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Selection of a chipper technology for small-scale operations – a Finnish case

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Abstract: The objective of this study was to determine the economic performance of alternative chipper choices for small-scale chipping based on unit cost (€ per chip-m^3) and net present value (NPV) calculations. For the chipping cost and investment profitability analyses four tractor-powered professional or semi-professional disc chippers and two professional drum chippers mounted on a truck or powered by tractor were selected. Initial investment, operating costs, and the cost of outsourced chipping were the key elements for comparing the profitability of investment alternatives. The average purchase prices, cost factors, and technical details of the chipper units were acquired from machine dealers, specification sheets, a literature review, and interviews with chipping entrepreneurs. The results of the three tractor-powered professional chippers involved in the comparison were very close to each other. The profitable running of a truck-mounted drum chipper calls for high annual chipping volumes: the chipper type is therefore a feasible choice for an entrepreneur in large-scale chipping. Semi-professional disc chippers offer lower investment costs, but their economic feasibility is relatively poor.

Keywords: investment; decision making; unit cost; chipping; entrepreneurship; productivity

Small-scale chipping can be defined as operations in which wood chips are produced to heat buildings or small district heating systems, usually in a scale between 500 and 2,500 kW (McCallum 1997). In Finland, small-scale chipping is a typical operation e.g. for heat entrepreneurs who operate locally and provide heat for a community from locally sourced wood fuels (Okkonen 2008; Okkonen, Suhonen 2010; Suhonen, Okkonen 2013). Quality requirements for fuel chips are high, and the efficient operation of several small-scale heating plants presupposes the use of delimbed wood as a raw material for the chips to remove needles or sticks from branches (Laitila et al. 2010; Laitila, Väätäinen 2012; Kühmaier, Erber 2018). The operational chain of heat entrepreneurship can be divided into heat production and fuel supply (Okkonen 2008; Okkonen, Suhonen 2010; Suhonen, Okkonen 2013). A heat entrepreneur can take care of all practical operations or use subcontracting for fuel procurement (Okkonen 2008; Okkonen, Suhonen 2010; Suhonen, Okkonen 2013). Nevertheless, this business model can only succeed if all steps in the operational chain are profitable for all parties involved in the business (Okkonen 2008; Okkonen, Suhonen 2010; Suhonen, Okkonen 2013).

Purchasing a chipper requires a significant investment. To make a good and balanced investment decision, the entrepreneur needs to be aware of every known consequence and outcome of different investment alternatives, including factors such as chippers' productivity, fuel consumption, maintenance costs, required initial investment, residual value, annual chipping volumes, and the quality requirements of the final product (e.g. Laitila, Väätäinen 2012; Laitila et al. 2017; Prinz et al. 2019).

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Underestimating the chipping cost will result in a financial loss for the entrepreneur, whereas an overestimate will make the entrepreneur less competitive on the open market (Spinelli, Magagnotti 2010). In some cases, the simplest solution for small-scale heating operators is to utilise the chipping service of a professional contractor (Spinelli, Magagnotti 2013) if it is available.

Chipping is the primary element of the forest chip supply chain and affects the whole system, because the location where comminution is performed determines the form of the material to be transported. Chipping is also an essential element of fuel supply e.g. to modern biomass boilers (Jensen et al. 2004; Hartmann et al. 2006; Strehler 2000; Lu et al. 2010; Spinelli, Magagnotti 2010; Spinelli et al. 2011a, b; Röser et al. 2012; Spinelli, Magagnotti 2013; Spinelli et al. 2013; Spinelli, Magagnotti 2014; Wolfsmayr, Rauch 2014; Ghaffariyan et al. 2017; Kühmaier, Erber 2018; Prinz et al. 2018). Particle size distribution also affects handling and combustion efficiency, and emissions at heating plants (Mattsson 1990; Kristensen, Kofman 2000; Jensen et al. 2004; Paulrud, Nilsson 2004; Bäfver, Renström 2013). In addition, chips have to be delivered regularly, which makes good planning a crucial issue (Spinelli, Magagnotti 2010; Windisch et al. 2015; Väätäinen et al. 2017). In turn, planning requires a correct estimate of chipping productivity and cost. Otherwise, shortfalls are experienced in both supply chain management and price setting (Spinelli, Magagnotti 2010; Spinelli, Magagnotti 2014; Windisch et al. 2015; Mola-Yudego et al. 2015; Väätäinen et al. 2017).

