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ORIGINAL PAPER

First trial of a prototype chainflail delimber for the European short rotation poplar plantations

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Abstract
Small tree size represents a main challenge for single-tree handling techniques and caps harvesting productivity in short rotation poplar (SRP) plantations. That challenge is best met by a shift towards mass-handling. Chainflail delimbing is one of the best solutions for multi-tree processing, but commercially available equipment is often too heavy and expensive for European operations. Therefore, an Italian company developed a compact chainflail delimber-debarker (CFDD) specifically designed for small-scale SRP. The machine was tested in Western Slovakia in early March 2022. The test included a five-days endurance trial and a controlled experiment on 16 carefully measured wood piles representing "strong" and "weak" trees, i.e. trees with a mean diameter at breast height (DBH) of 12 and 10 cm, respectively. The endurance trial was quite successful since no mechanical problems were recorded during the five-days period. Delimbing and crosscutting quality were as good as those obtained with a standard processor head, while log yield was generally better, averaging 42% and 68% for the "weak" and the "strong" trees, respectively. Productivity was on a par with the alternative cut-to-length technology options and can be significantly increased once the prototype will be further developed. In general, the new compact CFDD may become the best option for handling the small trees offered by underdeveloped SRP plantations, which cannot be efficiently harvested with the cut-to-length system.

Keywords Harvesting · Logging · Equipment · Operations · Productivity · Efficiency

Introduction

Chainflail delimber debarkers (CFDDs) are multi-stem processing machines that use fastly rotating chain links to remove branches and bark off cut trees (Watson et al. 1993). However crude, these machines are fast and effective, and their relative simplicity results in good reliability: after all, once the machine components are correctly dimensioned, there is very little that can fail. Simplicity and reliability are neither the only assets of CFDD equipment, nor the main ones. In fact, the most important benefit offered by CFDD technology is the capacity to easily handle more trees per cycle. Depending on machine type, tree size and expected work quality, a CFDD can efficiently process 3 to 7 trees at a time, which boosts productivity and represents a great advantage especially when handling small trees (Thompson and Sturos 1991). Through mass-handling, CFDDs can offset the productivity handicap imposed by small trees (Nakagawa et al 2007): as tree size gets smaller, more trees are gathered into the same load and through flow is stabilized (Mooney et al. 2000). Their ability to buffer tree size effects is best demonstrated by the failure of all CFDD productivity studies to estimate a strong relationship between productivity and stem volume, given that the strongest models yet produced have a coefficient of determination R^2 around 0.30 (McEwan et al. 2019; Hartsough et al. 2002; Ghaffariyan et al 2013). Furthermore, the delimbing principle adopted

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by chainflail machines does not rely on a knife sliding along the stem surface and its efficiency is less dependent on stem form (Labelle et al. 2016), so that a chainflail can turn into a usable product even those tree portions that are too small or too malformed for recovering with any other processing systems (Buggie 1991, Spinelli et al. 2020a). For that reason, CFDD technology is especially popular when dealing with small trees, as normally obtained from short-rotation industrial plantations designed to produce high-quality fiber for manufacturing pulpwood or other high-end commodities, rather than low-grade biomass (Spinelli and Hartsough 2006). An ideal field of application for this technology is represented by the new medium-rotation tree farms, established in Europe on agricultural land and designed for producing a mix of timber and biomass (Freer-Smith et al. 2019). There are currently at least 20 000 hectares of these plantations in Europe—especially in the Eastern regions (IPP 2019; Werner et al. 2012). Most of these plantations have been established quite recently and large scale harvesting has just started, so that both plantations managers and harvesting service providers are still searching for the best solutions to efficient harvesting (McEwan et al. 2020). One common challenge they all face is small tree size, which makes the mass-handling capability of CFDD equipment especially attractive. However, CFDD manufacturers are all concentrated in North America and they cater mainly for the Americas and Australia: they have not developed the European market, which held a much lower potential at the time when CFDD technology expanded (Raymond and Franklin 1990; Stokes and Watson 1991).

In fact, the European forest industry has shown some interest for CFDD technology, but its focus has been on early thinning operations, where low profitability prevents the major investment required by industrial operations (Kofman 2022). Over time, smaller-scale CFDD units have been developed within the scope of various R&D projects, especially in the Nordic regions (Alakangas 1995). Although short-lived, those experiences witness to a sustained interest in developing CFDD technology, and to a fundamental conviction of its large potential. Unfortunately, the focus on early thinning has condemned all those attempts to failure, given that early thinning—not CFDD development—is a problem that has found no satisfactory solution until now.

