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Productivity and work processes of small-tree bundler Fixteri FX15a in energy wood harvesting from early pine dominated thinnings

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First thinnings are often neglected in Europe due to high harvesting costs. The studied small-tree bundler (Fixteri FX15a) was developed in order to rationalize the integrated harvesting of small-diameter energy wood and pulpwood in thinning operations, and to reduce transportation costs through load compaction. For the time-and-motion study, three stand types were chosen, all dominated by Scots pine (Pinus sylvestris). Two were dense, small dimension stands. The third stand was a “normal” first thinning stand. The machine fells and accumulates small-trees, which are fed into the bundling unit, where crosscutting, compaction, winding, scaling, and output of bundles of approximately 0.6 m³ solid is performed in an automated process. The productivity in the dense stand with rich undergrowth was 9.7 m³/PMh (productive machine hour), with an average tree volume of 27 dm³ and 3216 trees felled per hectare. In the dense stand with no undergrowth, a productivity of 11.9 m³/PMh was reached. The average tree volume here was 44 dm³, and 2019 trees per hectare were harvested. In the normal first thinning stand with no undergrowth, the felled trees averaged 84 dm³, 1266 trees per hectare were felled, and a productivity of 13.8 m³/PMh was registered. When compared with the previous version, the Fixteri II, the productivity of Fixteri FX15a was 2.1–2.3 times higher, depending on the density and size of the removal. Several factors may explain the increased productivity, but one of the most prominent is an improved technical potential for multi-tree handling.

Keywords: bundling; dense stands; Fixteri; productivity

Introduction

First thinnings constitute an operational dilemma in Europe: they should be carried out to improve the development of the future stand, but are often neglected due to high harvesting costs. The causes of the high harvesting costs are the small stem size and low removals. In addition, dense undergrowth often weakens the profitability of early thinnings (Kärhä et al. 2006; Oikari et al. 2010). The cutting costs constitute almost half of the production costs of forest chips from small-diameter (DBH < 10 cm) whole-trees (Kärhä et al. 2006; Laitila 2008). In harvesting the small-trees, the biggest factor is falling-piling, which accounts for 60–75% of the costs (Iwarsson Wide 2010). Based on previous studies (e.g. Brunberg et al. 1990; Sluss 1991; Johansson & Gullberg 2002; Kärhä et al. 2004, 2005; Nurminen et al. 2006; Nuutinen et al. 2010), Belbo (2011) states the strong positive influence of stem size on the harvesting costs: “The hourly cost of the man-machine system is almost independent of the tree size, while the efficiency of the harvesting is highly dependent.”

According to Oikari et al. (2010), the cost efficiency of small-diameter energy wood harvesting could be increased by improving harvesting conditions (e.g. delaying harvesting operations and pre-clearance of dense undergrowth), by rationalizing harvesting methods (e.g. integrated pulpwood and energy wood harvesting), and by training forest machine operators.

Machine innovations and novel harvesting and hauling methods are other ways to decrease wood procurement costs of early thinnings. In the Nordic countries several different cutting techniques have been launched, during the last decade, to increase harvesting productivity in young stands (Bergström 2009; Belbo 2011; Laitila 2012). So far, the most
successful small diameter wood thinning supply chain has been multi-tree harvesting with a two-machine chain. In this system, a harvester or feller-buncher cuts the trees, and a forwarder hauls them to the roadside storage (Kärhä et al. 2005; Iwarsson Wide 2010). In multi-tree handling, the accumulating felling head is capable of felling and bunching several trees in each boom cycle (Bergström 2009; Iwarsson Wide 2010; Belbo 2011; Nuutinen et al. 2011).

In 2008, the EU announced the 20/20/20 targets (European Commission 2008). The targets call for a reduction in EU greenhouse gas emissions of at least 20% below 1990 levels, with 20% of EU energy consumption to come from renewable resources and a 20% reduction in primary energy use. For many European countries, forest biomass for energy plays an important role in achieving the national targets in the climate and energy strategy of the EU (Mantau et al. 2010; Bergström & Matisons 2014). For example, forest chip production for energy in Finland has increased from less than 2 TWh in the year 2000 to 15 TWh in 2011, with 1 TWh corresponding to approximately 0.5 million m$^3$ (Ylitalo 2012). In Sweden, the use of primary forest fuels (obtained directly from the forest) has decreased slightly and was 20 TWh in 2013 (Bergström & Matisons 2014; Brunberg 2014).

