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Productivity and Cost-Efficiency of Bundling Logging Residues at Roadside Landing

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Abstract – Nacrtak

The aim of this case study was to clarify the productivity and cost of a system based on bundling logging residues at the roadside landing with the forwarder-mounted logging residue bundler. In order to find the bundling productivity, a set of time studies was carried out, in which several working techniques were tested and evaluated. The cost-efficiency of the roadside bundling system was compared with the conventional bundling system, wherein the logging of residue logs is made directly in the terrain and, after bundling, the logging residue logs are forwarded to the roadside landing with a forwarder. The harvesting cost (bundling and forwarding) of the extracted wood biomass to the roadside landing was calculated for bundling systems using time study data obtained from this study and productivity models and cost parameters acquired from the literature.

The productivity of roadside bundling ranged from 48 to 53 logging residue logs per effective working hour (E_0h), depending on the working technique used, and the mean time required to produce one logging residue log ranged from 83.6 to 92.3 seconds (E_0h). The harvesting costs of the logging residue logs (€/m^3) at the roadside landing were 11.5–13.7 €/m^3 for the system based on bundling in terrain and 10.8–17.7 €/m^3 for the system based on bundling at the roadside landing, when the forwarding distance was in the range 100–600 m and the removal of logging residues was in the range 30–90 m^3/ha (m^3 = solid cubic metre). According to our results, bundling at the roadside landing allowed a reduction in harvesting costs, when the forwarding distance of the logging residues was 100 m or less and removal was beyond 50 m^3/ha. The cost savings were quite small, however, at 0.1–0.7 €/m^3.

Keywords: Bundling, logging residue logs, productivity, compaction, harvesting, forest biomass, logging residue bundler

1. Introduction – *Uvod*

The system, based on logging residue logs and comminution at a plant was launched into commercial use in Finland in the beginning of 2000, when the supply of forest biomass to the world's largest biofuel-fired CHP plant – Oy Alholmes Kraft Ab – was developed (Laitila 2000, Poikola et al. 2002). Due to the long transport distances, large procurement area and enormous annual harvesting volumes, the circumstances for introducing the novel large-scale production technology were favourable on the west coast of Finland. In addition, integration of bundle production into the procurement of industrial roundwood was straightforward, and the synergies were significant because the CHP plant Alholmens Kraft is located within the large pulp-, paper- and sawmill integrate of the forest industry company UPM (Laitila 2000, Poikola et al. 2002). Another benefit was that all the machines in the supply system were able to operate independently of each other, making the system more efficient and reliable (Laitila 2000, Poikola et al. 2002).

In the bundling method (Fig. 1), logging residues are bundled into cylindrical bales using the compacting device mounted on top of the forwarder deck (e.g. Laitila 2000, Ranta 2002, Cuchet et al. 2004, Johansson et al. 2006, Kärhä and Vartiamäki 2006, Stampfer and Kanzian 2006, Spinelli and Magagnotti 2009, Lindroos et al. 2010, Spinelli et al. 2012a, Spinelli et al. 2012b). Feeding and compacting is usually a continuous process, and for these bundling machines (e.g. Timber-

Fig. 1 Forwarder-mounted Timberjack/John Deere 1490D logging residue bundler operating in a clear-cut area

Slika 1. *Rad forvardera Timberjack/John Deere 1490D s ugrađenim bandlerom za šumski ostatak u čistoj sječi*

jack/John Deere 1490D, Pika/Pinox RS 2000), compacting can be divided into three phases (Ranta 2002). In the first phase, the collected logging residues are pressed by feed rollers. The compacting then continues in a rectangular presser. The last compacting phase ends with the binding of the pulse-fed logging residue bundle and, finally, the bundle is cut into the desired length with a chainsaw. The length of the bundle (logging residue log) can be selected but it is typically about 3 m with a diameter of 65–75 cm. The average weight is 418 kg (sd. 111), the solid volume 0.5 m^3 (sd. 0.09) and the energy content approx. 1 MWh (sd. 0.17) (Kärhä and Vartiamäki 2006).

To accrue the benefits of compaction as early as possible along the supply chain, log-like bundles are made directly at the stump (Fig. 1) and the bundler must therefore be installed on a vehicle capable of accessing the cut area (Laitila 2000, Asikainen et al. 2001, Ranta 2002, Cuchet et al. 2004, Kärhä and Vartiamäki 2006, Spinelli and Magagnotti 2009, Spinelli et al. 2012a, Spinelli et al. 2012b). At the stand, the bundler drives to the logging residue heap or windrow and stops to load logging residues into the bundler in-feed. The bundling unit follows an automatic cycle with actions activated by internal load sensors. Loading and in-feeding work continue until no more logging residue is within crane reach. Then the forwarder-mounted bundler moves to the next windrow and resumes the work cycle (Asikainen et al. 2001, Cuchet et al. 2004, Kärhä and Vartiamäki 2006).

In the studies conducted in Finland and France, the bundling productivities have ranged from 11 to 26 logging residue logs per operating working hour ($E_{15}h$) (Asikainen et al. 2001, Cuchet et al. 2004, Kärhä and Vartiamäki 2006). In the most recent Swedish follow-up study, the average bundling productivity was 28 logging residue logs per effective working hour (E_0h) for the John Deere 1490D logging residue bundler (Eliasson 2011).

After bundling, the logging residue logs are forwarded to the roadside landing with standard forwarders. At the landing, the logging residue logs are stacked alongside conventional timber assortments and transported with the standard timber trucks to the terminal or end-use facility (Laitila 2000, Asikainen et al. 2001, Ranta 2002, Johansson et al. 2006, Kärhä and Vartiamäki 2006, Stampfer and Kanzian 2006, Jylhä and Laitila 2007, Spinelli and Magagnotti 2009, Lindroos et al. 2010, Spinelli et al. 2012a, Spinelli et al. 2012b). Logging residue logs dry well and have good storage properties if handled correctly (Petterson and Nordfjell 2009, Eliasson 2011). The unloading of the logging residue logs takes place at the end-use facility with similar equipment to that for unloading saw logs or pulpwood. In the most efficient cases, the logging residue logs are unloaded directly from the timber truck to the feeding table of the stationary crusher (Laitila 2000, Asikainen et al. 2001, Ranta 2002).

