study.

<table>
<thead>
<tr>
<th>Study / Harvesting system</th>
<th>Number of sites</th>
<th>Number of loads</th>
<th>Volume, solid m$^3$</th>
<th>Number of whole-tree stems</th>
<th>Average stem size, dm$^3$</th>
<th>Average removal, solid m$^3$/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time study</strong></td>
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<tr>
<td>Two-machine systems</td>
<td></td>
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<tr>
<td>- Felling heads</td>
<td>12</td>
<td>41</td>
<td>201</td>
<td>10 545</td>
<td>24</td>
<td>60</td>
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<tr>
<td>- Harvester heads with feed rollers</td>
<td>9</td>
<td>36</td>
<td>183</td>
<td>9 734</td>
<td>22</td>
<td>60</td>
</tr>
<tr>
<td>Harwarder systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Harwarders based on forwarder</td>
<td>13</td>
<td>35</td>
<td>188</td>
<td>10 811</td>
<td>25</td>
<td>56</td>
</tr>
<tr>
<td>- Harwarder with rotating cab</td>
<td>10</td>
<td>25</td>
<td>129</td>
<td>8 743</td>
<td>24</td>
<td>56</td>
</tr>
<tr>
<td>Total</td>
<td>25</td>
<td>76</td>
<td>388</td>
<td>21 356</td>
<td>24</td>
<td>58</td>
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<tr>
<td><strong>Follow-up study</strong></td>
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<tr>
<td>Harwarder systems</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- Harwarders based on forwarder</td>
<td>75</td>
<td>2 578</td>
<td>13 393</td>
<td>-</td>
<td>-</td>
<td>52</td>
</tr>
<tr>
<td>- Harwarder with rotating cab</td>
<td>4</td>
<td>71</td>
<td>495</td>
<td>-</td>
<td>-</td>
<td>52</td>
</tr>
<tr>
<td>Total</td>
<td>79</td>
<td>2 649</td>
<td>13 888</td>
<td>-</td>
<td>-</td>
<td>52</td>
</tr>
</tbody>
</table>

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height and height were measured on sample trees in each stand. The stem volume of
the harvested trees was calculated using the volume functions of Laasasenaho (1982).
The volume of the tree branches and needles was determined using the oven dry mass
models of Hakkila (1991) and the basic densities of Hakkila (1978). The green density
of the whole-tree stems of each time study site was determined. On the average, the
green density of whole-tree stems harvested was 866 kg/solid m$^3$.

**Follow-up study**

Follow-up study material was collected from three energy wood harwarders which
were also involved in the time study. The follow-up study started in summer 2004
and ended in spring 2005. There were 79 different whole-tree harvesting sites in the
follow-up study. In the follow-up study a total of 12 360 green tons of whole trees were
harvested. In the follow-up study, 2649 whole-tree loads were hauled (Table 1).

Follow-up data from harwarders were collected using Telmu-100 data loggers.
The green tons of all harwarders used in the follow-up study were converted to solid
cubic metres to give a green density value of 890 kg/solid m$^3$. Hence, the total whole-
tree volume harvested in the follow-up study was 13 888 solid m$^3$.

**Harvesting machinery and working methods**

The four harwarders were tested in the time study. Three of the harwarders were
based on conventional forwarders (the medium-duty forwarders Ponsse S15 Bison and
Timberjack 1110C (weight 12–15 tons; max. load rating 10–11 tons), and the heavy-duty
forwarder Ponsse S16 Buffalo (weight >15 tons; max. load rating 14 tons)). The fourth
harwarder was the heavy-duty Valmet 801 Combi with a rotating cab. The Ponsse S15
Bison, Timberjack 1110C, and Valmet 801 Combi harwarders were equipped with the
Moipu 400E combination harvesting grapple. The Ponsse S16 Buffalo harwarder was
equipped with the Ponsse EH25 combination harvesting grapple.

With the harwarders – as was the case for whole-tree cutting using harvesters with
a felling head – the following working method was used for processing tall trees:
when the tree to be felled was to be cut to a 5–7 m haulage length for forwarding, the
combination harvesting grapple/felling head was first placed half way along the tree
to be felled and the top was cut, after which the harvesting grapple/felling head was
moved to the base of the tree in question and the tree was cut at the base.