So, when the new tree farms are finally offering a much more promising field of application to CFDD equipment, no such equipment is available—except for one lonely American CFDD that has worked for many years in an Italian logyard and now awaits scrapping in Portugal! Unable to obtain a test unit from the American manufactures, plantation managers have eventually supported the development of yet another European prototype, hopefully more successful than the previous ones. In 2021, Biomass Work Ltd. and Piacentini Metalworks joined forces to develop the initial prototype of a small-scale CFDD. Both companies are located in Lombardy, northern Italy, where chainflailing has been practiced for decades as a way to clean rootstock after extraction from clearcut poplar plantations (Spinelli et al. 2005). Hence, the familiarity of many Lombard companies with flailing technology and the availability of retired root-cleaning equipment, which was eventually tapped for components. The prototype was built at the end of 2021 and successfully tested in February 2022. Therefore, the goal of this paper is to describe the machine and present the results of its first working trials in terms of productivity (tons per hour), log yield (% log mass over total mass) and general reliability (frequency and duration of mechanical downtime events). Since the productivity of any machine is generally affected by piece size, the prototype was tested on two different feedstock types: "strong" and "weak" trees. Of course, that definition was relative to the type of plantation at hand, which generally offers small trees, only. In the case of this study, "strong" trees had a mean diameter at breast height (DBH) in the range of 12 cm, "weak" in the range of 10 cm. While apparently small, that difference has a significant impact on the performance of single-tree equipment and plays a crucial role in the profitability of short rotation poplar plantations (Spinelli et al. 2022a).

Materials and methods

The chainflail prototype was a built from a pre-existing root cleaner, consisting of a box-like structure supporting two rotating drums. The drums were mounted 1 m apart and were powered by two variable displacement hydraulic motors that would turn at 800–1000 rpm, depending on the rotational regime of the endothermic engine that fed them. Each drum carried 16 flails, consisting of 6 hardened chain links each. Normally, the device would be fed vertically from the top, so that the short rootstocks to be cleaned would dangle between the two drums and would be flailed until all the dirt was removed. Therefore, the first step in prototype development consisted in turning the device by 90° to enable horizontal feeding. Then, an infeed table was added, for supporting incoming tree bunches. At the other end of the flail, a metal chute was installed for holding that stem portion that had passed through the flail (Fig. 1). Two bump plates were added: one in front of the infeed table and the other at the end of the chute, for indexing tree butts and assuring accurate crosscutting of the whole bunch. Since the target log length was 4 m, the second bump plate—that at the end of the chute—was placed at 4 m from the centerline of the flail drums, so that the delimbed stem portion would extend to exactly 4 m and would be clearly visible at crosscutting. While the eventual commercial product would be fitted with its own hydraulic pump and power pack, this first prototype

