EFFORTE –
'Efficient forestry by precision planning and management for sustainable environment and cost-competitive bio-based industry'

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Deliverable 2.4. – Advanced biomass thinning		
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1. Background

In Sweden alone biomass with an energy yield of ca. 20 TWh could potentially be extracted from small diameter trees harvested in early thinnings and from marginal land (e.g. power line corridors and roadsides) (Fernandez-Lacruz et al. 2015). Improvements in cost-effectiveness of the supply systems are important requirements for sustainable extraction systems. However, results presented by Bergström and Di Fulvio (2014a) indicate that innovative bundle-harvester systems in combination with boom-corridor thinning (BCT) systems could provide much of the required improvements in cost-effectiveness of acquiring raw materials from young stands.

The overall aim was to develop and test new concepts of mechanized BCT of dense forest stands with small trees. The detailed aims were:

- to compare the productivity of BCT including felling, accumulation and forwarding in young dense stands with a reference alternative
- to verify functionality of BCT technique for a variety of relevant stand conditions concerning capacity to fell and accumulate trees in a continuous boom movement
- to model and simulate optimized boom corridor thinning and bundling technique.

2. Study design

2.1 BCT field trials

In central Finland first thinning trials were performed in autumn 2017 (Fig. 1). Trials were conducted on UPM Kymmene forests, which were dominated of *Pinus sylvestris* and had from no to minor amounts of undergrowth trees (Fig. 1). The stands were considerate to be conventionally managed. Tree sizes were of 60-70 dm^3 on average, and had an age of 35 years. The stand density were 2100 stems/ha. Two treatments were conducted: selective BCT and conventional selective thinning (SEL). Five time study plots were inventoried for each treatments. Each study plot had a size of 20x50m (0.1ha). A PONSSE Beawer harvester of 17.5t equipped with a conventional thinning head without accumulating grapple arms was used. One experienced operator performed both treatments.

Figure 1. To left: location of trials in Finland. In middle: photo of trial stands. Photographer: Dr. Yrjö Nuutinen, Luke. To right: Ponsse Beawer, picture taken from www.ponsse.com.

Time and motion studies of the thinning work were conducted as described in Nuutinen (2013). Thinning work were studied for a total of 4.66 productive machine work hours (PMH).

2.2 Field tests of a prototype felling head designed for BCT

Field trials of the Flowcut prototype head (Fig. 2) were performed in South Sweden April 2018 (Fig. 2) on Sveaskog forests. The forest stand was dominated of *Pinus sylvestris* with some *Betula pubescens* and had in average a stand density of ca 2500 trees/ha, a tree height of ca 9 m and diameter at breast height of ca 8 cm. The Flowcut head cuts trees with a circular saw (similar as used in sawmilling) and accumulate trees by using several groups of grapple that work in sequences. The base-machine was an EcoLog 560D (195 kW) equipped with an 11.5-m crane. The operator was experienced to thinning work but had only maneuvered the head few hours before tests.

Figure 2. To left: study site location in Sweden, Middle: site conditions during tests, to Right: The Flowcut prototype head.

Four time study plots were marked out and used for work studies. The width of the plots corresponded to the crane reach and was on average 19.2 m. The plots strip-road length was 78–135 m. Time study plots were inventoried in circular randomly distributed plots before thinning and in perpendicular to the strip-road 3m-wide transects after thinning. The thinning work was performed as follows:

- The strip-road trees of a study plot were cut and bunched in openings along the road
- The machined then reversed to the starting point and cut trees in ca 1m-wide boom-corridors between strip-roads

The operator decides which trees to cut and targeted a thinning intensity as in conventional thinning. Time studies were performed during this work and were separated for strip-road cutting and thinning between strip-roads. The work process was divided into the elements crane out, cutting/crane to next tree and machine movement, disturbance due to problems with cutting head, operator planning time and others. Also number of trees cut per crane cycle and trees pulled up by the roots (e.g. trees not cut but accumulated).