In the large-scale procurement of logging residue chips, bundling has proved to be cost-efficient when operating with long forwarding and road transportation distances (e.g. Andersson 2000, Laitila 2000, Asikainen et al. 2001, Kärhä and Vartiamäki 2006, Ranta and Rinne 2006). However, in current harvesting operations, e.g. in Finland, the average forwarding distances for logging residues are usually < 300 m, road transporting distances to CHP plants < 100 km and the annual consumption of forest chips per CHP plant almost invariably < 100,000 m^3 (solid) (Asikainen et al. 2001, Laitila et al. 2010, Karttunen et al. 2012), and the expected breakthrough of logging residue bundling technology was therefore not achieved. Kärhä and Vartiamäki (2006) underlined that the prerequisite for increased bundling volumes is a reduction in the cost of the most expensive sub-stage of the bundling supply chain, i.e. the bundling itself. This requires, e.g., improved recovering conditions at bundling sites, increased bundling productivity and the execution of bundling operations in two work shifts using an efficient bundler and efficient operator working methods (Kärhä and Vartiamäki 2006).

A less well-developed alternative in Nordic is to forward loose logging residues and bundle them at the landing. Potential benefits of such a bundling process include a higher concentration of logging residues be-

Table 1 Number of bundled logging residue logs per working technique and temperature during the time study
Tablica 1. *Broj izrađenih svežnjeva tijekom studija vremena po radnoj tehnici i temperaturi*

	Working technique I *Radna tehnika I*	Working technique II *Radna tehnika II*	Working technique III *Radna tehnika III*	Working technique IV *Radna tehnika IV*	Working technique V *Radna tehnika V*
No. of logging residue logs *Broj izrađenih svežnjeva*	201	193	82	94	113
Temperature, C° *Temperatura, C°*	–10	–3	–22	–3 & –22	–22

cause residue concentration and presentation have already been recognized as major variables affecting bundler productivity (Cuchet et al. 2004, Kärhä and Vartiamäki 2006) and avoidance of requirements for the expensive bundling vehicles to have off-road capabilities (Wittkopf 2004, Kanzian 2005, Stampfer and Kanzian 2006, Spinelli and Magagnotti 2009, Lindroos et al. 2010, Gallagher et al. 2010, Spinelli et al. 2012b). A truck-mounted bundler (Spinelli and Magagnotti 2009, Lindroos et al. 2010, Spinelli et al. 2012b) would also be a solution for more cost-efficient recovery of logging residues from small, scattered cutting areas due to the smaller relocation costs. One option tested in a Southern U.S. tree length logging operation, in order to reduce costs and maximize bundling efficiency, was to adapt the simplified bundler unit for a motorized trailer and feed it by the separate loader at the landing (Gallagher et al. 2010).

According to Spinelli and Magagnotti (2009), working at the roadside allows for a reduction in machine moving time from 1–2 min/ton (Cuchet et al. 2004) to 0.3–0.5 min/ton, but this fact alone does not seem to entail a marked productivity gain; in fact, the forwarder-mounted bundler seems to compensate for this with a faster bundling pace, which is the result of its capacity to bundle while moving. In this case, the time is recorded as »moving«, but the machine is also bundling during part of this time, thus maintaining sustained productivity.

2. Aim of the study – *Cilj istraživanja*

The aim of this case study was to clarify the productivity and cost of a system based on bundling logging residues at the roadside landing with the forwarder-mounted logging residue bundler (John Deere 1490D). In order to find the bundling productivity, a set of time studies was carried out, in which several working techniques were tested and evaluated. The cost-efficiency of the roadside bundling system was compared with the conventional bundling system, wherein bundles are made directly in the terrain, and, after bundling, the logging residue logs are forwarded to the roadside landing with a forwarder. The harvesting cost (€/m³) of wood biomass extracted to the road side landing was calculated for both bundling systems using time study data obtained from this study, and productivity models and cost parameters acquired from the literature (Ranta 2002, Kärhä et al. 2004, Laitila et al. 2010). The bundling system cost comparison was made at the stand level, and, in the cost comparison, the forwarding distance was in the range 100–600 m and the removal of logging residues was in the range 30–90 m³/ha.

3. Material and Methods – *Materijal i metode*

3.1 Time study of roadside bundling – *Studij vremena izradbe svežnjeva uz cestu*

The time study of roadside bundling was conducted in December 2009 at a roadside landing (62°19.398′N, 30°38.691′E) located in the province of North Karelia in eastern Finland. During the time study, 683 logging residue logs were bundled and five different working techniques were tested (Fig. 2, Table 1). The time study was carried out mainly in natural light during the daytime (7:00–6:00). The sky was cloudless and the temperature range was –3 to –22 C° (Table 1). The ground had snow cover of 0–1 cm during the experiments (Fig. 3). The length of the bundles was 3 m and the diameter 70 cm. In the time studies, the productivity unit logged residue logs per effective working hour (E_0h).

The bundled logging residues originated from a clear-cut stand dominated by Norway spruce (*Picea abies*), with an average age of the harvested trees of 90 years, height 24 m and diameter ($d_{1.3}$) 28 cm. The minimum length of the harvested industrial roundwood was 3 m and the minimum top diameter was 7 cm (over the bark). The clear cut had been carried out me-

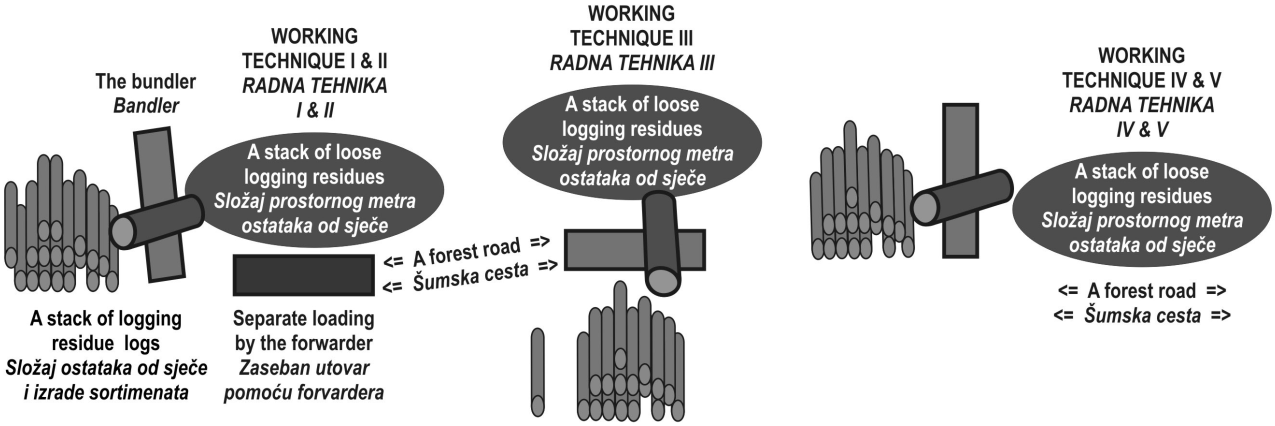

Fig. 2 Layout of the bundling study arrangements at the roadside landing using working technique I, II, III, IV or V