The studied whole-tree bundler was developed in Finland by Fixteri Oy in order to rationalize the integrated harvesting of small-diameter energy wood and pulpwood in thinning operations, and to reduce transportation costs through load compaction. Whole-tree bundling in early thinning can generate significant benefits for the procurement system, by increasing the productivity of forwarding and making long-distance transport economically feasible (Kärhä et al. 2009; Nuutinen et al. 2011). In the deepest mode of integration, the pulp and energy fractions may be separated in the debarking drum of the pulp mill (Kärhä et al. 2009; Jylhä et al. 2010). In the study by Jylhä and Laitila (2007), the productivity of this prototype was relatively low when compared to other available harvesting technology of whole-trees. However, the concept showed potential for further development. In 2007–2009, a second version (Fixteri II) was constructed by Fixteri Oy (Kärhä et al. 2009; Jylhä et al. 2010). The first prototype of the studied whole-tree bundler was launched in 2007 by Biotukki Oy (Jylhä & Laitila 2007). In the study by Jylhä and Laitila (2007), the productivity of this prototype was relatively low when compared to other available harvesting technology of whole-trees. However, the concept showed potential for further development. In 2007–2009, a second version (Fixteri II) was constructed by Fixteri Oy (Kärhä et al. 2009; Jylhä et al. 2010).

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The objective of this study was to evaluate the productivity level of Fixteri II was mainly a result of increased multi-tree felling and the introduction of grapple feeding of the whole-tree bunches. Furthermore, the improved hydraulic capacity of the base machine enabled more simultaneous working processes. Although the productivity of the second whole-tree bundler version was significantly higher than that of the first prototype, further development was still required. The wood supply system based on whole-tree bundling was not yet economical, as the cost savings in forwarding, long-distance transport, and integrated comminution did not cover the additional cost caused by compacting whole-trees into bundles (Kärhä et al. 2009; Jylhä et al. 2010; Nuutinen et al. 2011). In 2012, a third model whole-tree bundler, Fixteri FX15a, was launched (Figure 1).

The objective of this study was to evaluate the productivity level of this third model, Fixteri FX15a, in small-tree harvesting for different stand types. The specific objectives were to investigate the felling-feeding sequence and the functions of the bundling unit and to provide suggestions for further development of the concept.

**Materials and methods**

*The Fixteri FX15a small-tree bundler and its work process*

The studied whole-tree bundler consists of a Logman 811FC base machine, a Nisula 280E+ accumulating felling head, and a Fixteri FX15a bundling unit (Figure 1). The small-tree bundler is
890 cm long, 290 cm wide and 390 cm high. Its total weight (including the bundling unit of 6500 kg) was 23,500 kg. The bundling unit is 410 cm long, 240 cm wide and 280 cm high. The power for the electric and hydraulic systems of the bundler is supplied from the base machine (Fixteri Ltd. 2014).

The operation consists of two main processes: the whole-tree felling/feeding (=cutting process) and the subsequent bucking and compaction of trees into bundles (=bundling process) (Figure 2, Table 1). The Fixteri fells and feeds trees onto the feeding table of the bundling unit, where rollers feed the whole-trees into the feeding chamber. Then, the guillotine installed at the chamber gate bucks the trees in the feeding chamber into 2.6 m lengths. Next, the cut trees are lifted from the feeding chamber into the central chamber. When there is enough tree sections for one bundle, approximately 450–550 kg green mass, the undelimbed tree sections are elevated into the compaction chamber, where they are compressed and bound with cord or netting. Most of the bundling operation is automatic, enabling simultaneous felling during bundling. When ejected from the bundling chamber, each bundle is weighed before it is dropped on the ground. The bundles are later forwarded and stacked at a roadside landing.

**Time-and-motion study of cutting (sub-study 1)**
The productivity level of the new Fixteri FX15a system in small-tree harvesting was studied in three different stand types. The specific objectives were to investigate the felling-feeding sequence and the functions of the bundling unit and to provide suggestions for further development of the concept. The influence of tree volume (average whole-tree volume of harvested trees) on the operational efficiency was analyzed. The average

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**Figure 2.** Flowchart describing the work processes divided into work elements, for the study on the time consumption by operation for the whole-tree bundler.
whole-tree volume (dm$^3$) is the total above-ground solid average volume of harvested trees per time study plot.