Additional tests to investigate the possible cutting speed when felling head was continuously moving were done. This was tested in seven boom-corridors with a length of 5.7-10.2 m which had 3-7 stems The felling head were positioned just in front of the first tree to be cut and timing ended ca 1m after last tree been cut. Time consumption is given as PM time.

2.3 Simulation of innovative bundle-harvester systems in BCT

In this study we analyze the work time consumption of three innovative harvesting systems for early thinnings (designated FlowConv, Flowfix and FlowCin) at different stages of development along the concept to commercial product spectrum. We also analysed their forest-to-industry supply costs, including harvesting, forwarding and trucking costs with several selected levels of cutting work efficiency and transportation distances. FlowConv consists of a conventional harvester equipped with an innovative continuously cutting, accumulating and bunching head (the "Flowcut") (cf. Fig. 2 to right), a standard forwarder equipped with a grapple-saw and a customized truck for transporting loose tree-parts to industrial sites. The FlowFix system consists of a harvester equipped with the same cutting head and a Fixteri bundling unit (see www.Fixteri.fi), a standard forwarder with an extra pair of load stakes, and a conventional roundwood truck to transport bundles to industrial sites. FlowCin consists of a Cintoc harwarder (Fig. 3) equipped with the same cutting head, and the same forwarding and trucking units as in the FlowFix system.

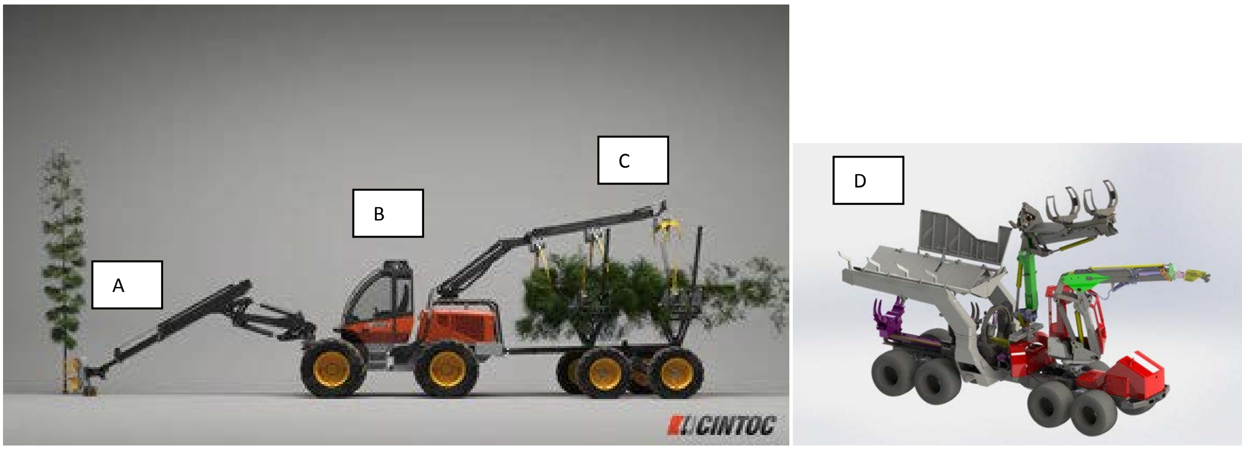

Figure 3. Schematic sketch of a bundle-harvester system equipped with a delivering crane, with: (A) a cutting crane, (B) delivering crane, (C) a cradle for intermediate storage/accumulation, and (D) bundling unit (www.Cintoc.se).

Data for three *Pinus sylvestris* dominated thinning stands and harvesters' cutting work efficiency were acquired from Bergström et al. (2010a). Means and standard deviations of crane cycle times in cutting work of the Bracke C16 (default) head obtained by Bergström et al. (2010a) were used for modelling the systems' cutting efficiency (Table 1). The productivity of a theoretical head for cutting and bunching trees was assumed to be 50% (Flowcut +50%) or 100% (Flowcut +100%) higher than that of the default Bracke C16 head (www.Brackeforest.com), while the standard deviations of the crane cycle times were assumed to be a constant proportion of the average times at both efficiency levels. For the cutting work it was assumed that the harvester head delivered one crane-cycle bunch per delivery to the biomass-receiving units in the FlowConv and FlowFix systems and two crane-cycle bunches per delivery in the FlowCin system (by the head producing a bunch and placing it on the ground, then producing another, grasping the first bunch and passing both bunches simultaneously to the delivering crane).