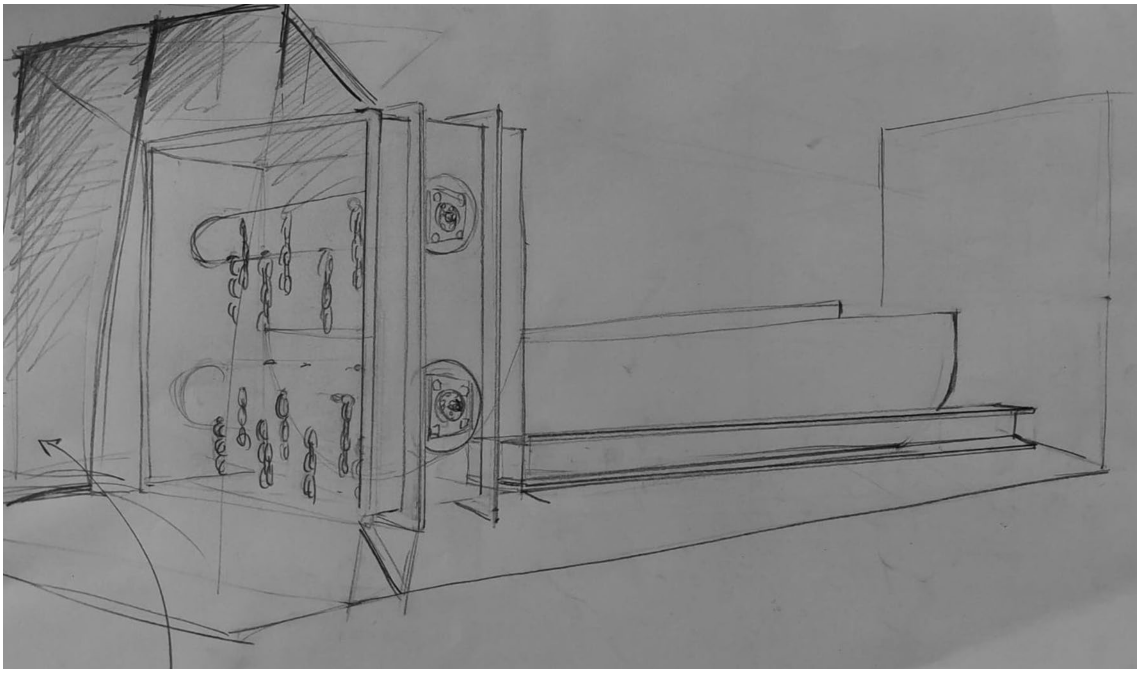


Fig. 1 A schematic drawing of the prototype CFDD

was designed for connecting to the hydraulic system of its transport, due to budget restrictions. All was mounted on a roll-on roll-off flat deck skip for easy transportation between sites: the total weight of the chainflail device was 3 t, including the skip that weighed 1 t itself. The whole operation was contained in a 6-axle truck-and-trailer rig, whereby the CFDD skip was loaded on the three-axle truck and the excavator tasked to feed it sat on the three-axle trailer. The excavator was a tracked 13-t model, fitted with a grapple saw. (Ruch et al. 2016) .The typical work cycle consisted of the following tasks: picking a bunch of trees off the pile with the excavator; pushing the bunch through the chainflail and back, until satisfactory delimbing would be achieved; placing the bunch on the ground and re-grabbing it at 4 m from the butt; crosscutting it at the 4 m length; repeating the operation if a second 4-m long log could be obtained; finally, stacking the logs and the tops onto their respective piles (Fig. 2). One operator was enough to relocate and operate the whole system.

After a brief test run near the workshop in Italy, the machine was moved to Western Slovakia and tested on one of the short-rotation poplar plantations managed by IKEA Industry near Malacky, in close proximity of a major particle board factory tasked with producing a highly innovative

Fig. 2 The machine at work in Western Slovakia

poplar based lightweight panel. In particular, the test plantation was located near Gajary (48° 29′ 10.87″ N; 16° 55′ 25.52″ in WGS84), in the Morava river floodplain. Local climate was described as "warm temperate, fully humid, with hot summer climate" (Cfb) according to the Köppen-Geiger classification (Rubel et al 2017). The mean annual temperature was 11 °C in the 2014–2020 interval and the average annual precipitation was 742 mm. Soil was a Mollic Gleysol, with sandy texture and groundwater levels between 1.5 and 2.0 m from the surface. The test was conducted in early March 2022. Weather during the test was consistently warm and dry, with occasional light precipitation. Air temperature varied between −2 and + 14 °C. The plantation was a 6-year-old poplar stand established at a square spacing of 3.0 m × 2.0 m with hybrid poplar (*Populus x euramericana* Dode (Guinier)), clone 'AF18 '(Heilig et al. 2021; Landgraf et al. 2020; Meyer et al. 2021).

The test machine was operated by the owner of Biomass Work Ltd., who was a qualified forestry professional with many years of experience in poplar harvesting work. He had also operated the chainflail for many years, although only in the rootstock cleaning configuration, given the absolute novelty of the new machine derived from it (Fig. 3). Nevertheless, he was quite familiar with the working principle, the expected results and the hazards of chainflail operation. Before starting the study proper, the operator worked half a day on an unmarked stack in order to perfect his routine and iron out possible difficulties. After that, the experiment proper commenced. The machine was run continuously for 5 work shifts and during that time all mechanical downtime would be recorded, together with its cause. That general trial was integrated with a time and motion study conducted over two different feedstock types: standard trees and underdeveloped trees—respectively, the "strong" and the "weak" tree treatments. The former would normally yield at least one 4-m log—more often two; the latter would only yield one 4-m log, if any at all.

Fig. 3 The two chain drums adapted for horizontal feeding

The experimental design was a factorial scheme where each treatment was repeated 8 times. Each repetition consisted of one pile of approximately 130 trees, in order to reflect the same batch size adopted in other similar studies conducted under the same research programme—thus achieving comparability, in case of further use of the same datasets. The chainflail would process the piles in a random order, to neutralize any potential background noise derived from machine wear or operator fatigue. To minimize the latter effect, at the end of each pile the study was halted to allow for the operator to rest, while the support team cleaned and inspected the machine for any signs of malfunction (e.g. leaks, accelerated wear etc.). Taking a brief rest pause every hour of work is a recommended practice in commercial operations, too.