A time-and-motion study was carried out in Central Finland in late winter in March 2013 (Björheden & Nuutinen 2014; Nuutinen & Björheden 2014). In modern usage, time-and-motion studies cover broad and practical applications, combining the time study work of Taylor and the motion study work of Gilbreth (Niebel 1988; Nuutinen 2013). Time study covers all the ways in which time consumption is measured and analyzed in work situations (Groover 2007). The purpose of motion study is to describe the work motions and to reduce ineffective movements (Niebel 1988; Groover 2007). Data were collected from nine time study plots located in three separate stands. The productive working time with all delays excluded of each time study plot was about 1 hour. In each stand, three time study plots were established. To investigate the effects of stand density, undergrowth and tree size on productivity the plots in the stands were selected to represent the following stand types:

- dense, pine dominated, with rich undergrowth, removal 6–9 cm DBH;
- dense, pine dominated, with little or no undergrowth, removal 6–9 cm DBH;
- normal pine dominated first thinning, removal 10–14 cm DBH.

Time study plots were 50 m long and 20 m wide and included two rectangular stand data plots of 100 m$^2$ from which stand data were collected (Figure 3). Table 2 presents the stand characteristics of the time study plots.

The output was recorded through the whole-tree bundler’s on-board production statistics system (time and weight of each bundle, as recorded by the computer) in the three stand types, as the number of bundles per time study plot and m$^3$/PMh with all delays excluded. In the Nordic countries PMh is to equivalent to Effective time, E$_{0}$h or G$_{0}$h, (Nordic Forest Work Study Council 1978). The bundle weights were transformed into solid cubic meters using the conversion factor 855 kg = 1 m$^3$ (Lindblad et al. 2010a, 2010b; Lindblad 2013). No samples were
collected to define the volume conversion factor. In the study by Kärhämä et al. (2009), the volume conversion factor varied from 809 – 988, with an average of 906 and the standard error 41. In this study, the dry masses of whole-trees were transformed into fresh weights using a moisture content of 55%. In the study by Kärhämä et al. (2009), the moisture content of fresh bundles varied in the range of 53 – 57%.

The time-and-motion study of cutting involved one researcher observing the work, using a handheld field computer (Rufco DL 2). Time was recorded using the continuous timing method, and work elements were separated from each other by numeric codes. The work processes were recorded and divided into work elements according to Table 1. The time study data was recorded by the first author, a professional work study researcher with several years of experience on time studies of mechanized logging (Nuutinen et al. 2008; Nuutinen 2013). During the experiment, the researcher observed the work productivity outside the risk zone, so that he was not disturbing the work of the operator. Furthermore, the observer had all the work safety equipment according to industrial safety legislation: an orange safety vest and a safety helmet with hearing protectors.

The main purpose of the time-and-motion study of cutting was to evaluate the felling-feeding sequence of the Fixteri. When recording the work elements, the crane functions had the highest priority, and the moving and bundling elements were next in priority, respectively (Table 1). In other words, during crane functions, other simultaneous work elements were not recorded.

In the experiment of this study, the operation consisted of the felling of whole-trees and the bucking-compaction of whole-trees into energy wood bundles. The time study experiments were conducted in a traditional strip road thinning method (Figure 3). During the experiments, the smallest trees (DBH <6 cm) were harvested and compacted into bundles only when they were included at no extra time expenditure, meaning together with larger trees, otherwise they were left in the stand.

It is a well-known fact that the operator, machine, and environment have a substantial influence on the general work output, particularly in mechanized logging (Kariniemi 2006; Väätäinen et al. 2005; Ovaskainen 2009; Palander et al. 2012). In the present study, the terrain conditions were equal on all time study plots. Using only one skilled operator under comparable conditions strengthens the reliability of the results regarding the effects of stand density and tree size on productivity.

**Technical function test (sub-study 2)**

The studied Fixteri whole-tree bundler concept consists of three sub-systems:

1. A machine platform (chassis), providing power (hydraulics) and mobility;
2. A felling-feeding system (crane and accumulating felling head);
3. A bundling system (the Fixteri bundling unit).