Slika 2. *Prikaz raspodjele stadija izradbe svežnjeva na pomoćnom stovarištu pomoću radne tehnike I, II, III, IV ili V*

chanically in April 2009 using a cut-to-length method adapted for the recovery of logging residues (Brunberg 1991, Wigren 1991, Wigren 1992, Nurmi 1994). In July 2009, after drying, »brown« logging residues were forwarded to the roadside landing and piled into stacks with a width of 7 m and a height of 5 m (Fig. 3). The total area of the clear cut was extraordinarily large (50 hectares), which made it possible to carry out the bundling study at one stand with homogeneous raw material and similar bundling conditions for each working technique at the roadside landing. The bundle properties (moisture, solid content, etc.) were not studied because they were expected, as estimated by the author, to be similar for all the studied working techniques due to the homogenous bundling material and the same logging residue bundler. It was also deemed that the properties of the logging residue logs produced at the roadside landing do not differ from those produced in the terrain, as the raw material and compacting unit/bundler are the same.

The layout of the studied working techniques is described in Fig. 2. In working techniques I and II, two machines were operating at the roadside landing because the feeding of the bundler was carried out with a separate loader (forwarder) in order to steer the full hydraulic capacity of the logging residue bundler into the bundling process. The bundler was located across from the logging residue stack, and the loader (forwarder) was on the forest road parallel to the logging residue stack (Fig. 2 and 3). The piling of the bundles in the roadside stack was carried out as a separate operation with the loader (forwarder) at the end of the roadside bundling operation (I) or during the bundling process with the crane of the logging residue bundler (II). In working techniques III, IV & V, the feeding of the bundler was carried out with the crane of the logging residue bundler, and one machine was operating at the landing. The piling of logging residues was carried out either as a separate operation after bundling (III and IV) or during bundling (V). In working technique III, the logging residue bundler was located on the forest road parallel to the logging residue stack, whereas in working techniques IV and V, the bundler was located across from the logging residue stack (Fig. 2).

Fig. 3 Separate loading of logging residues with the Valmet 840.3 forwarder to the feeding table of the John Deere 1490D logging residue bundler (working methods I and II)

Slika 3. *Odvojen utovar šumskoga ostatka forvarderom Valmet 840.3 na opskrbnu traku bandlera za izradbu svežnjeva John Deere 1490D (radna metoda I i II)*

The machines used in the study were a John Deere 1490D Eco III logging residue bundler and a Valmet 840.3 eight-wheel forwarder (Fig. 3). The crane models of the bundler and forwarder were John Deere CF7 and Cranab CRF 8.1 C, and both were equipped with a special logging residue grapple (e.g. Ranta 2002, Kärhä and Vartiamäki 2006). Skilful and motivated machine operators were pre-trained for the studied working techniques and they had more than five years working experience in bundling or forwarding logging residues and logging residue logs.

The time study was carried out manually using the Rufco-900 field computer (Nuutinen et al. 2008). The output was estimated by counting all the logging residue logs produced during the observation time. The working time was recorded by applying a continuous timing method in which a clock runs continuously and the times for different elements are separated from each other by numeric codes (e.g. Harstela, 1991). The logging residue bundler working time was divided into effective working time (E_0h) and delay time (Haarlaa et al. 1984, Mäkelä 1986), which is a common method employed in Nordic work studies. Effective working time was divided into the following work phases in order of priority:

Loading and bundling: The work cycle began when the grapple started to move towards the logging residue stack and ended when a residue bunch was lifted and placed on the feeding table or into the chamber of the bundler and the feed rollers started to pull residues into the bundler or the compressing cylinders of the bundler started to pull residues into the chamber of the bundler.

Bundling (loading is idled): This began when the feeding rollers or belts of the bundler started to pull residues into the bundler or the compressing cylinders of the bundler started to pull residues into the chamber of the bundler and ended when the individual logging residue log was wrapped. The number of binding points was chosen to be six with double twines, because frozen and dry logging residue is breaking easily and requires more binding.

Cross-cutting (bundling and loading are idled): This began when a chainsaw emerged from a defence case and ended when the bundle dropped off.

Moving: This began when the bundler or the separate loader (forwarder) started to move and ended when the bundler and/or loader stopped moving to perform other activity. The moving time consisted of the short move from one work location to another at the roadside landing.

Piling: The piling of logging residue logs onto the roadside stack while bundling or as a separate operation after roadside bundling from the bundle heaps with the crane of the bundler or the separate loader (forwarder).

Arrangements: Repositioning of logging residues on the roadside stack in order to improve the loading work or shake off snow, ice or other impurities.

Delays: Time not related to productive bundling work but with the reason for the interruption recorded. The main reasons for the delayed times being less than 15 minutes were bundler maintenance (e.g. tightening or replacing the sawchain and adding a bundling cord to the wrapping unit of the bundler), organizational delays (e.g. telephone calls) or personal breaks.

3.2 Cost comparison of bundling methods
Usporedba troškova među metodama izradbe svežnjeva

The cost comparison of bundling systems was made at stand level and in the cost comparison, the forwarding distance was in the range 100–600 m and the removal of logging residues was in the range 30–90 m^3/ha. At the stand, logging residues were stacked in good heaps and the heaps were located on both sides of the strip road. The nature and slope of the ground surface were normal = flat (Tavoiteansioon perustuvat puutavaran … 1990).