The cutting crane-cycle time according to findings presented by Nuutinen and Björheden (2015) and Bergström et al. (2016), for delivering biomass to the bundling unit was used to model the FlowFix system's maximum efficiency and was adjusted from an ideal state to a more "likely" level when used in practice. FlowCin: In this system it was assumed that the cutting head places cut trees in a standing position at a delivering point ca. 2-3 m in front of the machine on the strip road area. Additional time were added to the cutting crane-cycle time to account for the time needed to pick up the first bunch cut and bunched on the ground then move the two bunches to the delivering point (requiring two extra short movements). The cycle time of the delivering crane was assumed to be constant (according to the developers' expectations for the fully developed system). The delivering crane delivers biomass to an intermediate storage unit, the cradle, which when full (with biomass corresponding to one bundle) delivers the biomass to the bundling unit. The cycle time for delivering the biomass from the cradle to the bundling unit, bundling and dropping the bundle on the ground beside the strip road, i.e. total bundling time, was assumed to be constant (again according to the developers' expectations for the fully developed system).

Table 1. Characteristics of harvested stands (in average value for the three stands), harvested biomass, and time consumption and productivity of the cutting work. Data acquired from Bergström et al. (2010a).

	Mean
Stands before harvest	
Density (trees/ha)	11317
DBH_{BA} (cm)	10.5
H_{BA} (m)	8.7
Performance, Default head	
Harvested density (trees/ha)	2654
Harvested biomass (OD ton/ha)	24.8
Biomass per tree (OD kg)	10.0
Biomass volume per tree (dm^3 solid)	24.9
Harvested trees per crane-cycle	4.0
Biomass per crane-cycle (OD kg)	37.7
Time per crane-cycle (PM_0-sec)	25.6
Time per crane-cycle, sd (PM_0-sec)	9.6
Productivity (OD ton/PM_0-hour)	4.9

DBH_{BA}=basal area-weighted diameter at breast height, H_{BA}=basal area-weighted tree height. PM_0=effective work time excluding delays.

The tree-cutting and -bundling time consumption of the FlowFix and FlowCin systems was simulated using ExtendSim software (ExtendSim, Imagine That Inc.). The only random variable in the simulations was the crane-cycle time, which was assumed to be normally distributed. Each simulation covered 2 PM_0-hours of work time for every combination of system and stand type (treatment), each treatment was repeated five times and average values of the biomass processed during 2 PM_0-hours were used to calculate the productivity of the machines in each system.

The forwarding productivity for tree-parts and bundles was based on data presented by Bergström and Fulvio (2014a, 2014b) and a full load when handling bundles was set to ca. 9 ton (4.5 OD ton TS), corresponding on average to 17 bundles for 2.6 m bundles and 12 for 4.9 m bundles. A full load for loose tree-parts was set to 5.2 ton (2.6 OD ton).

The operational cost of the harvester, including cutting head, in the FlowConv system was set to 138.95 Euro/PM_{15}-hour (currency rate 9.5 SEK/Euro), ca. 20% higher than if a conventional head such as the Bracke C16 was used. The operational cost of the harvester in the FlowCin system was assumed to be the same (according to the developers' expectations when it is fully developed and constructed). The operational cost of the harvester in the FlowFix was set 17.4% higher, at 163.16 Euro/PM_{15}-hour, based on data presented by Nuutinen (2013). The operational cost of forwarding bundles was set to 85.47 Euro/PM_{15}-hour according to Bergström and Di Fulvio (2014a). The corresponding cost for loose tree parts was 3.2% higher (88.21 Euro/PM_{15}-hour) due to the cost of the grapple-saw required for loading and bucking work (Bergström & Di Fulvio 2014a). Forwarding of loose tree-parts with load-compression devices, resulting in 30% higher payloads, was also considered, and set to 90.00 Euro/PM_{15}-hour, 5.3% higher than forwarding bundles (cf. Bergström et al. 2010b).