As part of the evaluation a technical function test was carried out, to investigate if bottlenecks between the sub-systems 2 and 3 were restricting overall productivity (Björheden & Nuutinen 2014; Nuutinen & Björheden 2014). The technical function test was based on the information in Table 3. There, the total above-ground (= whole-tree, including

<table>
<thead>
<tr>
<th>Table 2. Stand characteristics of the time study plots.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand measurement</td>
</tr>
<tr>
<td>Stand before cutting</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Removal, whole-trees</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Stand after cutting</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Notes: a without top and branches; b the tree species mixture-%, of number of trees.
pre-commercial top and branches) fresh weights of removed trees is presented, based on the functions of Repola (2009), with an assumed moisture content of 55%. Tree heights were computed using the model of Siipilehto (1999). The fresh weights were converted into solid volumes using the conversion factor 855 kg = 1 m$^3$ (Lindblad et al. 2010a, 2010b; Lindblad 2013).

### Capacity of the crane work

For the crane work, the productivity analysis was conducted for the range of removed whole-tree sizes that the studied felling head was able to effectively handle, with stump diameters ranging from 5 cm (= 4.50–5.49 cm) to 17 cm (Table 3). For the analysis, ideally sized grapple bunches were constructed. An ideal bunch was defined as the maximum number of trees of a certain size that fits in the felling head. The felling head’s maximum capacity (Table 3) was defined by the manufacturer Nisula Forest Ltd.

The maximal number of trees in the felling head is a theoretical mean value, which means that in practice, the number of trees in the full felling head may differ from these values. The reason for this is the variation of branches, curves, and lengths in the trees. In addition, the position of the tree in the head and the operator’s working technique play important roles for the proportion of multi-tree handled trees. According to the manufacturer, the studied felling head is not able to effectively fell and feed trees larger than stump diameter 17 cm.

The crane cycle time model (Equation 1, Table 4) was formulated through regression analysis. The time consumption of felling-feeding (sum of work elements: crane out, fell A/B, crane in, feed) (Table 1) was the dependent variable, and the number of accumulated trees in a full felling head was the independent variable. The time function was based on the actual data of the time-and-motion study from the study stand “young, dense, no undergrowth”.

### Capacity of the bundling unit

For the bundling unit analysis, in September 2013, in the region of Kuhmoinen, a second field experiment was conducted wherein the studied bundle harvester’s operation was video-recorded for approximately 1 hour. From the video, the work elements of the bundling processes (see Figures 1 and 2) were determined. The durations and proportions of the work elements were also analyzed. The video analysis gave an overall picture of the bundling unit’s function for the further detailed simulation of the bundling unit operation.

For the technical function test, an ideal processing rate was simulated for the bundling unit. In actual operation, the bundling unit gets the power for its electrical and hydraulic system from the base machine, and the bundling capacity is reliant on the power fed by the base machine.

The simulation was carried out using the Excel software-based technical function matrix of the bundling unit provided by Fixteri Ltd. The bundling unit’s ideal processing rate was simulated for the same sizes of whole-trees as in the crane work analysis (Table 3). For each tree size, a goal weight

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**Table 3.** The features of whole-trees used in the technical function test.