The selected test metrics were: productivity (mass output/time input), log yield (log mass/total mass) and mechanical reliability (frequency and duration of mechanical downtime over the total test time). Therefore, we measured: tree size, product mass (separately for logs and biomass), time input, frequency and duration of any mechanical stops.

The circumference at breast height of all trees in all piles was measured manually with a measuring tape and then converted into diameter at breast height (DBH), over bark. Furthermore, 6 trees covering the whole DBH distribution were destructively sampled in order to determine their total height and weight, separately for the theoretical log and chip portions (Krejza et al. 2017; Urban et al. 2015). Destructive sampling allowed estimating the relationship between DBH, total height and mass, which was used to predict the mass packed into each individual pile (Headlee and Zalesny 2019). Previous studies have shown that it is possible to build reliable allometric functions with such a small sample, when tree variability is as small as found in even-aged clonal poplar (Hartmann 2010; Hjelm 2015; Verlinden et al. 2013). Initial mass estimates were later adjusted using ad-hoc correction factors obtained by matching the estimated log and biomass yields with the actual amounts taken to the factory weighbridge. That was done separately for the log and for the chip portion obtained from each of the two treatments, in order to account for variations in log recovery that might be associated with the treatments (i.e. 4 correction factors). Moisture content was determined both at the time of destructive sampling and at the time of delivery to the factory, so as to match dry mass estimates with dry mass weighbridge data. In both cases, moisture content was determined with the gravimetric method, according to EN ISO 18134–2:2015. Mean moisture content at delivery was 55% (standard deviation = 2.7%). Depending on treatment, the ratio between factory dry mass and inventory dry mass varied from 0.75 to 1.12 with an overall average at 0.85—meaning that the field inventory overestimated actual harvest by about 15%.

Delimbing quality was visually assessed by the factory production managers who attended the trials. Log length was regularly checked with a tape measure all along the duration of the trials. The machine was set for delimbing, not debarking.

During the test, researchers determined the time taken by the CFDD to process each individual pile, using a stopwatch accurate to the second. Both productive time and delay time were recorded (Bjorheden et al. 1995), but the latter was excluded from the study, where it was replaced by a 20% delay factor. That was done because the time spent on each pile was too short (about 1 h) to accurately estimate delay time. The 20% increase applied to the data was consistent with the findings of previous published studies, with special reference to the harvesting of plantation forestry (Spinelli and Visser 2008). That figure was also quite close to the sum of all delays recorded during the complete study, as conducted on the 16 piles.

The pile-level time study was accompanied by a parallel cycle-level elemental time study (Magagnotti et al. 2011). That would cover more than half of chainflail cycles on each pile, where cycles were identified as the time to complete the processing of a tree bunch broken off the pile and fed to the chainflail. The total cycle then included all tasks required for turning a group of trees from the test pile into logs and biomass stacked onto their respective piles. The goal of this study component was to determine if treatment would specifically impact one or more work steps within the complete flailing task. Furthermore, the elemental time study would indicate which ones were the most time-consuming work steps and address future improvements of the prototype. This study split the complete cycle into the following work tasks (elements):

Grab = Time spent grabbing a tree bunch and indexing the trees against the bump plate. It ends when the bunch is inserted between the rotating flails (easily identified through the flail-on-wood noise). The record includes a count of trees in the bunch;

Process = Time spent delimbing the bunch and crosscutting it. It ends when the last log obtained from the bunch is crosscut. The record includes a count of the logs produced from the original bunch;

Stack logs = Time spent moving the crosscut logs onto the log stack;

Pile residues = Time spent moving the residues (tops and branches) onto the biomass pile;

Other work time = any other work time—typically clearing debris from under the infeed opening and chute etc.

The pile-level study data were used to quantify operation productivity and log yield (dependent variables) as average values, and the differences between alternative treatments (independent variables) was checked using nonparametric statistics as a safeguard against possible violations of the parametric assumptions. Given that only two treatments were being compared ("weak" vs. "strong"), a nonparametric test would not be much less informative than a standard parametric test, while being more robust—hence more reliable. In particular, the Mann–Whitney unpaired comparison test was used for this study. Since we renounced the normality assumption, centrality was represented through Medians—not Means. For all analyses, the significance level was set at $\alpha < 0.05$. The analyses were implemented with the software Minitab 17, one of the most popular statistical software in the field of engineering (Okagbue et al. 2021).

Results

The trials lasted 5 full work days, so that one could get an overall impression of machine reliability and endurance. No mechanical failures were recorded during those five shifts. Within that period, the time study occupied 2 days, during which the machine processed 52 bone dry tons (BDT) of wood—i.e. the 16 test piles.