It was assumed that loose tree-parts would be transported with a customized truck, with a net load capacity set to 25 ton (12.5 OD ton) and operational costs set to 18.65 Euro/load + 1.08 Euro/km, according to Bergström and Di Fulvio (2014a). Trucking with 30% higher (compressed) payloads was also considered, which increased the fixed trucking cost by 9.5%, to 20.42 Euro/load. The variable costs were assumed to be the same. It was assumed that bundles would be transported by a conventional logging truck, with a net load capacity set to 34 ton (17 OD ton) for 2.6 m long bundles, corresponding to 62-74 bundles. The operational costs were set to 17.82 Euro/load + 0.95 Euro/km, according to Bergström and Di Fulvio (2014a). The harvesting costs of the systems were calculated as a function of stand type and one-way forwarding distance (0-500 m). The supply systems' total costs were calculated as means for the three stands at a forwarding distance of 300 m and as a function of road transportation distance (one-way; 0-225 km).

3 Results

3.1 BCT field trials

BCT had a 44% higher productivity than SEL which can partly explained by the fact that in BCT on average 32% larger trees were cut (Table 2, Fig. 4). However, in BCT the time consumption of thinning 1 ha area was 31% shorter.

Table 2. Operational work time results of thinning treatments SEL (selective thinning) and BCT (boom-corridor thinning) in average values. Relative differences (Diff.) is calculated with SEL as denominator

	Treatments		
Properties	**SEL**	**BCT**	***Diff. (%)***
Harvested area (ha)	0.5	0.5	*0*
Operational time (PMsec)	2702	2044	*-24.4*
Cut trees (no.)	514	388	*-24.5*
Total Cut stem volume (m3)	32.4	31.9	*-1.5*
Average tree size cut (dm3)	63.8	84.4	*+32.3*
Efficiency (PMsec/tree)	5.3	5.3	*0*
Productivity (ha/PMH)	0.67	0.88	*+31.3*
Productivity (m3/PMH)	12.0	17.3	*+44.2*

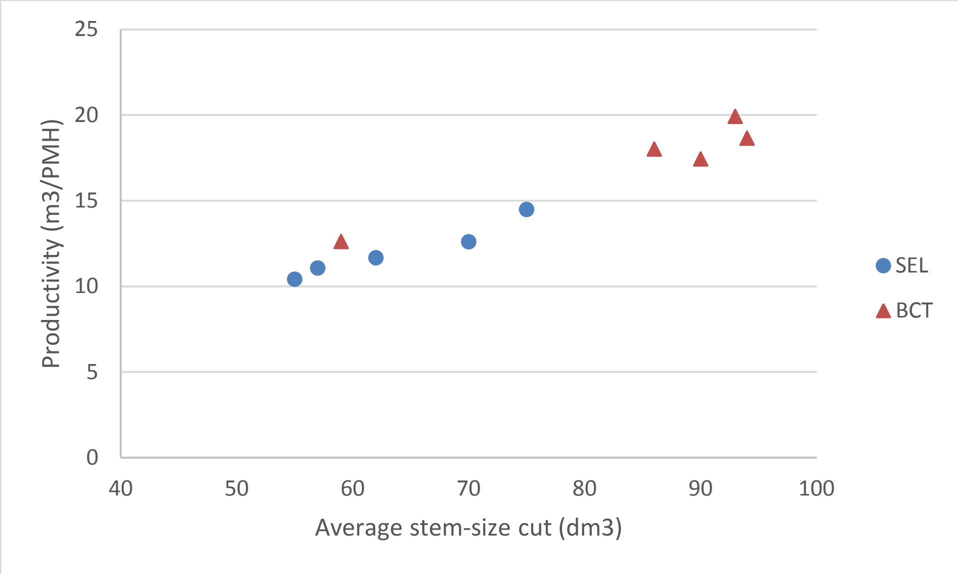

Figure 4. Productivity of thinning treatments as function of average stem-size of cut stems. SEL=selective and BCT=boom-corridor thinning.