<table>
<thead>
<tr>
<th>Stump diameter (cm)</th>
<th>Breast height diameter (cm)</th>
<th>Height (m)</th>
<th>Total above-ground solid volume (dm$^3$)</th>
<th>Total above-ground fresh weight (kg)</th>
<th>Number of trees in full grapple bunch (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.4</td>
<td>3.9</td>
<td>3.0</td>
<td>2.6</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>4.0</td>
<td>5.9</td>
<td>7.5</td>
<td>6.4</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>5.6</td>
<td>7.5</td>
<td>15.4</td>
<td>13.2</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>7.2</td>
<td>8.8</td>
<td>27.5</td>
<td>23.5</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>8.8</td>
<td>9.9</td>
<td>44.4</td>
<td>38.0</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>10.4</td>
<td>10.7</td>
<td>66.3</td>
<td>56.7</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>12.0</td>
<td>11.5</td>
<td>93.2</td>
<td>79.7</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 4.** Statistical information on the regression model for the time consumption of cutting ($t_c$), with time consumption of cutting (in seconds) being the dependent variable and the natural logarithm of the number of accumulated trees (Ln($n_{trees}$)) in the full felling head being the independent variable (Equation 1, Figure 9). The model is based on 171 observations ($n$), and yielded an $r^2$ of 0.252.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter estimate</th>
<th>SE</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>20.946</td>
<td>1.652</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Ln($n_{trees}$)</td>
<td>10.982</td>
<td>1.456</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
bundle was defined, being as close as possible to 500 kg (approximately 0.6 m\(^3\) solid), with an integer number of ideally sized grapple bunches (Table 3). In the simulation, the ideally sized grapple bunches were assumed to feed without interruption into the bundling unit. For each tree size class, an ideal time for processing the goal bundle was simulated. The ideal time is the shortest technically possible time needed to perform the sum of work elements of the bundling process (feeding, cross-cutting, lifting, and compacting the tree bunches to achieve a goal weight bundle). In the simulation, the variables for each tree size class were:

- goal weights of the bundles for each tree size class;
- the stump diameter, length, and solid volume of a tree in a specified tree size class;
- the number of trees in an ideally sized grapple bunch for each tree size class;
- the number of ideally sized grapple bunches needed to achieve a goal bundle.

In the simulation, the numbers represent an ideal situation that is not likely to occur in real operations. However, this is of minor importance for this part of the study, since the aim of this analysis is to investigate the balance between the two interdependent work processes of felling-feeding and bucking-bundling, respectively.

**Results**

**Distribution of effective work time**

According to the observations of sub-study 1 (Table 1), the operation of the whole-tree bundler consists of three main work processes:

1. The work process *felling-feeding* includes cutting the whole-trees and bringing them to the bundling unit (work elements: crane out, fell A/B, crane in, and feed);
2. The work process *arrangement of products* includes sorting the felled trees and processed bundles on the ground (work elements: arrangement of trees and arrangement of bundles);
3. The work process *operation excluding crane work* includes moving during the operation, cutting the whole-trees in the bundling unit, compressing and binding the bunch of trees, weighing, and dropping the bundle onto the strip road (work elements: moving, bundling, and dropping/weighing a bundle).

When recording the entire working process, *felling-feeding* and *arrangement of products* had the highest priority. Work elements of these work processes were conducted using the harvester crane. The third process, *operation excluding crane functions*, consisting of the work elements moving, bundling, and dropping/weighing a bundle, was next in priority (Table 1). Occasionally, the work elements moving, bundling, and dropping/weighing a bundle occurred simultaneously with the crane functions (felling-feeding and arrangement of products). Such overlapping durations were not recorded.

The proportion of the work process felling-feeding decreased from 83 to 61% as the average volume of the removed trees increased from 27 to 84 dm\(^3\) (Figure 4, Table 2).

**Productivity**

The observed productive machine hour, PMh, was 9.7 m\(^3\) in the dense young stand with rich undergrowth (removal 3216 trees per hectare with an average whole-tree volume of 27 dm\(^3\)). In the dense stand with no undergrowth, a productivity of 11.9 m\(^3\)/PMh was reached (removal 2019 trees per hectare, 44 dm\(^3\)/tree). In the first thinning, at an average whole-tree volume of 84 dm\(^3\) and a removal of 1266 trees per hectare, the productivity was 13.8 m\(^3\)/PMh (Figure 5).

The work process felling-feeding averaged 10.6 seconds per tree, with 8.2 seconds per tree in the dense stand with rich undergrowth, 10.1 seconds per tree in the dense stand with no undergrowth, and 13.4 seconds per tree in the first thinning stand.
For the previous prototype, Fixteri II, in the studies of Kärhä et al. (2009) and Nuutinen et al. (2011), the same work process averaged 16.3 seconds per tree (Figure 6), at an average tree size of 40 dm³.

On average, 4.3 trees were accumulated per crane cycle in the dense stand with rich undergrowth, 3.3 trees in the stand with no undergrowth and 2.1 trees in the first thinning stand. An average of 2.9 trees were accumulated per crane cycle by the previous prototype, Fixteri II (Kärhä et al. 2009; Nuutinen et al. 2011) (Figure 7).