Three different working methods were tested in the time study (Figure 1):
- The A1 working method: The harwarder was reversed into the stand while, at the
  same time, the trees on the strip road were felled and bunched into piles beside
  the strip road. When the operator estimated that there was enough wood for one
  load, the harwarder was driven forward out of the stand while, at the same time,
  both sides of the strip road were thinned and the bunched stems were loaded.
- The A2 working method: The harwarder was driven forward into the stand while,
  at the same time, the trees on the strip road were felled and bunched into piles
  beside the strip road. At the end of the strip road the harwarder was turned around
  and it was driven forward along the harvested strip road while, at the same time,
  both sides of the strip road were thinned and the bunched stems were loaded.
- The B working method: The harwarder was driven forward into the stand while,
  at the same time, the trees on the strip road were felled and bunched and both
  sides of the strip road were thinned and the bunched stems were loaded.

Analysis of whole-tree cutting using the two-machine harvesting system showed
that there was a total of five different energy wood harvester heads in use during
The A1 working method

The A2 working method

The B working method

Figure 1. Three working methods tested in the time study on energy wood harvesters. The A1 working method was used with harvesters based on a conventional forwarder, and the A2 and B methods with a harvester with a rotating cab.

the time studies. Three of the tested energy wood harvester heads were accumulating felling heads: Abab Klippen 250, Moipu 400E and Ponsse EH25. In addition, two roller-fed energy wood harvester heads were researched: Logset 4M Hamster and Valmet 945 Shear-head. Table 2 shows a summary of the properties of the energy wood harvester heads tested and the base machines used in the time studies. Whenever the felled trees required cross-cutting to 5–7 metre lengths for forest haulage using Logset 4M Hamster and Valmet 945 Shear-head harvester heads, the process was carried out by feeding the bunch through the feed rollers and by delimbing the bunch with the delimbing knives up to the cross-cutting point.

Forest haulage of felled whole trees was mainly carried out by medium-duty forwarders (Logman 811F, Ponsse S15 Bison and Valmet 840-8). A small, less than 12 tons forwarder (Norcar 600 and Timberjack 810B) was used in two stands.

Six different harvester operators, five different harvester operators, and six different forwarder operators participated in the time studies. The operators’ work experience in the type of work studied and the harvesting machine varied from half a year to two years. In addition to the above mentioned work experience, almost all the operators had several years of work experience in other forest machine work.
Harvesting sites
In the time study, the average size of the whole-tree stem in the energy wood thinning sites was 24 dm³ (varying by site from 3 to 66 dm³) (Table 1). Calculation of the average size of the felled stems in the total whole-tree removal gave an average felled stem size of 18 dm³. Most of the whole-tree stems felled had a breast height diameter of 3–8 cm. The average removal density by site in the time studies was 3189 trees/ha, and the variation range from under 1000 trees/ha to almost 9000 trees/ha. In the time study, the average whole-tree removal was 58 solid m³/ha (varying by site from 26 to 97 solid m³/ha) (Table 1). The whole-tree removal calculated from the total data was 52 solid m³/ha, and the removal density 2878 trees/ha. Significant correlations were found between the average stem size removed from the stand, removal density, and whole-tree removal:
- the smaller the felled stems, the bigger the removal density, and
- the smaller the felled stems, the smaller the whole-tree removal.

The majority (59%) of the trees harvested in the time-study stands were broadleaf, mostly birch (Betula pubescens Ehrh., Betula pendula Roth.), but also grey alder (Alnus incana (L.) Moench), European aspen (Populus tremula L.) and goat willow (Salix caprea L.). One third of the harvested stems were Scots pine (Pinus sylvestris L.) and approximately one tenth Norway spruce (Picea abies (L.) Karst.). On average, 1471 trees/ha were left in each time study stand. The variation range by site was 800–2120 trees/ha. In the follow-up study, the average whole-tree removal in the energy wood thinning sites was 52 solid m³/ha, and the mean size of the stands 3.7 ha. The average whole-tree removal was 185 solid m³/stand.