3.2 Prototype head

In total 988 trees were cut during 138 PMmin. 461 of trees were cut in the strip-road ad 527 trees in 101 boom-corridors. There were no significant different in time taken per tree to cut trees in boom-corridors (6.9 sec/tree) compared to strip-road trees (8.5 sec/tree). On average 5.1 trees were accumulated when cutting in boom-corridors and 4.0 when cutting strip-roads. In 9.2% of crane cycled one or several trees were cut without being accumulated. In 3.6% of crane cycles trees were uprooted without being cut. There were however no significant differences between work in strip-roads or in boom-corridors.

Tests showed that the speed of which the head could cut and accumulate trees during a continuously movement was 0.4–0.8 m/s. The speed was not affected by number of stems cut neither diameter of trees.

3.3 Simulation

The productivity of cutting and bundling work in the FlowFix and FlowCin systems (at the 50% higher (Flowcut +50%) than default cutting efficiency) was ca. 1% and 3% lower, respectively, than that of the FlowConv system (Table 3). Corresponding values for the 100% higher than default cutting efficiency (Flowcut +100%) were 6% and 4% lower, respectively. Thus, with the FlowFix system, productivity losses for these work elements increase with increases in cutting efficiency, due to increases in waiting time. This is clearly illustrated by the 15.6% lower productivity for harvesting stand B with the FlowFix system at the Flowcut+100% cutting efficiency, relative to the FlowConv productivity (the corresponding loss for the FlowCin system was 6%), because of increases in the time consumed by the cutting crane waiting for the bundling unit to be ready to receive biomass. On average, operational costs of cutting were 13-17% lower for the FlowCin system than for the FlowFix system.

Table 3. Productivity levels of the bundle-harvesters' cutting work. Cutting efficiency refers to the increase in cutting efficiency relative to levels (+50% and +100%) with the default Bracke C16 head.

	Productivity level of cutting work	
	+50%	***+100%***
Prod. (OD ton/PM$_0$-hour)		
FlowConv	*7.4*	*9.9*
Diff. vs FlowConv. (%)		
FlowFix	*-0.9*	*-5.7*
FlowCin	*-2.7*	*-3.9*
Prod. (bundles/PM$_0$-hour)		
FlowFix	*29.1*	*36.7*
FlowCin	*19.8*	*25.9*
Prod. (OD ton/PM$_{15}$-hour)		
FlowCon.	*5.7*	*7.6*
Diff. vs FlowConv (%)		
FlowFix	*-0.9*	*-5.7*
FlowCin	*-2.7*	*-3.9*
Cost (Euro/OD ton)		
FlowConv	*27.1*	*20.3*
Diff. vs FlowConv (%)		
FlowFix	*+18.4*	*+25.4*
FlowCin	*+2.9*	*+4.0*

Harvesting (cutting and forwarding) costs were lowest for the FlowCin system, regardless of stand type and forwarding distance (Figure 5). The costs of the bundle-based systems (FlowFix and FlowCin) had relatively low sensitivity to forwarding distance compared to the FlowConv system with lower payloads. There were minor differences in FlowFix and FlowCin harvesting costs at Flowcut+50% cutting efficiency with short forwarding distances, due to FlowCin's relatively high operational costs. However, with a forwarding distance of 300 m, costs of the FlowCin system were 22% and 10% lower than those of the FlowConv and FlowFix systems, respectively, at Flowcut+50% cutting efficiency (and higher - 26% and 12%, respectively - at Flowcut+100% efficiency).