The distribution of crane cycles by degree of accumulation (Figure 8) demonstrates the technical suitability of the equipment and the applied working method in the study stands. The proportion of grapple bunches with two or more trees was 90% for the dense stand with undergrowth, 94% for the stand with no undergrowth, and 68% for the first thinning stand. The values indicate that the undergrowth occasionally delimited the possibility to accumulate. The corresponding proportions of grapple bunches with three or more trees were 78, 68, and 31%. It is logical that the tree size is more of a determining factor in multi-tree handling, when more than two trees are accumulated. In the study stands, the new prototype reached an average proportion of 84% of crane cycles including multi-tree handling (Figure 8). The average proportion of multi-tree felling with the second prototype was 80% (Kärhä et al. 2009; Nuutinen et al. 2011).

**Technical function test**

**Capacity of the crane work**

The productivity of felling-feeding depends on the size of the grapple bunch, and on the time for moving and positioning the head to fell the trees included in the grapple bunch, the time for felling the individual trees, and the time for feeding the ready grapple bunch into the bundle unit. The size of the grapple bunch is the sum of the volumes of the individual trees in a grapple bunch. The cycle time for felling-feeding was predicted on the basis of the observed...
average time for felling-feeding various numbers of accumulated trees, expressed by the function (Equation 1, Figure 9, Tables 1, 4):

\[ t_c = 10,982\ln(n_{\text{trees}}) + 20,946 \]  

(1)

where

- \( t_c \) = the time consumption of cutting (work elements: crane out, fell A/B, crane in, feed), s
- \( n_{\text{trees}} \) = the number of accumulated trees in the full felling head
- number of grapple bunches (n) = 171
- \( r^2 \) = coefficient of determination = 0.252

Although the equation is based on a regression of observed values (see Table 4), it represents an ideal value, especially for the smallest tree size classes, through the assumption that even very high numbers of trees may be accumulated without problems, until the basal area of the trees completely fills the accumulation area of the felling head. In reality, branches and imperfections in stem form will delimit the degree of accumulation before the maximum theoretical basal area is reached.

The productivity of crane work increased significantly when the size of the accumulated trees increased: when the stump diameter/size of the cut tree was 5 cm/3.0 dm\(^3\), the productivity of felling-feeding was 2.5 m\(^3\) per Effective working hour (m\(^3\)/PMh). For the biggest trees, stump diameter 17 cm and size 93.2 dm\(^3\), the productivity increased to 16.0 m\(^3\)/PMh. The felling head was able to handle multiple trees of up to a stump diameter of 13 cm. When the stump diameter of the trees increased from 13 to 15 cm, the trees were processed individually, and in that case the productivity increased only from 11.2 to 11.4 m\(^3\)/PMh (Figure 10).

**Capacity of bundling unit**

The production capacity of the bundling unit varied from 23.3–36.3 m\(^3\)/PMh. To produce one goal weight bundle (approximately 500 kg) 198–6 whole-trees were needed for stump diameter classes from 5–17 cm (Table 3). When the length and size of grapple bunch trees increased, the productivity also increased slightly. The reason for this was that the duration of feeding and cutting the tree bunches in the feeding chamber decreased when the length and size of the grapple bunches increased. The highest productivity figures (36.3 m\(^3\)/PMh and 29.1 m\(^3\)/PMh) were reached for processing the biggest goal bundles (526.4 kg and 531.5 kg). The results indicate that the bundle size has a positive influence on productivity (Figure 11).
Balance between the bundling unit and felling-feeding

The bundling unit has a significantly higher capacity than the crane and felling head. The balance between these two sub-systems was analyzed by setting the capacity of the bundling unit to 1 and thereafter comparing the respective relative capacity of felling-feeding. The analysis shows that the felling-feeding sub-system restricts the production of the concept. The capacity of felling-feeding varied from 11–57% of the capacity of the bundling depending on tree size (Figure 12).