Cost calculation of harvesting machinery
Operating hour cost calculations were performed for small harvesters (weight <13 tons; in the study Logman 801 and Logset 506H), harvesters for thinnings (weight 13–15 tons; Valmet 901-4) and medium-duty harvesters (weight 15–17 tons; Ponsse HS16 Ergo) equipped with either a felling head or a roller-fed harvester head. In the two-machine system, whole-tree forest haulage was assumed to be carried out by medium-duty forwarders (weight 12–15 tons, max. load rating 10–11 tons; in the study Logman 811F, Ponsse S15 Bison and Valmet 840-8). In addition, operating hour cost calculations were performed for medium-duty and heavy-duty (weight >15 tons, car-
rying capacity 14 tons) harwarders based on a forwarder and heavy-duty harwarder with a rotating cab (Valmet 801 Combi).

Table 3 shows the VAT-free purchase prices used in the cost estimates for the machines. With all machines, the annual operating hours were standardised as 2564 operating \( (E_{15}) \) including delayed times shorter than 15 minutes) hours. The operating hour productivity of each machine unit is listed in Table 3. In addition, Table 3 shows the load sizes of the forwarders and harwarders and the annual performance of each machine. The operating hour costs for harvesters equipped with a felling head were 67–74 \( €/E_{15} \) (Table 3). When the harvesters were equipped with a roller-fed harvester head, the operating hour costs were 5 € per operating hour higher than those of harvesters equipped with a felling head. The operating hour costs for forwarder were 59 €/h, and for harwarders 67–78 €/h (Table 3).

Table 3. Data used in the cost calculation of whole-tree harvesting machinery.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Purchase price, € (VAT 0%)</th>
<th>Productivity, solid m(^3)/E(_{15})</th>
<th>Load size, solid m(^3)</th>
<th>Working volume, solid m(^3)/a</th>
<th>Operating hour costs, €/E(_{15})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvester</td>
<td></td>
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<tr>
<td>Small harvester</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Felling head</td>
<td>213 000</td>
<td>3.9</td>
<td>10 000</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>- Harvester head with feed rollers</td>
<td>225 000</td>
<td>4.4</td>
<td>11 280</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Harvester for thinnings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Felling head</td>
<td>280 000</td>
<td>3.9</td>
<td>10 000</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>- Harvester head with feed rollers</td>
<td>292 000</td>
<td>4.4</td>
<td>11 280</td>
<td>77</td>
<td></td>
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<tr>
<td>Medium-duty harvester</td>
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<td></td>
<td></td>
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<tr>
<td>- Felling head</td>
<td>303 000</td>
<td>3.9</td>
<td>10 000</td>
<td>74</td>
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<tr>
<td>- Harvester head with feed rollers</td>
<td>315 000</td>
<td>4.4</td>
<td>11 280</td>
<td>79</td>
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<tr>
<td>Medium-duty forwarder</td>
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<td>7.7</td>
<td>6.0</td>
<td>19 745</td>
<td>59</td>
</tr>
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<td>Harwarder</td>
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<tr>
<td>Based on forwarder</td>
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<tr>
<td>- Medium-duty</td>
<td>243 000</td>
<td>2.5</td>
<td>5.0</td>
<td>6 410</td>
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<tr>
<td>- Heavy-duty</td>
<td>257 000</td>
<td>2.6</td>
<td>6.0</td>
<td>6 670</td>
<td>68</td>
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<td>Harwarder with rotating cab</td>
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<td></td>
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<tr>
<td>- Heavy-duty</td>
<td>395 000</td>
<td>2.8</td>
<td>7.0</td>
<td>7 180</td>
<td>78</td>
</tr>
</tbody>
</table>

Results

Bunch size and multiple-tree processing

The average bunch size for harwarders was 2.92 stems/bunch. The bunch size for harvesters in the time study was smaller than that for harwarders (average 2.43 stems/bunch). The stem size of the marked stand had a strong correlation with the bunch size. When felling trees of 6–15 dm\(^3\) in size (4–7 cm breast height diameter trees), the average bunch size with harwarders was 3.58 trees/bunch, with feller-bunchers 3.05 trees/bunch, and with harvesters with a roller-fed harvester head 3.00 trees/bunch.