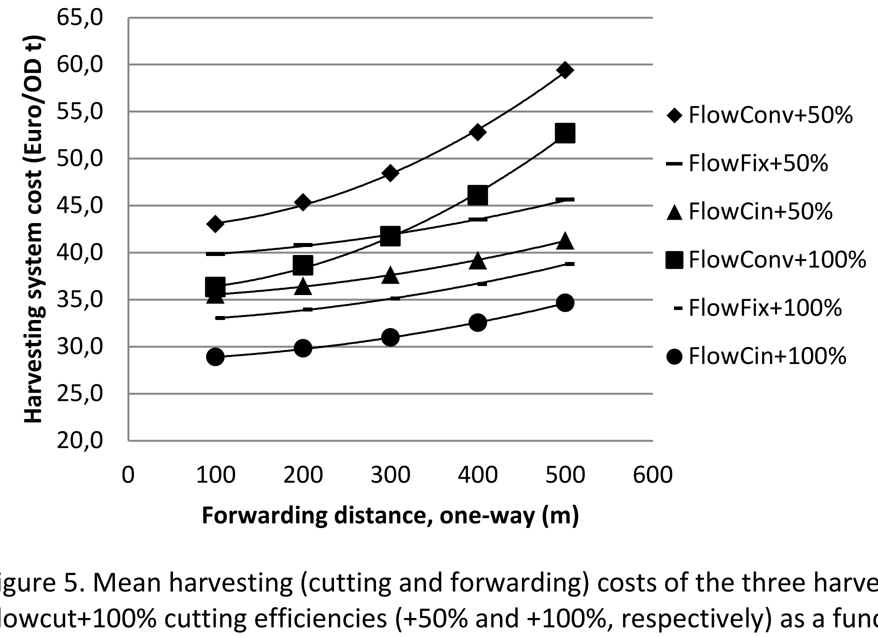

Figure 5. Mean harvesting (cutting and forwarding) costs of the three harvesting systems, at the Flowcut+50% and Flowcut+100% cutting efficiencies (+50% and +100%, respectively) as a function of forwarding distance (one-way).

Relative costs of the bundling systems decreased with increases in transport distances (Figure 6). With a forwarding distance of 300 m, the FlowCin system was found to have 24-26%, 26-28% and 27-29% lower supply costs than the FlowConv system, and 9-10%, 7-8% and 6-7% lower supply costs than the FlowFix system, at road distances of 20, 75 and 150 km, respectively.

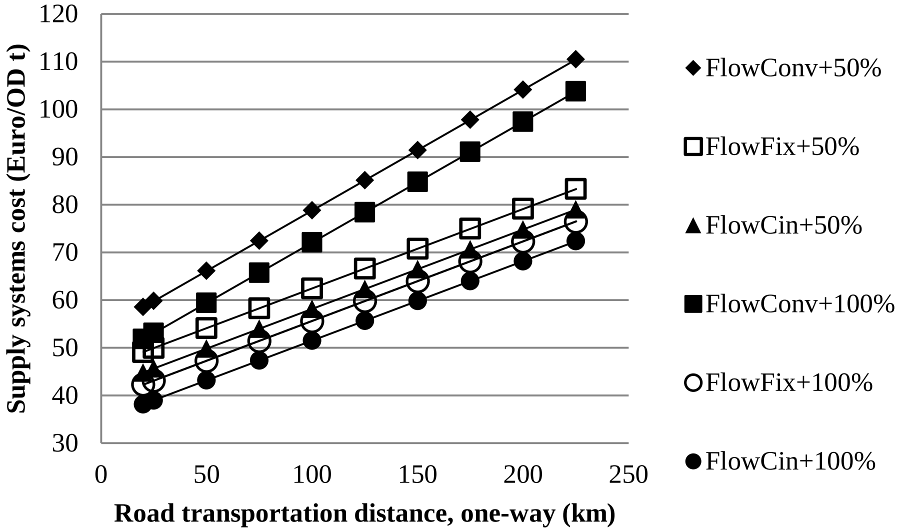

Figure 6. Mean supply costs of the three harvesting systems, at the Flowcut+50% and Flowcut+100% cutting efficiencies (+50% and +100%, respectively), with 300 m forwarding distance, as a function of road transportation distance.