Discussion

The productivity of the Fixteri FX15a whole-tree bundler is significantly higher than reported for the previous prototype, Fixteri II. In the dense stand with undergrowth, the productivity for the Fixteri FX15a was 9.7 m³/PMh, and in the dense stand with no undergrowth, a productivity of 11.9 m³/PMh was reached (Figure 5). In the studies of Fixteri II by Kärhä et al. (2009) and Nuutinen et al. (2011), the average productivity was 5.1 m³/PMh, when the density of removal was 1400 trees per hectare and the average tree volume was 40 dm³, thus under similar conditions. With an average whole-tree volume of 31 dm³ and a removal density of 2850 trees per hectare, a productivity of 4.6 m³/PMh was reached. Thus, the productivity of the Fixteri FX15a is 2.1–2.3 times higher, depending on stand density and average whole-tree volume of the removal (Figure 13).

The higher productivity of the new Fixteri FX15a results from increased multi-tree felling-feeding, resulting in a decrease of 35% in crane cycle time per tree, compared to the previous Fixteri II model (Figure 6). The increased performance of crane
work enables more effective feeding of the bundling unit. The new felling head could also transfer more trees per grapple bunch to the bundling unit. The average number of trees per crane cycle was 4.3 trees for the dense stand with undergrowth, 3.3 trees for the stand with no undergrowth, and 2.1 trees for the first thinning stand. Respectively, on average, 2.9 trees were accumulated per crane cycle by the previous prototype, Fixteri II (Kärhä et al. 2009; Nuutinen et al. 2011) (Figure 7). Iwarsson Wide (2010) states that the number of trees per crane cycle is a critical parameter for multi-tree handling in small diameter stands. Belbo (2011) showed, through simulation, that the optimal number of accumulated trees in multi-tree cutting is 4–5 trees per crane cycle.

The two young dense study stands, where the average volume of removed whole-trees was 27 and 44 dm$^3$ respectively, proved to be a more suitable operating area for the accumulating felling head than the first thinning stand. There, the removed trees, averaging 84 dm$^3$, were too large for multi-tree handling. The conclusion is based on the following observations:

- duration for the work element arrangement of felled trees (Table 1) increased from a level of 3% in young stands to more than 7% in the first thinning; and
- the average proportion of multi-tree handled trees (meaning grapple bunches with two or more trees) was only 68% in the first thinning, compared to 90% and 94% in young stands.

In the technical function test, the ideal production capacity of the bundling unit was from 2–10 times higher than the possible level of felling-feeding in the working environment of sub-study 1 (Figure 12). The results indicate that the studied whole-tree bundling concept is optimal when processing trees of an average DBH of 6–9 cm. For bigger trees, felling-feeding became more difficult, while for smaller trees, the harvesting cost is probably too high.

The capacity of felling-feeding was mostly dependent on the size of the trees and on the grapple bunch size. The productivity of felling-feeding decreased significantly for the smallest trees (stump diameter <9 cm, Figure 10). The studied felling head could handle multiple trees of up to a stump diameter of 13 cm. Trees from stump diameter 15 cm were processed individually, indicating that accumulation of two 15 cm trees was not practicable (Figure 10, Table 3). These findings should be confirmed by further experiments.

In the actual time-and-motion study, for the study stand young dense no undergrowth, the average duration of accumulation of the trees (work element: fell A/B) increased from 3.4 to 21.5 seconds per grapple bunch, when the number of accumulated trees increased from 1 to 5 trees. Respectively, the combined duration of the work elements crane out, crane in, and feed stayed at a constant level, in the range of 17.6–20.4 seconds per grapple bunch cycle (see Figure 8, Table 1). These results indicate that felling-accumulation is an important development target for multi-tree cutting.
The results of the technical function test imply that felling-feeding is a bottleneck for the studied machine concept. In order to increase the performance, the efficiency of felling-feeding should be increased, for example by:

- improved crane work by, e.g. optimal crane-geometry, cabin design, and semi-automation;
- improved function of the felling head for the accumulation, sorting and handling of felled trees;
- developing feeding of the tree bunches into the bundling unit;
- applying a technology that enables continuous accumulation and felling of trees;
- especially in harvesting trees of a whole-tree volume of less than 15–20 dm$^3$, considering some other technical felling-head solution as the studied head.

The simulation of the ideal productivity of the bundling unit indicates that the best bundling productivity is reached by producing the biggest bundles possible. This demands cutting and feeding the longest and biggest whole-tree bunches possible into the bundling unit (Figure 11). The size and length of the whole-tree bunches seem to have the most significant influence on the feeding and cutting speed of stems in the bundling unit. The reason for this is that, when compacting the shorter trees, a larger number of tops that are under 2.6 m long decreases the feeding speed of tree bunches.