When the stem size was over 35 dm\(^3\) (breast height diameter more than 9–10 cm), the average bunch size remained below two stems, i.e. the majority of the trees were felled as single trees. In the study, less than 15% of the trees were felled as single trees, i.e. the proportion of multiple-tree handling was 85%. When multiple trees were collected, the bunch typically consisted of 2–4 stems. This indicates that all of the tested energy wood harvester heads were well suited to the handling of several trees, i.e. multiple-tree handling.
Load size
With medium-duty forwarder-based harwarders (Ponsse S15 Bison and Timberjack 1110C), the load size in both the time study and the follow-up study was predominantly 4.0–5.9 solid m³. In the time study and follow-up study, the average load size with medium-duty forwarder-based harwarders was also at the same level (around 5.0 solid m³). With heavy-duty forwarder-based harwarders (Ponsse S16 Buffalo), the load size was about 1.0 solid m³ larger than with medium-duty forwarder-based harwarders. With the Valmet 801 Combi harwarder, 63% of all the full whole-tree loads forwarded in the time study fell within the 8.0–8.9 solid m³ class. The average load size in the time study was 8.8 solid m³. In the follow-up study, the load size of Valmet 801 Combi harwarder was significantly lower (average 7.0 solid m³) than in the time study.

In the whole-tree forwarding time study, the average load size was 6.1 solid m³ with medium-duty forwarders and 3.5 solid m³ with small forwarders. In stands of very small stem size (average size of marked trees below 5 dm³) the load size remained small (below 3 solid m³). The load size increased along with increasing average size of the whole-tree stems in the stand. The increase in load size evened out when the average stem size of the stand reached 20–30 dm³. The load size did not significantly increase from this value as the average stem size increased.

Productivity of cutting
As the time consumption models for stem processing with different feller-bunchers (Abab Klippen 250, Moipu 400E, Ponsse EH25) were highly similar, a common model was constructed for whole-tree feller-bunchers on the basis of the harvester head-specific time consumption models. Similarly, the stem-processing time consumption models for the studied roller-fed, deliming harvester heads (Logset 4M Hamster, Valmet 945 Shear-head) were very compatible. Thus, a common stem-processing time consumption model was constructed for roller-fed harvester heads. With harwarders, the stem-processing time consumption modelling was performed in the same way as for the energy wood harvester heads: first by stand and then by operator. The stem-processing time consumption model for harwarders was constructed on the basis of the time consumption models for operators using the Moipu 400E combination harvesting grapple. The stem-processing time consumption of the Valmet 801 Combi harwarder operator was not significantly less than that of the Timberjack 1110C and Ponsse S15 Bison harwarder operators.

When cutting very small, below 5 dm³ trees (d₁₃≤ 4 cm), the whole-tree cutting productivity remained low at under 2 solid m³/effective (E₀, excluded delay times) hour with both the feller-bunchers and roller-fed harvester heads (Figure 2). Cutting productivity with feller-bunchers was higher than with roller-fed harvester heads when the marked stem size was below 8 dm³. With bigger stem sizes, the cutting productivity of the roller-fed harvester heads surpassed that of the feller-bunchers.

When the stem size of the marked stand was 20 dm³, the whole-tree cutting productivity per effective hour using roller-fed harvester heads was 6.1 solid m³/E₀ and using feller-bunchers 5.5 solid m³/E₀. As the size of the marked stem increased, the disparity between whole-tree cutting productivity increased. The main reason for the cutting productivity disparity between feller-bunchers and roller-fed harvester heads was the time consumption difference in cross-cutting. The stem cross-cutting time consumption of the feller-bunchers was approximately double that of the roller-fed harvester heads.
Productivity of forest haulage

At a whole-tree load size of 6 solid m$^3$ and a whole-tree removal of 60 solid m$^3$/ha, the productivity of whole-tree forest haulage was 10.0 solid m$^3$/effective hour at a forwarding distance of 250 metres (Figure 3). In similar harvesting conditions, forest haulage productivity was 11.3 solid m$^3$/effective hour at a whole-tree load size of 9 solid m$^3$, and 7.5 solid m$^3$/effective hour at a whole-tree load size of 3 solid m$^3$ (Figure 3). The impact of whole-tree removal on the productivity of forest haulage was smaller than that of load size or forwarding distance.
Productivity of harwarder

In the study, the stem-processing time consumption of harwarders was 8% less than that of harvesters equipped with a felling head. Furthermore, the average time consumption for loading with harwarders was 13–17% less than that of forwarders, even though during the harwarder time studies the working locations (0.25 solid m³) were on the average about one third less than those in the forwarding time studies (0.38 solid m³). When the B working method was used with a harwarder with a rotating cab, the loading time consumption was not significantly less than the A1 and A2 working methods.