In small-scale chipping operations, three basic types of chipper are used: disc type, drum type, and screw type (McCallum 1997; Eriksson et al. 2013; Spinelli et al. 2013; Wolfsmayr, Rauch 2014). Drum and disc chippers are the primary technology used, whereas screw chippers are rarely used (McCallum 1997; Eriksson et al. 2013; Spinelli et al. 2013; Wolfsmayr, Rauch 2014). Drum chippers are more expensive to manufacture. In addition, power demand and fuel consumption are somewhat higher compared with disc chippers, due to a bigger cutting angle (McCallum 1997). With disc chippers, the infeed angle of stems into the chipper disc knives is about 45°. Stems are fed into the drum chipper at an angle perpendicular (90°) to the drum axis and chipper knives. The infeed opening on drum chippers is wide but limited in height, whereas the infeed openings of disc chippers are almost square (McCallum 1997; Eriksson et al. 2013). The infeed opening effectively defines the maximum diameter of log that can be chipped, and the wide infeed opening of the drum chipper favours the chipping of branchy whole trees or logging residues (Eriksson et al. 2013; Kühmaier, Erber 2018). To control the oversized splitters, the drum chipper can be equipped with a built-in screen, through which the reduced material passes before leaving the chipper (Eriksson et al. 2013; Kons et al. 2015; Kühmaier, Erber 2018). The use of narrower screens improves product quality but decreases productivity and increases fuel consumption (Kühmaier, Erber 2018). Disc chippers vary in their ability to produce quality chips from whole trees including limbs (McCallum 1997).

Truck-mounted chippers are most suitable for entrepreneurs with large annual chipping volumes and wide procurement areas, whereas tractor-powered chippers are interesting options for entrepreneurs who work locally (Spinelli, Magagnotti 2014; Laitila, Routa 2015; Kühmaier, Erber 2018). During the cold season, chipping machinery is intensively used, while during the summer months, the problem is a lack of work (Spinelli, Magagnotti 2014; Laitila, Routa 2015; Väätäinen et al. 2017). Tractor-towed chippers are usually powered by the tractor's power take-off (PTO), and it is possible to utilise the tractor for other purposes when there is no chipping work (Spinelli, Magagnotti 2014; Eliasson et al. 2015). Tractor-powered units are also cheaper to acquire and easier to resell in sections compared with truck-mounted chippers (Spinelli, Magagnotti 2014). However tractor-powered units have certain disadvantages compared with truck-mounted chippers: first, their chipping productivity is lower; second, they cannot relocate between working sites as quickly as truck-mounted units (Spinelli, Magagnotti 2013, 2014).

Choosing the appropriate technology means a technology appropriate for the conditions in question, and this can be based on several criteria (Harstela 1991). In forest technology, the comparison of chippers' performance often focuses on productivity or quality issues, and the amount of produced fuel chips is measured e.g. as a solid volume (m^3), bulk volume (chip-m^3), fresh weight (kg),

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dry weight (kg), or according to energy content (MWh) (Magagnotti, Spinelli 2012; Eliasson et al. 2018). Correspondingly, chipping time consumption can be defined as effective time (E_0h) or gross effective time (E_{15}h) (Harstela 1991; Björheden, Thompson 2000; Uusitalo 2010). Since normal machine work always includes short breaks or pauses, gross effective working time is more precise in describing actual work productivity (Harstela 1991; Björheden, Thompson 2000; Uusitalo 2010). In addition to short breaks or pauses, the degree of machine utilization (MU) depends on the technical reliability of the machine and the organisation's operational efficiency (Harstela 1991).

Comparing the profitability of investments alternatives may be feasible using different calculation methods instead of an intuitive decision-making process (Öhlmér, Lönnstedt 2004; Virlics 2013). The objective of this study was to determine the economic performance of alternative chipper choices for small-scale chipping, based on unit cost (e.g. Harstela 1991; Uusitalo 2010; Ackerman et al. 2014; Di Fulvio et al. 2017; Kaleja et al. 2018) and net present value (NPV) calculations (e.g. Beranek 1975; Levy, Sarnat 1994), thus offering an insight into price setting for small-scale chipping operations and the profitability of chip production.