Bundling productivity in terrain was calculated using the time-consumption model made for the Timberjack/John Deere 1490D logging residue bundler (Kärhä et al. 2004). Bundling productivity at the roadside landing was based on working technique V reported herein. The solid volume of the logging residue logs was 0.55 m^3 (Kärhä et al. 2004) for both bundling methods. The length of the logging residue logs was 3 m and it was bound at six points. The effective working hour productivity (E_0h) of the bundler in terrain or at the landing was converted into operating hour productivity ($E_{15}h$) by the coefficient 1.274 (Kärhä et al. 2004). The bundling productivity at the landing was 33.8/$E_{15}h$ logging residue logs and in terrain it was calculated as 17–18/$E_{15}h$ logging residue logs as a function of logging residue removal (30–90 m^3/ha).

The figures for the forwarding productivity of the logging residues and logging residue logs from the clear cut with a heavy forwarder (Fig. 4) were calculated using the time consumption models presented in studies by Ranta (2002) and Kärhä et al. (2004), and the effective working hour productivity (E_0h) of forwarding was converted into operating hour productivity ($E_{15}h$) by the coefficient of 1.224 (Kuitto et al. 1994, Kärhä et al. 2004). The payload of the forwarder

Fig. 4 Forwarding of pre-piled logging residues with a heavy forwarder at the stand

Slika 4. *Izvoženje neuhrpanoga šumskoga ostatka s teškim forvarderom u sastojini*

was set at 7.2 m³ for logging residues and 25 pieces (13.8 m³) for logging residue logs. The forwarding productivity of the logging residues was in the range 5.5–11.8 $m^3/E_{15}h$ as a function of forwarding distance and removal of the logging residues. The forwarding productivity of the logging residue logs was in the range 15.2–30.8 $m^3/E_{15}h$.

The operating hourly costs of the forwarder and forwarder-mounted logging residue bundler were based on the study by Laitila et al. 2010 and updated to the current cost level (November 2012) with the cost index of forest machinery »MEKKI« produced by Statistics Finland (http://www.stat.fi/til/mekki/yht_en.html) in order to guarantee the validity of the cost comparison results. The operating hourly costs of the forwarder and logging residue bundler in this study were 71.8 €/$E_{15}h$ and 85.3 €/$E_{15}h$, respectively.

4. Results – *Rezultati*

4.1 Results of the time study – *Rezultati studija vremena*

In relative terms, combined loading and bundling required on average 55–68 % and cross-cutting 12–21 % of the effective working time ($E_{15}h$), when bundling logging residues at the roadside landing (Fig. 5). The piling of logging residue logs took time, 11–13 %, except for working technique II (0 %), in which piling was carried out with the crane of the logging residue bundler during the other work phases (Fig. 5). With working tech-

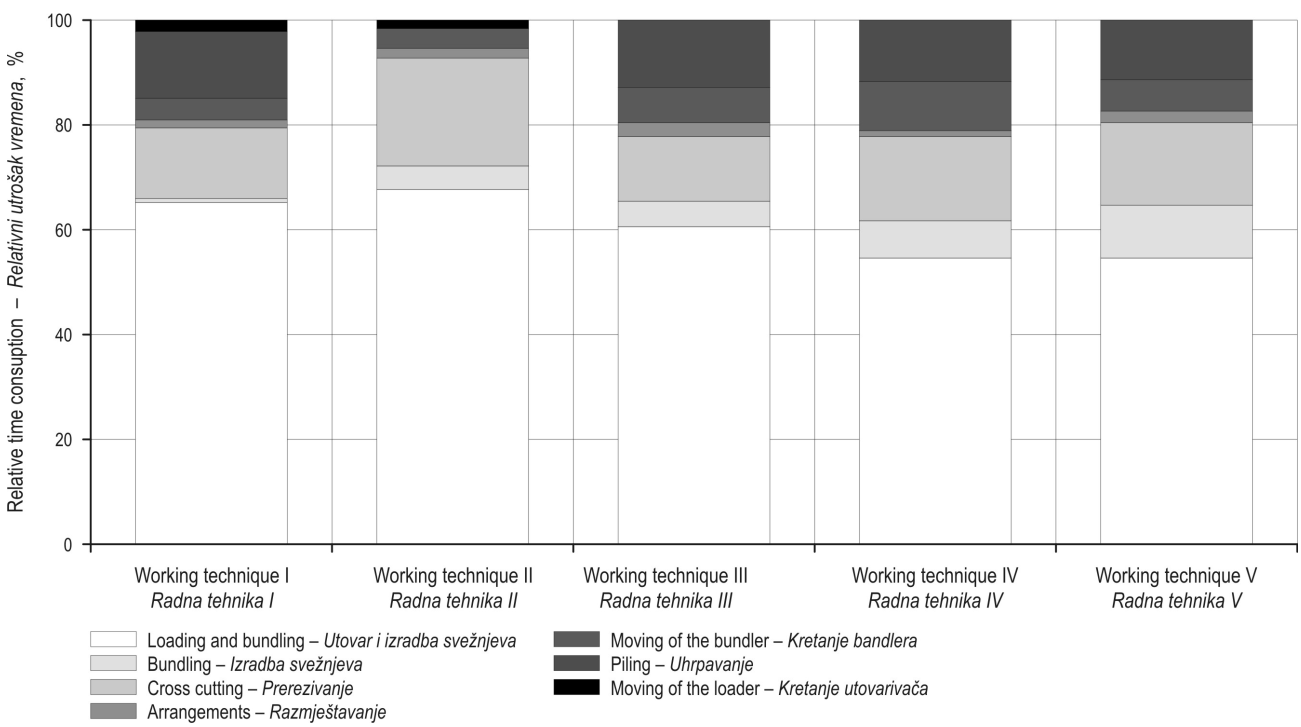

Fig. 5 Relative time consumption of work phases (%), when bundling logging residues at the roadside landing

Slika 5. *Relativan utrošak vremena po radnim fazama (%) pri izradbi svežnjeva na pomoćnom stovarištu*

Table 2 Average time consumption of the work phases per logging residue log and working technique

Tablica 2. *Prosječan utrošak vremena radnih sastavnica po izrađenom svežnju i radnim tehnikama*