Correspondingly, with harwarders unloading was on the average one third slower than with forwarders. With harwarders, the average size of the unloading bunch in the study was 15% smaller and the average time required to unload one bunch was 14% more than with a forwarder. With forwarders, the average time consumption of unloading was 0.65 min/solid m³. With harwarders the corresponding average time consumption was 0.87 min/solid m³.

When applying the A1/A2 and B working methods, the only difference in effective time consumption was the fact that the B working method involved no moving between working locations. In the B working method, all moving of working locations that occurred after the first loading stage were classified as driving for loading times.

Evaluation of the productivity of whole-tree harvesting with harwarders reveals that the stem size of the marked stand, together with the whole-tree removal, forwarding distance, load size, and working method used, had an impact on the productivity of whole-tree harvesting (Figures 4 and 5). When the A1/A2 working method was used, and the harvested stem size 20 dm³ and the forwarding distance 250 m, the whole-tree harvesting productivity was 3.4 solid m³/effective (E₀) hour at a load

![Figure 4](image-url)

Figure 4. The effective (E₀) hour productivity of whole-tree harvesting with a harwarder as a function of the stem size harvested for varying load sizes. Whole-tree removal increased from 20 solid m³/ha (stem size 2 dm³) to 99 solid m³/ha (80 dm³), the forwarding distance was 250 m, and the A1/A2 working method was used (see Figure 1).
The size of 5 solid m³. With a load size of 7 solid m³ in similar harvesting conditions, the productivity totalled 3.6 solid m³/E₀.

When the B working method was applied, whole-tree harvesting productivity was about 5% higher than that of the A1/A2 working method when the load size was 5–7 solid m³, the stem size of the removed stand 20 dm³, and the forwarding distance 250 m.

Comparison of the harvesting systems
Figures 6–8 show the relative costs of whole-tree harvesting in relation to the stem size of the marked stand (whole-tree removal), forwarding distance, and stand size. The figures show that whole-tree harvesting costs with the two-machine systems and with harwarders were at a relatively similar level. Nevertheless, according to the results, harwarders are best suited for harvesting sites where:

- the forwarding distances are short (<150 m),
- the whole trees to be harvested are relatively small (<20 dm³), and
- the total volume of the whole trees removed is relatively low (<55 solid m³/ha, <100 solid m³/stand).

Correspondingly, Figures 6–8 illustrate that the two-machine (harvester-forwarder) whole-tree harvesting system is more competitive in harvesting conditions where:

- the stem size removed in young stands is relatively large (>20 dm³),
- the whole-tree removal is higher than the average (>55 solid m³/ha),
- the stand size is over 2 hectares, and
- the forwarding distance is more than 150 m.
Figure 6. Effect of the harvested stem size on the relative whole-tree harvesting costs with different harwarder and two-machine (harvester and forwarder) systems. Whole-tree removal increased from 20 solid m$^3$/ha (stem size 2 dm$^3$) to 99 solid m$^3$/ha (80 dm$^3$), and the forwarding distance was 250 m. The A1 working method was used with harwarders based on a conventional forwarder, and the B working method with a harwarder with a rotating cab. Harvesting costs 100 = Two-machine system (Harvester for thinnings equipped with felling head) with a stem size of 20 dm$^3$.

Figure 7. Effect of forwarding distance on the relative whole-tree harvesting costs with different harwarder and two-machine harvesting systems. The harvested stem size was 20 dm$^3$ (whole-tree removal 57 solid m$^3$/ha), and the working methods for the harwarders were as shown in Figure 6. Harvesting costs 100 = Two-machine system (Harvester for thinnings equipped with felling head) with a forwarding distance of 250 m.
Discussion and conclusions

Material and methods
The time-study and follow-up study material was collected for the study from whole-tree harvesting using traditional two-machine harvesting systems and energy wood harvesters. A total of nearly 400 solid $m^3$ of material was collected for the time study. The follow-up study material was collected only from energy wood harvesters. The follow-up study material totalled nearly 14 000 solid $m^3$. The amount of study material collected was extensive in comparison with that of small-diameter tree harvesting studies carried out earlier in the 2000’s (e.g. Eriksson & Rytter, 2000; Hämäläinen et al., 2001; Kärhä et al., 2002; Mäkelä et al., 2003; Kärhä, 2004; Laitila et al., 2004a; Heikkilä et al., 2005).