Delimbing quality was considered satisfactory by the factory production managers on site and at the receiving facility. In fact, visual inspection of the log piles showed that delimbing quality and surface damage were not much different from those offered by the cut-to-length processor that worked alongside the CFDD on the same landing (Fig. 4). Cutting length accuracy was also comparable and generally satisfactory (overlength = 2 to 10 cm).

By design, piles with "strong" trees had been sourced from higher-yielding areas of the plantation (48 BDT ha^{-1} vs. 37 BDT ha^{-1}): they were significantly larger (3.7 vs. 2.7 BDT), as they contained more and larger trees (better survival and growth). In particular, median DBH was 14% larger (12.4 cm vs. 10.9 cm) and tree mass 20% higher (28 vs 23 kg dry matter) for the trees in the "strong" piles (Table 1). That was part of the plan and the data confirmed that part succeeded, at least.

Fig. 4 Delimbing quality obtained with a cut-to-length processor (left) and the prototype CFDD (right)

Table 1 Characteristics of the test tree piles

Piles		Strong	Weak	MW *p*-Value
Observations	n°	8	8	
Mass	BDT	3.73	2.72	0.0018
Trees	n°	134	119	0.0176
DBH	cm	12.4	10.9	0.0070
Height	m	14.7	14.3	0.0060
Mass	kg DM	28	23	0.0176
Stocking	Trees ha^{-1}	1725	1661	0.3446
Stocking	BDT ha^{-1}	47.9	37.3	0.0008

Median values; *BDT* = bone-dry tons (0% water mass fraction); *DBH* = diameter at breast height; *DM* = dry matter; *MW* = Mann–Whitney nonparametric test for unpaired comparison (two levels)

Table 2 Chainflail productivity and log yield as derived from the pile-level study

Piles		Strong	Weak	MW *p*-Value
Observations	n°	8	8	
Logs	BDT	2.57	1.14	0.0008
BiomassChips	BDT	1.16	1.58	0.0742
Log yield	%	68.8	41.9	0.0008
Time	SMH	1.34	0.62	0.0008
Productivity	Trees SMH^{-1}	103	193	0.0008
Productivity	BDT SMH^{-1}	2.88	4.13	0.0008

Median values; *BDT* = bone-dry tons (0% water mass fraction); Log yield % = 100 * log mass/total mass; SMH = Scheduled Machine, Hour, including delays (here estimated at 20% of the net work time); *MW* = Mann–Whitney nonparametric test for unpaired comparison (two levels)

Table 3 Results of the cycle-level study

		Strong	Weak	MW *p*-Value
Observations	n°	8	8	
Cycles $observation^{-1}$	n°	16	15	
Trees $cycle^{-1}$	n°	4.9	6.4	0.0127
Logs $tree^{-1}$	n°	1.5	0.9	0.0034
Cycle time	s	130	106	0.0281
Work pace	Cycles PMH^{-1}	28	34	0.0281
Productivity	Trees PMH^{-1}	137	218	0.0034

Median values; *PMH* = productive machine hour, excluding delays; *MW* = Mann–Whitney nonparametric test for unpaired comparison (two levels)

Chainflail productivity ranged between 2.5 and 4.7 BDT SMH^{-1}: it was 40% higher for the "weak" treatment compared with the "strong" one, and the difference was statistically significant (Table 2). In contrast, log yield was significantly higher for the "strong" treatment, with 69 percent points or a 40% increment over the "weak" treatment that plateaued at 42 percent points.

The elemental cycle-level time study confirmed the results of the pile-level study and showed the mechanisms regulating productivity (Table 3). In particular, it offered a direct witness to the mass-handling capacity of the chainflail and of the associated benefits. Under the "weak" treatment, more trees (6.4 vs. 4.9) were processed in each cycle. The maximum was 8 trees per cycle on a pile average, but the maximum for an individual cycle could reach or exceed 10 trees. The number of logs per tree was obviously lower for the "weak" treatment compared with the "strong" one, since trees in the latter group would normally offer two 4 m logs per stem, instead of one. For that reason, cycle time was 20% lower for the "weak" treatment.

As a matter of fact, manufacturing a second log from the same tree was rather cumbersome. After crosscutting the first set of logs from the butt section, the whole processing sequence had to be repeated. The bunch had to be indexed again, fed into the chainflail and pulled out; the second set of logs was crosscut and finally the logs and the biomass were moved to their respective piles.