MATERIAL AND METHODS

Four tractor-powered professional or semi-professional disc chippers and one professional drum chipper with an intake opening in a range of 26 to 45 cm and a power requirement of between 90 kW and 150 kW were selected for the chipping cost and investment profitability analyses. A truck-mounted drum chipper powered by the truck's 338 kW engine and with an intake opening of 45 cm were also included in the analyses. The purchase prices of the chipper units were in the range of €96,301 to €368,363, and chipping productivity was in the range of 24 to 136 chip-m^3 (bulk) per operating hour (Table 1). The commands for manoeuvring the timber loader and chipper were positioned in the cabin of the tractor or truck. The average purchase prices, cost factors, and technical details of the chipper units (Table 1) were acquired from machine dealers, specification sheets, a literature review, and interviews with chipping entrepreneurs. Classification to professional or semi-professional chippers were based on recommendations for the intended use and from chipper manufacturers. Chipping of delimbed stems was expected to be undertaken at the heating plant or at the terminal. For heat entrepreneurs, the most convenient way to receive chips is if they are chipped directly into the silo at the heating plant. Conversely, chipping at the terminal is a feasible choice, e.g. if other activities are disturbed by a loud and dusty chipping operation at the heating plant.

The operating hour costs (excluding value added tax) of the chippers (Table 1) were calculated per gross effective hour (E_{15}h), and the costs were presented in euros (€). The costs included both fixed costs (e.g. capital depreciation, interest expenses, insurance fees, and administration expenses) and variable operating expenses (e.g. fuel, repairs, service, and machine transfers). In addition to the annual total cost, 5% extra was added to take the risk of entrepreneurship into account. Capital costs were calculated using an interest rate of 5%. In the operating cost, analyses were expected to include chipping work of between 50 and 500 operating hours by the tractor, chipper translocating time of between 19 and 185 operating hours, and other tractor work (without a chipper) of 500 operating hours per year (Table 1). Because a purpose-built truck-mounted chipper cannot be used for other purposes, the annual operating hours of the chipper were between 50 and 500 hours, and the translocating time was between 12 and 120 operating hours. The unit cost of chipping (Table 1 and Fig. 2), which is calculated based on the chipper's hourly cost and productivity (e.g. Uusitalo 2010), was defined as: Euros per bulk volume of produced chips (€/chip-m^3).

The profitability of the alternative chipper choices was calculated using the method of net present value (NPV), with the following Eq. 1 (Levy, Sarnat 1994):

$$NPV = \sum_{t=1}^{n} \frac{S_t}{\left(1+k\right)^t} - I_0 \qquad (1)$$

where:

S_t – the expected net cash receipt at the end of year t,

I_0 – the initial investment of the chipper unit,

k – the discount rate, i.e., the required minimum annual rate of return on new investments (5%),

n – the investment's duration in years (10).

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Table 1. Investment and unit cost calculation details of tractor-powered and truck-mounted chipper units

	Semi-professional disc chipper		Professional disc chipper		Professional drum chipper	Professional truck-mounted drum chipper
	(max. ø 26 cm)	(max. ø 32 cm)	(max. ø 38 cm)	(max. ø 45 cm)	(max. ø 45 cm)	(max. ø 45 cm)
Purchase price of the tractor or the truck (€)	55,195	130,000	130,000	130,000	145,000	125,000
Purchase price of the chipper equipped with crane (€)	41,106	80,920	66,100	104,067	137,313	243,363
Total purchase price of the chipper unit (€)	96,301	210,920	196,100	234,067	282,313	368,363
Depreciation time (years)	10	10	10	10	10	10
Annual depreciation of purchase price (%)	–17	–17	–17	–17	–17	–17
Residual value of the chipper unit (€)	14,942	32,726	30,427	36,318	43,804	57,155
Interest rate (%)	5.0	5.0	5.0	5.0	5.0	5.0
Annual depreciation (€)	8,136	17,819	16,567	19,775	23,851	31,121
Annual interest cost (€)	2,984	6,537	6,077	7,254	8,749	11,416
Annual overhead, insurance cost (€)	10,871	14,882	14,364	15,692	17,381	20,393
Annual chipping hours (h)	50–500	50–500	50–500	50–500	50–500	50–500
Annual translocating time (h)	19–185	19–185	19–185	19–185	19–185	12–120
Other working hours per year (h)	500	500	500	500	500	0
Total working hours per year (h)	569–1,185	569–1,185	569–1,185	569–1,185	569–1,185	62–620