The whole-tree cutting time studies included five energy wood harvester heads: three felling heads and two roller-fed, deliming harvester heads. The current energy wood harvester head technology was thus well represented in the study. However, the material for harvester heads with feed rollers was relatively small in the study.

In the whole-tree forest haulage time study, 8 out of a total of 41 loads forwarded were classified as deficient. This was due to the fact that, in the whole-tree cutting time studies, it was impossible to accurately estimate whether the volume of wood felled is sufficient for, e.g. three loads. Whole trees were forwarded in the time study mainly by medium-duty forwarders. The time study aimed to use medium-duty forwarders as much as possible, because this reflects the way in which whole trees are nowadays primarily forwarded.

Figure 8. Effect of stand size on the relative whole-tree harvesting costs with different harvester and two-machine harvesting systems. The harvested stem size was 20 dm$^3$ (whole-tree removal 57 solid $m^3$/ha), the forwarding distance 250, and the working methods for the harvesters was as shown in Figure 6. Harvesting costs 100 = Two-machine system (Harvester for thinnings equipped with felling head) with a stand size of 185 solid $m^3$. 

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The amount of study material collected from each of the studied harwarders was relatively similar, with the exception of the Ponsse S16 Buffalo harwarder, which harvested only three whole-tree loads in one time-study stand in the time study. The Valmet 801 Combi harwarder mainly used the A2 working method in the time studies. The B working method was studied only in two time-study stands. The amount of study material on the B working method thus remained relatively small. This must be taken into account when evaluating the time consumption and productivity of harvesting work using the B working method.

The quality of the follow-up study material was weakened by the fact that comprehensive follow-up study material was obtained from only two medium-duty forwarder-based harwarders (Ponsse S15 Bison and Timberjack 1110C). The amount of follow-up study material obtained from Valmet 801 Combi harwarder was small. Long-term data concerning harvesting conditions and load sizes produced in the follow-up study were highly congruent with the harvesting conditions and load size distributions of the time-study stands. Load size differed significantly between the time studies and follow-up studies only in the case of the Valmet 801 Combi harwarder: in the time study the average load size was nearly 9 solid m$^3$, and in the follow-up study it was 7.0 solid m$^3$. One explanation for this may be the small, possibly significantly deficient loads forwarded in the follow-up study, which lowered the average load size in the follow-up study. In accordance with the prudence principle, the load size was taken to be 7 solid m$^3$ in this study for the evaluation of Valmet 801 Combi harwarder time consumption, productivity and harvesting costs.

**Results**

In the study, whole-tree harvesting time consumption equations were constructed for energy wood harwarders. The following conclusions can be drawn on the basis of comparison of the equations for the cutting and forest haulage time consumption models of two-machine harvesting system:

- In harwarder operations, the different stages of cutting and forest haulage can be effectively overlapped, which means lower time consumption during cutting (stem processing stage) and forest haulage (loading stage) than in the two-machine system:
  - With harwarders, trees felled with the harvesting grapple are loaded directly into the load space, thus decreasing the processing time consumption per stem (the bunch is transferred to the load space immediately after the last stem in the bunch is cut, as opposed to bunching them into piles beside the strip road).
  - In addition, the loading time consumption of the harwarder is further reduced in comparison to the forwarder because the bunch does not need to be loaded from the ground, but preferably the tree bunch held in the harvesting grapple is transferred directly to the load space.
- With harwarders, unloading was on the average one third slower than with forwarders. According to Laitila et al. (2004b), the time consumption of both unloading and loading is higher with a harwarder than with a forwarder. In terms of loading time consumption, the findings of this study do not support the results presented by Laitila et al. (2004b).
- In all other respects, no significant differences were found between the time consumption of the different work stages of the harwarders and two-machine system.
Comparison of the whole-tree harvesting system carried out with energy wood har-warders and with two-machine harvesting systems showed that the harvesting costs are not dramatically different for these two harvesting systems (harwarder vs. two-machine system). Nevertheless, based on the findings of this study, the energy wood harwarders should preferably be used at harvesting sites where small-sized whole trees are harvested, the whole-tree removal is small, and the forwarding distance is short. These harvesting condition factors have also been presented in earlier studies on merchantable roundwood harwarders (e.g. Kärhä, 2001; Jylhä et al., 2006).