The combined effect of a shorter cycle time and a larger number of trees per cycle caused a dramatic increase of tree-based productivity under the "weak" treatment, when the chainflail was able to process over 200 trees per hour. Mass-handling allowed offsetting the tree size handicap, which is what multi-tree machines are designed for.

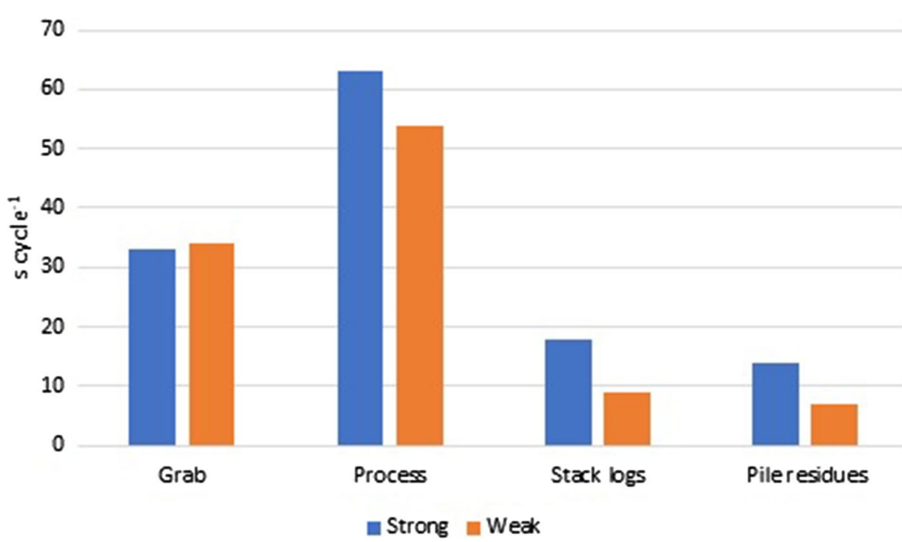
A more detailed analysis of the main work elements indicated that processing (i.e. delimbing and crosscutting) was the largest contributor to cycle time, accounting for approximately half of the total time consumption regardless of treatment (Fig. 5). Log stacking and residue piling took twice as much time per cycle under the "strong" treatment than under the "weak" one (18 s vs. 9 s and 14 s vs. 7 s, respectively). That difference was statistically significant and is likely due to the larger mass per cycle handled under the "strong" treatment. In contrast, grabbing and indexing the trees before processing took about the same time per cycle, regardless of treatment. In absolute terms, cycles were longer under the "strong" treatment simply because more mass was handled per cycle. Besides, the current machine design was not ideal for repeated crosscutting, as was described just above.

Discussion

Like most studies, this one has its own limitations that must be addressed before endeavouring into any meaningful discussion, so that readers can judge for themselves how reliable is the information contained in this manuscript and how it could be transferred to their own work environment. The first and obvious limitation is the prototypal character of the equipment on test. For that reason, all results must be interpreted with much caution, and especially those that concern operational productivity. The machine can and will be improved. In particular, the cumbersome processing sequence must be streamlined: in any efficient conversion process, the raw material must come in from one end and the processed product must fall out from the other end. The current in-and-out work sequence is inefficient and requires iterative indexing of the tree bunch, which is a time-consuming operation.

The second limitation is the collective analysis of the cycle-level data at the pile level. That is, the data that were collected on a cycle basis were later grouped by pile and the average element and cycle time were extracted. Therefore, the cycle-level study results were not reported at the cycle-level. That finds its justification in the specific work routine of the CFDD in its current configuration. The in-and-out work mode implied that the second batch of logs from trees in one cycle would often be processed together with the first batch of logs from trees in the next cycle, so as to have the stronger logs supporting the weaker ones for minimum breakage. Similarly, the logs and the biomass would be piled intermittently and only when their quantity were large enough to hinder further work, not regularly with its cycle. Therefore, frequent non-cyclic activities made it very

Fig. 5 Results of the elemental time study



difficult to keep cycles exactly separated, justifying collective data analysis (Punnett and Wegman 2004).

The third limitation of this study is the usual concern about operator selection: testing just one operator makes one wonder how much the data obtained from this study can be generalized (Leonello et al. 2012). The question is compounded by the fact that the machine is a first prototype and therefore no operator—not even our test operator—could possibly achieve any significant experience with its operation. True, the operator selected for the test had long-term experience of flailing rootstocks in vertically-fed rootstock cleaners, but flailing 1-m long taproots in a vertical tub is not the same as flailing 14-m long trees in a horizontal device. All the above strongly suggests that the productivity data must be taken with much caution, as they are likely to change quite dramatically once the machine has received the necessary improvements and the operator has gained more experience with its use.