	Working technique I *Radna tehnika I*	Working technique II *Radna tehnika II*	Working technique III *Radna tehnika III*	Working technique IV *Radna tehnika IV*	Working technique V *Radna tehnika V*
Moving time of the loader, s *Premještanje utovarivača,* s	2.0	1.2	–	–	–
Piling of the logging residue logs to the stack, s *Uhrpavanje izrađenih svežnjeva na složaj,* s	10.8	–	11.8	9.8	9.4
Moving time of the bundler, s *Premještanje bandlera,* s	3.4	2.5	6.2	7.9	5.1
Arrangements of the logging residue stack, s *Razmještavanje složaja šumskoga ostatka,* s	1.2	1.3	2.5	1.2	1.8
Cross-cutting of the logging residue logs, s *Prerezivanje izrađenih svežnjeva,* s	11.5	14.9	11.3	13.6	13.2
Separate bundling of logging residues, s *Zasebna izradba svežnjeva od šumskoga ostatka,* s	0.8	3.1	4.6	6.0	8.6
Loading and bundling of logging residues, s *Utovar i izradba svežnjeva od šumskoga ostatka,* s	55.5	48.5	55.9	46.8	45.6
Total time, s *Ukupno vrijeme,* s	85.3	71.6	92.3	85.3	83.6

Table 3 Average time consumption of the loading cycle (grapple load time) and the average number of grapple loads per logging residue log and working technique used

Tablica 3. *Prosječan utrošak vremena ciklusa utovara (vrijeme utovara kliještima) i prosječan broj zahvata hvatalom po izrađenom svežnju i korištenoj radnoj tehnici*

	Working technique I *Radna tehnika I*	Working technique II *Radna tehnika II*	Working technique III *Radna tehnika III*	Working technique IV *Radna tehnika IV*	Working technique V *Radna tehnika V*
Grapple load time, s *Vrijeme utovara kliještima,* s	16.4	15.5	15.7	15.7	17.1
Average number of grapple loads per bundle *Prosječan broj utovara kliještima po svežnju*	3.4	3.1	3.6	3.0	2.7

niques I and II, the shares of mere bundling were 1 % and 4 %, respectively and, with working techniques III, IV and V, the shares were 5–10 % (Fig. 5). The share of arrangements was 1–3 % for all the working techniques. The moving time for the logging residue bundler was 6–9 % of the effective working time when using working techniques III, IV and V (Fig. 5). With working techniques I and II, the total moving time was 6 % out of which the loader accounted for 2 and the logging residue bundler for 4 % (Fig. 5).

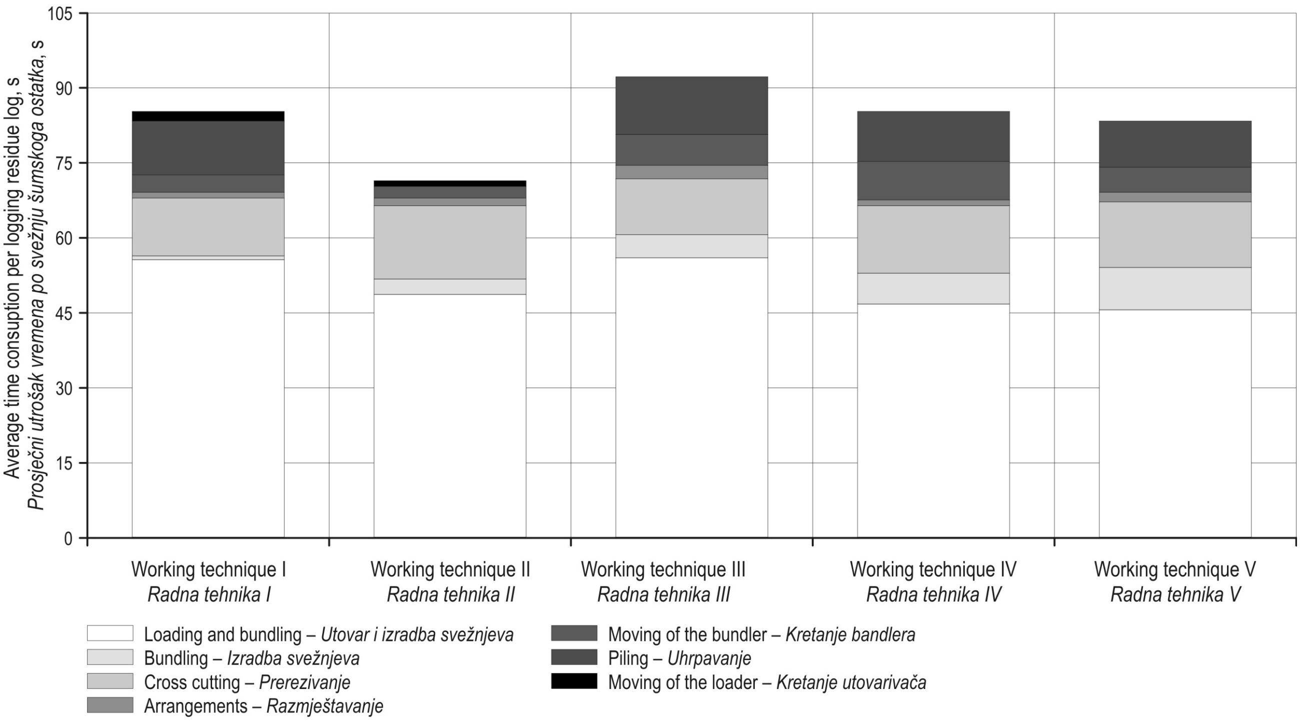

Fig. 6 Average time consumption of work phases per logging residue log in seconds

Slika 6. *Prosječan utrošak vremena radnih sastavnica po izrađenom svežnju u sekundama*

Combined bundling and loading of logging residues at the roadside landing took on average 45.6–55.9 seconds per logging residue log (Fig. 6 and Table 2). The mean number of crane grapple loads required to produce a logging residue log ranged from 2.7 to 3.6 and the average grapple load time was in the range 15.5–17.1 seconds per crane cycle (Table 3). The total mean time required to produce one logging residue log ranged from 71.6 to 92.3 seconds depending on the working technique used (Table 2, Fig. 6).