Correspondingly, according to the results of the study, the two-machine harvesting system is the most cost-efficient in harvesting conditions where larger than average, small-sized whole-tree stems are harvested, the whole-tree removal is higher than the average, the size of the harvesting site is more than two hectares, and the forwarding distance is more than 150 m. The two-machine system was at its most competitive when using a small harvester in the harvesting system. When a medium-duty harvester was used for whole-tree cutting, the harvesting system lost its competitive advantage with respect to the harwarder.

With the heavy-duty harwarder with a rotating cab (Valmet 801 Combi), the harvesting costs were higher than with harwarders based on a conventional forwarder (Figures 6–8). Stem-processing time consumption would have been expected to be lower with a Valmet 801 Combi harwarder than with forwarder-based harwarders. However, the time studies found no significant difference between the stem-processing time consumption of the Valmet 801 Combi harwarder and forwarder-based harwarders. Whole-tree harvesting costs for heavy-duty forwarder-based harwarders were slightly lower than for medium-duty forwarder-based harwarders. The difference was due to the bigger load size of heavy-duty forwarder-based harwarders, which enabled a higher productivity.

On the basis of the results, the most efficient working method when using the harwarder with a rotating cab is the B working method, in which no separate felling of the strip road is performed, but preferably the trees on the strip road are felled and the areas between the strip roads thinned simultaneously. When using the B working method, the number of movings from one working point to another is halved compared to the A2 working method, in which the trees on the strip road are first felled and bunched into piles beside the strip road, and then both sides of the strip road are thinned and the bunched stems are loaded.

Compared to productivity functions of Laitila and Asikainen (2006) for the energy wood harwarder, the harvesting productivity is at approximately same level. However, when operating with bigger whole trees (>30 dm³) in young stands, the productivity of the energy wood harwarder in our study was to some extent higher than that in the study of Laitila and Asikainen (2006).

The cutting costs calculated in the study indicate that the energy wood harvester head has a lesser impact on cutting costs than the stem size of the marked stand. In order for whole-tree harvesting to be cost-effective, the average stem size of the whole trees in young stands must exceed 10 dm³, and the trees with a breast height diameter of 1–2 cm should not be harvested at all as whole trees. On the basis of the study, the guidelines for whole-tree harvesting are as follows:

- no individual trees of below 5 cm breast height diameter should be cut, whereas
- trees of 3–4 cm breast height diameter growing in sprouts can be cut.

These explicit guidelines should increase the cutting productivity and thus decrease the whole-tree cutting costs.
In addition to cutting productivity and costs, the stem size also influenced the whole-tree forest haulage productivity and costs: with a small stem size, the whole-tree load size remained small. Similar findings have been earlier presented by Kahala (1982). Small stem size often also means lower whole-tree removal, lower roadside tree density and smaller working locations. With small load sizes of 2–4 solid m$^3$, the costs of whole-tree forwarding rose considerably, particularly at longer forwarding distances. Load size must be maximised in forest haulage. Maximisation of load size is facilitated if the felled trees are cross-cut as long as possible to 6–7 metre, or even 8 metre logs. In this case, the strip road network of energy wood thinning stands must be planned carefully and any sharp turns avoided.

In order to reach the goal set for the annual use of forest chips for 2010, the 1.0–1.5 million solid m$^3$ of chips obtained from small-sized trees is needed. Consumption and harvesting volumes should thus double from their current levels by the year 2010. Growth in harvesting volumes requires, in turn, intensified procurement: harvesting operations must expand to include smaller and poorer quality sites. This places additional cost pressures on the production of small-sized wood chips. Energy wood harwarders offer a means of combating these cost pressures; as the study revealed, the energy wood harwarder is the most competitive in whole-tree harvesting sites with a low energy wood removal and small size, where the stem size of the marked stand is relatively small.

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