Ala-Varvi and Ovaskainen (2013) studied the competitiveness of the Fixteri FX15a small-tree bundler, compared to the cutting of undelimbged trees with a John Deere 1070D harvester equipped with a H412 accumulating harvester head. In the study, the productivity of Fixteri FX15a was 9.7 m$^3$/PMh with an average tree volume of 37 dm$^3$. Respectively a productivity of 10.5 m$^3$/PMh was reached in cutting of undelimbged trees with an average tree volume of 48 dm$^3$.

Ala-Varvi and Ovaskainen (2013) determined the costs of cutting and forwarding of both supply chains at an average tree volume of 40 dm$^3$, forwarding distance of 300 m and harvesting removal of 60 m$^3$ per hectare. The cost of whole-tree bundling operation was 13.6 €/m$^3$ and for cutting of undelimbged trees 15.3 €/m$^3$. The cost for forwarding the bundles was 3.57 €/m$^3$ and respectively for delimbed trees 5.56 €/m$^3$. They found the total cost of the wood chip supply chain of whole-tree bundling (46.7 €/m$^3$) to be lower compared to undelimbged trees (50.2 €/m$^3$) if the average volume of removed trees was less than 85 dm$^3$.

Also Bergström et al. (2015) studied the effect of tree size and undergrowth on the operational efficiency of the Fixteri FX15a bundle harvester in early fuel wood thinnings in the North of Sweden. Their studies of the machine productivity focused on stands with an average harvested tree size below 30 dm$^3$ (the average tree volume in the time study plots varied from 15–43 dm$^3$). The harvested forest was 30–35-years-old and composed mostly of Scots pine, Norway spruce and birch. The recorded performance is similar to the findings of this study.

In the dissertations of Bergström (2009), Belbo (2011), Jylhä (2011), Röser (2012), Laitila (2012), and Nuutinen (2013), the feasibility of methods and techniques in pre-commercial and early thinning was evaluated and developed. The studies aimed to increase the understanding of the functions of harvesting work, develop the efficiency of supply chains and estimate their costs, evaluate existing technology and suggest improvements for reducing costs and evaluate the effects of using new methods and techniques intended to increase the efficiency. These studies have confirmed that new techniques and methods can significantly increase the productivity and cost-efficiency of small-diameter harvesting.

Several studies have shown that the operator has a significant effect on harvesting productivity (e.g. Kariniemi 2006; Sirén 1998; Ryynänen & Rönkkö 2001; Laamanen 2004; Vääätäinen et al. 2005; Purfürst & Erler 2006). In the study by Vääätäinen et al. (2005), the differences between the harvester operators in thinning productivity varied from 40–55%, depending on the stem size processed. The productivity leap of the new Fixteri model recorded in the present study, from 111 to 133% compared to the previous model, is so significant that, although the operator was not the same as in previous studies, the new technical features of the whole-tree bundler are likely to account for a substantial part of the increased productivity.

The findings of this and other recent studies (Ala-Varvi & Ovaskainen 2013; Bergström et al. 2015) of the Fixteri FX15a indicate that bundling whole-trees is an interesting alternative for harvesting small-diameter trees. The competitiveness is highly dependent on wood chip prices, energy and forest policies etc. as well as on the characteristics of the stand. Further studies of the bundling operation in varying harvesting conditions and methods are desirable.

Disclosure Statement
No potential conflict of interest was reported by the authors.
References


Lindblad J. 2013. Energipuun mittauksen kehittäminen – hankkeen loppuraportti [Developing measurement of energy wood – final report]; 12 p. [In Finnish].

Lindblad J, Äijälä O, Koistinen A. 2010a. Energipuun mittaus [Energy wood measurement]; 31 p. [In Swedish].

Lindblad J, Äijälä O, Koistinen A. 2010b. Mätning av energiver. [Energy wood measurement]; 31 p. [In Swedish].


Röser D. 2012. Operational efficiency of forest energy supply chains in different operational environments [dissertation]. University of Eastern Finland, Faculty of Science and Forestry. Dissertationes Forestales 146; 83 p.