There were no big differences between the working techniques in terms of bundling productivity per effective working hour (pieces/E_0h) during the time studies and the feeding of the bundler with a separate loader did not improve the bundling productivity compared with the self-loading logging residue bundler. The productivity of mere bundling was in the range 48–53 logging residue logs per effective working hour (E_0h) depending on the working technique used (Fig. 7). When calculating the bundling productivity, the mere bundling included the time consumption of the work phases loading and bundling, bundling, cross-cutting and arrangements. The bundling productivity was 45–49 pieces/E_0h at the roadside landing when the moving time of the bundler and loader were included in the effective working time and 39–43 pieces/E_0h when the piling time was included (Fig. 7). The bundling productivity of working technique III was somewhat lower than that of the other techniques, but this can be explained by the fact that the bundler operator fell ill with the flu on the day of the time study.

4.2 Results of the bundling method cost comparison – *Rezultati usporedbe troškova među metodama izradbe svežnjeva*

The harvesting costs of the logging residue logs (€/m^3) at the roadside landing were 11.5–13.7 €/m^3 for the system based on bundling in terrain and 10.8–17.7 €/m^3 for the system based on bundling at the roadside landing, when the forwarding distance was in the range 100–600 m and the removal of logging residues was in the range 30–90 m^3/ha (Fig. 8, Table 4, cf. section 3.2 in the article). According to our results, bundling at the roadside landing enabled a reduction in harvesting costs when the forwarding distance of the logging residues was 100 m or less and the removal was beyond 50 m^3/ha (Fig. 8, Table 4). The cost savings, however, were quite small, 0.1–0.7 €/m^3. Traditional terrain bundling was clearly more cost-competitive in all stand circumstances when the forwarding distance was more than 200 m (Fig. 8, Table 4).

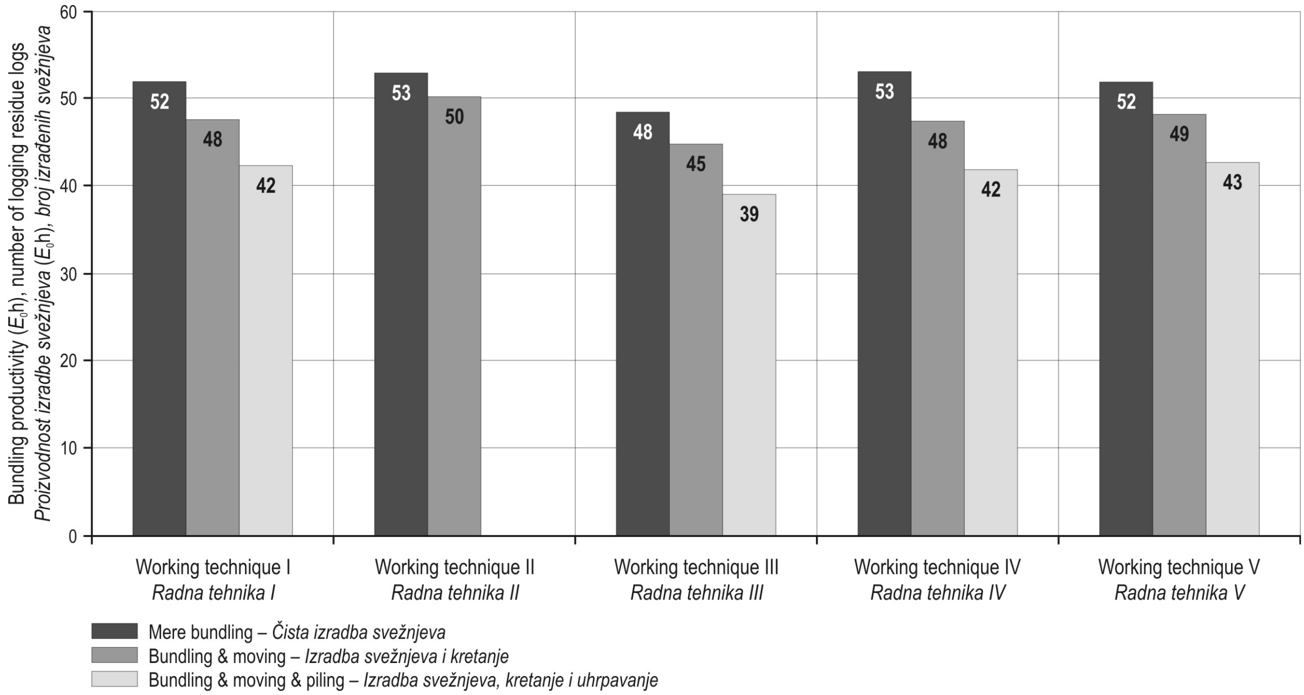

Fig. 7 Average time consumption of work phases per logging residue log in seconds
Slika 7. *Prosječan utrošak vremena radnih sastavnica po izrađenom svežnju u sekundama*

5. Discussion – *Rasprava*

According to our time study, feeding the bundler with a separate loader did not improve the bundling productivity compared with the self-loading logging residue bundler, when the length of the logging residue logs was 3 m. The main reason for the result is that the combined loading and bundling work phase was interrupted after every 3–4 grapple loads to cross-cut the produced logging residue log, which means that there was no time for the loading to become a bottleneck in the bundling system even though the efficiency and hydraulic capacity of the compacting unit itself would enable higher productivity. In order to improve the efficiency of a continuous bundling process, either a more efficient cross-cutting of bundles should be developed, or the current length of the logging residue logs should increase within the constraints imposed by the off- and on-road transportation and durability of the logging residue logs. In the studies by Spinelli and Magagnotti (2009), and Gallagher et al. (2010) the highest bundling productivity was achieved with the longest target lengths of logging residue logs. In the study by Gallagher et al. (2010), the bundling productivity was 15.9 tons/E_0h when the length of the bundles was 2.5 m and 17.2 tons/E_0h for a bundle length of 3.5 m.

The productivity (39–43 pieces/E_0h) achieved in this study is higher than that reported in the others studies conducted on the truck-mounted logging residue bundler under central European conditions in Germany, Austria and Italy (Wittkopf 2004, Kanzian 2005, Spinelli and Magagnotti 2009, Spinelli et al. 2012b). In Germany, Wittkopf (2004) reports productivity of 12 pieces/E_{15}h and in Austria, Kanzian (2005) mentions productivity of 11.5–15.2 pieces/E_0h. In Italy, the productivity varies between 14 and 22 pieces/E_0h (Spinelli and Magagnotti 2009). In studies conducted in Germany and Austria, the length of the logging residue logs was 3 m (Wittkopf 2004, Kanzian 2005), whereas in Italy, the target lengths were 4 and 3 m (Spinelli and Magagnotti 2009).