As of now, it is difficult to make any solid projections about the future long-term productivity of an improved version of the compact CFDD presented in this study. However, it is unlikely that a streamlining of the material flow through the machine could significantly affect log stacking and residue piling, which are virtually independent of CFDD design. The main benefits of the new design would be accrued at the processing stage, which accounts for roughly half of the total cycle time. Therefore, if the improvements could decrease processing time to ½ or 1/3 of the actual duration recorded in this study, overall cycle time would drop by 25% or 33%, respectively. Since a stronger effect would be expected on the "strong" trees compared with the "weak" ones, the hypothetical productivity would increase to 3.8 BDT SMH^{-1} (i.e. 2.9 * 1.33) and 5.2 BDT SMH^{-1} (i.e. 4.1 * 1.25), respectively. For the measured moisture content of 55% and after rounding, those figures would amount to approximately 9 and 12 green tons (gt) SMH^{-1}, respectively. That is still much below the productivity reported for commercial CFDD models deployed on SRF poplar and eucalypt tree farms (Table 4). Those machines are at least 4 times more productive than the prototype presented here, even after its eventual upgrading. On the other hand, they are much heavier, more powerful and expensive than our prototype. A base CFDD unit like—for instance—the Peterson Pacific 4810F weighs over 20 t, is powered by a 260 kW engine and sells at over 500,000 USD (Cordes 2020): so definitely another league. In fact, the small prototype flail developed as part of this research has neither the potential nor the intention to compete for the same market sector against the larger and more mature North-American products. The idea is rather to find a solution for those many European entrepreneurs who will never be able to purchase such a machine, nor to find large enough tracts for its successful deployment. If one must be found, the main competitor is rather the roadside processor, which the new CFDD could try to replace whenever tree size was too small for effective single-tree operation.

The work quality assessment presented in this report is much more robust compared with the productivity assessment. There is no reason to expect a dramatic improvement in that department, nor any need for it: length accuracy, delimbing quality and log recovery rate are already quite good, although minor improvements can and will be achieved in the future. In particular, log recovery rate (i.e. log yield) is better than recorded for all the other tests conducted with the alternative technologies on the same

Table 4 Productivity of CFDD used in hardwood tree farms: summary of bibliographic information

Make	Model	Chipper	Species	Piece size, t	t SMH^{-1}	Utilization %	Country	Reference
Peterson Pacific	DDC 5000	Yes	Populus sp	0.131	52	89	USA	Spinelli and Hartsough (2006)
Morbark	2455	Yes	Populus sp	0.143	48	89	USA	Spinelli and Hartsough (2006)
Peterson Pacific	DDC 5000	Yes	Populus sp	0.180–0.200	49	95	USA	Hartsough et al. (2002)
Peterson Pacific	DDC 5000	Yes	Eucalyptus sp.	–	38	45	Brazil	Spinelli and Moura de Arruda (2019)
Peterson Pacific	DDC5000	Yes	E. globulus	0.105–0.344	27	57	Australia	McEwan Et Al. (2019)
Husky Precision	FD 4300	Yes	E. globulus	0.105–0.344	23	56	Australia	McEwan Et Al. (2019)
Morbark	2455	No	E. globulus	0.204	59	20	Chile	McEwan Et Al. (2017)
Peterson Pacific	DDC 5000	Yes	E. globulus	0.010	40–45	20	Australia	Spinelli et al. (2020a, b)°
Husky Precision	FD 2300	Yes	E. globulus	0.200	53	92	Australia	Ghaffariyan et al. (2013)
Peterson Pacific	DDC 5000	Yes	Eucalyptus sp.	0.134	26	77	USA	Spinelli et al. (2002)
Morbark	2348	Yes	Eucalyptus sp.	0.086	34	75	USA	Spinelli et al. (2002)

Chipper = if Yes the CFDD is integrated with the chipper, if No it is not; *SMH* = scheduled machine hour, including delays; Utilization = Productive hours/Scheduled hours