4 Conclusions

4.1 BCT field trials

The stand thinned on boom-corridors with the conventional harvester were homogeneous in spatial tree distribution and tree sized and the density was around 2000 trees/ha. During trials no accumulation in crane cycles were done as stands were sparse. The results show that BCT had no significant effect on efficiency but can be explained by the fact the used stands are far from being optimally for BCT as Bergström (2009) discusses. However, the methodology render higher areal cutting efficiency as higher concentration of trees are cut per machine position thus meaning that the machine can move forward longer between stops. Additional trials will be conducted in 2018 in stands with more undergrowth trees in which we expect differences in efficiency (cf. Bergström et al. 2010).

4.2 Prototype head

The conducted trials were the most extensive ever made on the Flowcut head and is unique as this is in fact the first tests ever on a felling head designed to continuously cut and accumulate small diameter trees in boom-corridors. The test was trivial as the intention with the field test were just to get the technology running and stress the system. This version has progressed since the first version (cf. Grönlund et al. 2015) but is still not ready leaving the prototype stage. The inventor is still working on optimizing the cutting and accumulation technology and algorithms to help maneuvering the functions, especially sequences of accumulating grapple arms. The crane of the used machine was not suitable to efficiently maneuver the head at a even distance above ground when moving it forward in corridors. It had a boom crane, and optimally a parallel-type crane should be used.

The stands used in tests were little too sparse in density as the felling head and methodology is developed for cutting of were dense stands. However, in the next steps of tests, which will be performed during Autumn 2018, very dense stands will be used, were also extensive time and motion studies will be performed. Thus, the trials were only a pilot for the coming trials where an optimized head will be studied over a long period in suitable stands.

4.3 Simulation

If the Cintoc bundle-harvesting system is combined with a cutting head enabling a 50-100% increase in cutting efficiency (as in the FlowCin system) the total forest-to-industry supply cost of bundles is 6-10% lower than for a corresponding system based on the Fixteri bundle-harvester system. Moreover, the FlowCin system was found to be 24-29% more cost-effective than a reference system with a harvester and a forwarder handling loose tree-parts. The Cintoc system is not yet a commercial product, and many levels of the settings used in the simulations are uncertain. Thus, the hourly operational costs of the system will probably not match those of a single standard harvester (although the developers claim that is possible), but it still seems possible to keep the costs lower than those of the Fixteri system, which are quite high. Moreover, when handling loose tree-parts there is also potential to increase pay-loads as loads of loose tree-parts can be significantly compressed at high cost efficiency (Anon. 1977, Bergström et al. 2010b), thereby significantly increasing the cost efficiency of supplying loose tree-parts.

Results of this analysis should be treated very cautiously as the modelled systems are hypothetical and their performance and costs when built and operational are still highly uncertain, and thus based on assumptions.

However, the analysis shows the potential of systems if implemented. Even with a 10% increase in hourly operational costs, calculated supply costs of the FlowCin system were lower than those of the FlowFix system. The FlowCin system was also less sensitive to increases in cutting crane efficiency, as the bundling system can more readily match increases in biomass delivery rates. Thus, the FlowCin system can be more easily equipped with machinery enabling large increases (e.g. ≥ 100%) in cutting efficiency relative to the best current options (such as the Bracke C16 cutting head). Key features of the Cintoc system (which minimize possible waiting times during operation) include its buffering cradle and delivery of biomass acquired in two cutting crane cycles to the intermediate delivering crane. The analysis is based on data acquired from observations in and of relatively young and biomass-dense first-thinning stands that had not been subjected to pre-commercial thinning. These are highly similar to stands targeted by the Cintoc system's developers. However, for high cost-efficiency the Cintoc system must be equipped with cutting head efficiency that is much higher (such as (maybe!) the Flowcut when fully developed) than current best options and is not sensitive to large amounts of undergrowth (as in stands that have not been pre-cleared).

5 Acknowledgements

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The simulation study presented in this report has been submitted to the Croatian Journal of Forest Engineering and are undergoing revisions for possible acceptance and publication during later part of 2018. In this report only parts of the study is presented and readers can address the full paper when published.

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