All these studies were conducted on the very same machine, the Timberjack/John Deere 1490 bundler on a 6 x 6 MAN truck (Spinelli et al. 2012b). The unit is powered by the 353 kW engine of the truck and fed by a Timberjack CF 710 crane. The truck is equipped with a modified cab incorporating the crane control seat: this constitutes a second rotating chair mounted to the right of the driving seat with an extended rear window. The overall weight of the truck-base bundler is 24 tons (Spinelli et al. 2012b).

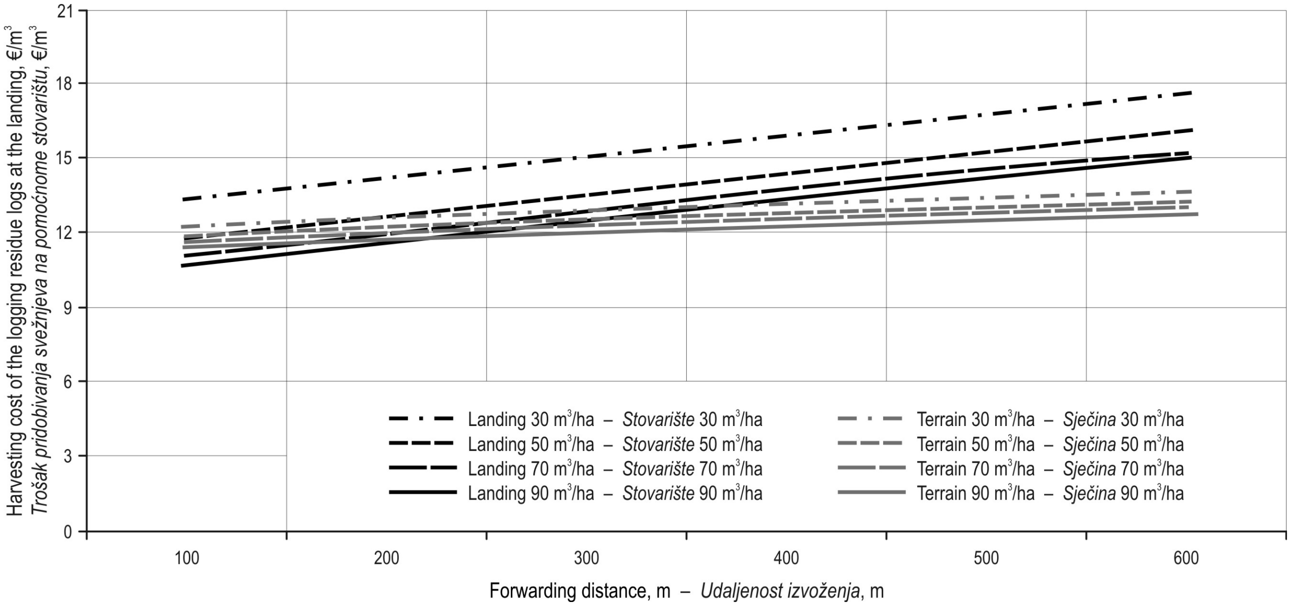

Fig. 8 Harvesting cost of the logging residue logs (€/m^3) at the roadside landing as a function of forwarding distance (100–600 m) and biomass removal (30–90 m^3/ha)

Slika 8. *Troškovi pridobivanja svežnjeva (€/m^3) na pomoćnom stovarištu u ovisnosti o udaljenosti izvoženja (100–600 m) i sječnoj gustoći biomase (30–90 m^3/ha)*

Table 4 Harvesting cost (€/m^3) of logging residue logs at the roadside landing when the bundling is done either in terrain or at the roadside landing. The removal of logging residues is 30, 50, 70 or 90 m^3/ha and the forwarding distance is in the range 100–600 m

Tablica 4. *Troškovi pridobivanja (€/m^3) svežnjeva na pomoćnom stovarištu kada se svežnjevi izrađuju na sječini ili na pomoćnom stovarištu. Uklanjanje je šumskoga ostatka 30, 50, 70 ili 90 m^3/ha, a udaljenost je izvoženja u rasponu 100–600 m*

Forwarding distance *Udaljenost izvoženja*	Terrain 30 m^3/ha *Sječina* 30 m^3/ha	Landing 30 m^3/ha *Stovarište* 30 m^3/ha	Terrain 50 m^3/ha *Sječina* 50 m^3/ha	Landing 50 m^3/ha *Stovarište* 50 m^3/ha	Terrain 70 m^3/ha *Sječina* 70 m^3/ha	Landing 70 m^3/ha *Stovarište* 70 m^3/ha	Terrain 90 m^3/ha *Sječina* 90 m^3/ha	Landing 90 m^3/ha *Stovarište* 90 m^3/ha
100 m	12.4	13.4	11.9	11.9	11.7	11.2	11.5	10.8
200 m	12.7	14.3	12.3	12.7	12.0	12.1	11.9	11.7
300 m	13.0	15.1	12.6	13.6	12.3	12.9	12.2	12.5
400 m	13.3	16.0	12.9	14.5	12.6	13.8	12.4	13.4
500 m	13.5	16.9	13.1	15.3	12.9	14.7	12.7	14.3
600 m	13.7	17.7	13.3	16.2	13.1	15.3	12.9	15.1

The original invention of the logging residue bundler was developed by Swedish company Fiberpak AB in 1995, and the first bundling units were mounted on standard forwarders as an attachment. In addition, the bundling unit was operated with a separate control system and steering of the bundling unit was managed with own independent hydraulic pump. Whereas e.g. in the John Deere 1490D logging residue bundlers, steering of the bundling unit is shared with the hydraulic line and pump of the forwarder crane. Sharing of the steering system with the forwarder crane limits the maximum power execution for the bundling unit and in principle the maximum productivity of the bundling unit is not possible to achieve without installing an independent hydraulic system or stopping the movements of the forwarder crane completely.