Table 5 Log yield obtained from the harvesting of SRP plantations

Case n°	Place	Method	Equipment	DBH	kg tree^{-1}	SED	Log Yield	
1	Malacky (SK)	WTH	Chain flail	11	51	7	42	*This study*
2	Malacky (SK)	WTH	Chain flail	12	62	7	69	*This study*
3	Kwydzyn (PL)	CTL	Harvester	12	56	7	37–42	Magagnotti et al. (2021)
4	Malacky (SK)	CTL	Harvester	12	58–70	7–8	50–61	Spinelli et al (2022b)
5	Malacky (SK)	CTL	Harvester	12	65–75	8	52–60	Spinelli et al. (2022c) (in press)
6	Malacky (SK)	CTL	Harvester	10	29	7	26	Spinelli et al. (2022a) (in press)
7	Malacky (SK)	CTL	Harvester	12	62	7	62	Spinelli et al. (2022a) (in press)
8	Cossato (I)	WTH	Grapple-saw	15	103	7	80*	Spinelli et al. (2020b)
9	Sezzadio (I)	WTH	Grapple-saw	15	95	7	41	Spinelli et al (2021a)
10	Skalica (SK)	WTH	Grapple-saw	12	51	7	51**	Spinelli et al (2021b)

DBH = diameter at breast height; *SED* = small-end diameter; Log yield = 100 * Log mass/Total mass; CTL = Cut-to-Length; WTH = Whole-Tree Harvesting; *eventually reduced to 40% due to high rejection rate; **poor delimbing quality; In all cases, trees were processed into 4-m long logs

feedstock type. Table 5 reports the tree characteristics and the log yield results obtained from other similar trials conducted by the same team, with the same methods and for the same log yield specifications: 4 m log-length and 7 (or 8) cm small end diameter. Those trials were conducted with a variety of different equipment, such as harvesters, processors and grapple saws. Since the different figures originated from different datasets collected within distinct trials, we did not attempt a direct statistical comparison with the results of this study: that has been planned for another study and is already in progress. However, the table indicates that the log yield recorded for the prototype CFDD is already at least as good as the best figures obtained with the previous trials of the alternative technologies. What is most interesting, the edge gained by the CFDD is especially large for the smallest trees (DBH < 12 cm), which qualifies the new machine as especially suited for low-yield plantations (Buggie 1991).

Visual observation of the work process suggested that the better log yield recorded for the CFDD was due to the tested CTL heads inflicting excessive damage to the processed stems, especially the smallest ones. That seems to contradict the high level of stem damage generally associated with CFDD operation (Favreau 1997). In fact, that association is generally made for machines used for combined delimbing and debarking—not just delimbing (Chahal and Ciolkosz 2019). Obviously, flail action must be much more energetic for thoroughly peeling the stem surface, rather than just knocking off the few scattered (and often dry) branches that one may find on the basal portion of a young poplar stem grown in dense plantations. In fact, those branches are generally so light and scarce that the WTH trials n° 8 and 10 in Table 5 adopted a simple grapple saw to process the trees, on the assumption that most limbs would be crashed during handling (Spinelli et al. 2019). However, delimbing quality was not deemed satisfactory in those two cases, and the relatively high log yield figures associated with them should be significantly reduced due to high factory rejection rates. For that reason, post-processing motor-manual trimming of surviving branches and branch stubs was introduced with trial n° 9, but that solution lacked long-term financial and social sustainability: hence, the idea of introducing a CFDD.

While the machine in this study was used for delimbing only, it can certainly be set for integrated delimbing and debarking, if the need arises. To that end, one could simply extend the permanence of the stems under the flail, change the flail rotation speed or replace the chains with a more aggressive type (Spinelli et al. 2020a). However, such adjustments would likely decrease productivity and log yield, so they should be pursued only if necessary (Hartsough et al. 2000). Nevertheless, easy switching to the debarking mode may further expand the CFDD's potential and make it appealing to the many stakeholders who are trying to reintroduce in-field debarking to European forest operations in an attempt to mitigate insect outbreaks and/or soil nutrient removal (Heppelman et al. 2019, Holzleitner and Kanzian 2022, Mergl et al. 2021).

In any case, the machine is still quite new and it can be significantly improved and expanded, both as a pure delimber and as an integrated delimber-debarker. Further studies will guide improvement and allow defining the optimum configurations and settings for each job and tree type.

Conclusions

Even as an early prototype, the compact CFDD presented in this study offered a very good performance. Productivity and product quality were on a par with alternative and more mature CTL technology options currently applied to those stands, while value recovery was generally better. Reliability was exceptionally good for a prototype, since no mechanical problems were recorded during the five-days endurance test. The machine works best with the smallest trees, which are a challenge for all other options. Compared with the industrial CFDD already available on the market, the machine on test is much smaller, lighter and less expensive. While not as productive, it is definitely more affordable for European contractors and can be deployed on small-scale operations. Due to its compact size, it could also be installed on a forwarder and operated at the stump-site wherever soil fertility concerns make it preferable to leave branches and bark inside the stand. Further improvements are planned and they may greatly increase the efficiency of the new machine.

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Declarations

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