6. Conclusions – *Zaključci*

According to the results, bundling at the roadside landing with a forwarder-mounted bundler made it possible to reduce the harvesting costs to 0.1–0.7 €/m³ when the forwarding distance of the logging residues was 100 m or less and the removal was beyond 50 m³/ha. In practical operations, roadside bundling should be carried out outside the road area because of the large amount of material (needles, bark, small branches) that will be dropped on the ground while bundling 'brown' residues. In addition, road traffic may disrupt the bundling work, especially on the public road area, which also limits the usability of truck- and trailer-mounted logging residue bundlers. In wintertime, the cover of snow and frozen logging residues are obviously a problem too for a roadside bundling system in Nordic conditions. In Finland, the average forwarding distances are close to 300 m (Asikainen et al. 2001, Jylhä et al. 2010), which also limits the wide implementation of a roadside bundling system.

The results reported in this paper were based on theoretical time consumption models and cost parameters from earlier bundling and forwarding studies and rather limited time study data on bundling productivity at the roadside landing, which limits the generalization of the results. The study also focused on the effective working time (E_0h), which is only part of the total working time. Nevertheless, the results give new estimates for the performance and cost competitiveness of the roadside bundling system in Nordic conditions and the operators involved in the study were skilled, using machinery representatives for the current machines in use. In order to guarantee the reliability of the reported case study observations (Hellström and Hyttinen 1996), the results must be compared with the results of similar case studies, and efforts should be made to verify the observed phenomenon.

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Sažetak

Djelotvornost izradbe svežnjeva od šumskoga ostatka na pomoćnom stovarištu – proizvodnost i trošak

U radu se prikazuje istraživanje proizvodnosti i troškova sustava temeljenoga na izradbi svežnjeva od šumskoga ostatka na pomoćnom stovarištu pomoću forvardera s ugrađenim bandlerom (John Deere 1490D). Radi utvrđivanja proizvodnosti izradbe svežnjeva proveden je studij vremena u kojem je ispitano i ocijenjeno nekoliko radnih tehnika (slika 2). Šumski ostatak za izradbu svežnjeva potječe iz sastojine gdje je obavljena čista sječa, uz prevladavanje obične smreke (Picea abies) s prosječnom dobi stabala od 90 godina, visine 24 m i prsnoga promjera ($d_{1,3}$) 28 cm. Tijekom studija vremena izrađena su 683 svežnja od ostatka sječe. Duljina je svežnjeva iznosila 3 m, a promjer 70 cm. Studij je vremena proveden uglavnom u prirodnom svjetlu tijekom dana (7:00–16:00). Nebo je bilo bez oblaka, a raspon je temperature bio od –3 do –22 °C (tablica 1). Velika je površina radilišta omogućila provedbu studija izradbe svežnjeva u istoj sastojini s homogenom sirovinom i sličnim uvjetima rada za svaku radnu tehniku na po-

moćnom stovarištu. Iskusni i motivirani rukovatelji mehanizacije, prethodno osposobljeni za ispitivanu radnu tehniku, imaju više od pet godina radnoga iskustva na izradbi svežnjeva, izvoženju šumskoga ostatka i/ili izvoženju izrađenih svežnjeva.

Ekonomičnost sustava izradbe svežnjeva na pomoćnom stovarištu uspoređena je s konvencionalnim sustavom izradbe pri čemu se svežnjevi izrađuju u sastojini (na radilištu), a naknadno se pomoću forvardera izvoze na pomoćno stovarište. Troškovi pridobivanja (€/m³) dobivene šumske biomase na pomoćnom stovarištu izračunati su za oba sustava izradbe svežnjeva na temelju podataka dobivenih studijem vremena, modelima proizvodnosti i cijenama parametara dobivenih iz literature. Trošak sustava izradbe svežnjeva napravljen je na razini sastojine (radilišta), a u usporedbi troškova korištena je srednja udaljenost izvoženja u rasponu od 100 do 600 metara i uklanjanje ostatka sječe u rasponu od 30 do 90 m³/ha.

Proizvodnost izradbe svežnjeva na pomoćnom stovarištu (slika 7) kretala se od 48 do 53 svežnja šumskoga ostatka po efektivnom satu rada (E_0h), ovisno o radnoj tehnici i prosječnom vremenu potrebnom za proizvodnju jednoga svežnja (slika 6) koje se kretalo od 83,6 za 92,3 sekunde (E_0h). Prosječan broj zahvata hvatalom dizalice potreban za proizvodnju svežnjeva kretao se od 2,7 do 3,6, a prosječno vrijeme utovara kretalo se u rasponu od 15,5 do 17,1 sekunde po ciklusu dizalice (tablica 3). Troškovi izradbe svežnjeva (€/m³) na pomoćnom stovarištu (slika 8, tablica 4) bili su od 11,5 do 13,7 €/m³ za sustav koji se temelji na izradbi svežnjeva u sastojni i od 10,8 do 17,7 €/m³ za sustav koji se temelji na izradbi svežnjeva na pomoćnom stovarištu kada se udaljenost izvoženja kretala u rasponu od 100 do 600 m, a uklanjanje šumskoga ostatka u rasponu 30–90 m³/ha.

Temeljem dobivenih rezultata izradba svežnjeva na pomoćnom stovarištu omogućuje smanjenje troškova pridobivanja kada je srednja udaljenost izvoženja šumskoga ostatka 100 m ili manja i kada je uklanjanje šumskoga ostatka iznad 50 m³/ha. Uštede su vrlo male, u rasponu od 0,1 do 0,7 €/m³. Tradicionalna izradba svežnjeva u sastojini je više troškovno kompetitivna u svim sastojinskim okolnostima kada je srednja udaljenost izvoženja veća od 200 m (slika 8, tablica 4). U praksi izradbu svežnjeva na pomoćnom stovarištu treba provoditi izvan cesta zbog velike količine materijala (iglice, kora, grančice) koji padne na tlo. Osim toga, cestovni promet može poremetiti izradbu svežnjeva, pogotovo na javnim cestama, koje ograničavaju iskoristivost kamiona i prikolica s ugrađenim bandlerom. U zimskim mjesecima pokrov snijega i smrznuti šumski ostaci također su ograničavajući čimbenik za sustav izradbe svežnjeva uz prometnice, npr. u nordijskim uvjetima.

Ključne riječi: izradba svežnjeva šumskoga ostatka, proizvodnost, šumska biomasa, bandler

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