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Table 1. to be continued

	Semi-professional disc chipper		Professional disc chipper		Professional drum chipper	Professional truck-mounted drum chipper
	(max. ø 26 cm)	(max. ø 32 cm)	(max. ø 38 cm)	(max. ø 45 cm)	(max. ø 45 cm)	(max. ø 45 cm)
Hourly wage of the worker (€)	17.5	17.5	17.5	17.5	17.5	17.5
Hourly wage cost total (€)	29.4	29.4	29.4	29.4	29.4	29.4
Fuel price (€ per litre)	0.87	0.87	0.87	0.87	0.87	0.87
Fuel consumption (litre per produced chip-m^3)	0.35	0.35	0.35	0.35	0.5	0.5
Chipping productivity (chip-m^3 per operating hour)	24	56	70	80	112	136
Hourly fuel consumption during chipping (litre)	8.4	19.6	24.5	28	56	68
Hourly fuel cost during chipping (€)	8.7	20.3	25.4	29.0	48.6	59.0
Hourly fuel consumption during translocating (litre)	10.0	10.0	10.0	10.0	10.0	30.0
Service and maintenance (€ per chipping hour)	26.1	44.2	52.1	57.7	75.8	89.3
Hourly operating cost of the chipper unit (€)	108.3–87.8	168.1–131.5	176.2–141.9	195.4–155.8	251.4–205.6	1,257.6–298.4
Unit cost of chipping (€/chip-m^3)	4.5–3.7	3.0–2.3	2.5–2.0	2.4–1.9	2.2–1.8	9.2–2.2

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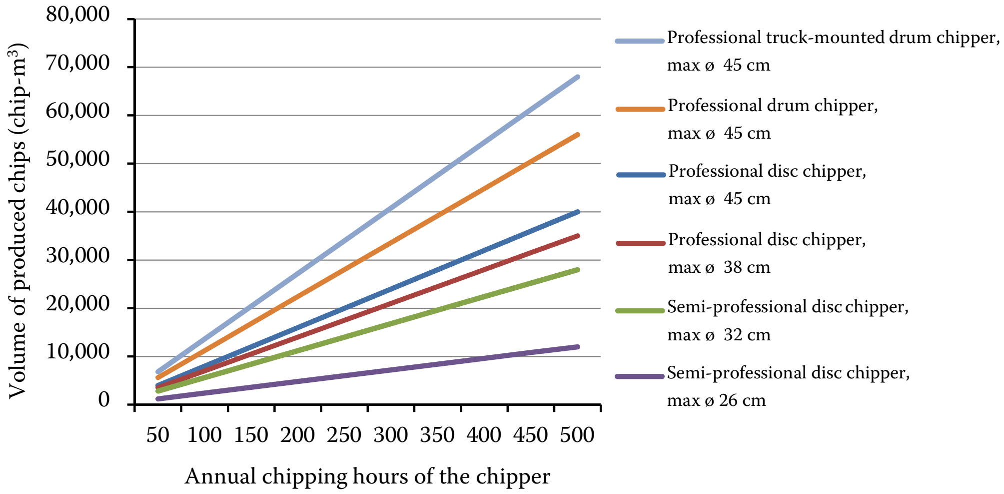

Fig. 1. The volume of produced chips as a function of the annual operating hours of the chippers

The cost of outsourced chipping was defined as €4.0/chip-m^3, and it was determined by interviews with chipping entrepreneurs. The profitability of the alternative chipper choices was evaluated as a function of the annual chipping hours or the annual volume of produced chips. If NPV displays a positive result, the investment yields a positive payback compared with the initial investment costs. When an NPV calculation result is zero, the investment reaches break-even given the required rate of return. If the calculation displays a negative result, the investment does not yield sufficient cash flows to balance out the initial investment cost. The most feasible investment option is the chipper option which yields the highest positive NPV (e.g. Beranek 1975, Levy, Sarnat 1994).

RESULTS

The cost of chipping

The volume of produced chips increased as a function of annual operating hours (50–500), depending on chipper choice (Fig. 1). The professional truck-mounted drum chipper had the highest productivity and volume of produced chips (6,800 to 68,000 chip-m^3). The small semi-professional chipper had the lowest productivity and lowest volume of produced chips (1,200–12,000 chip-m^3).

The operating hour costs (Fig. 2) and the unit costs (Fig. 3) decreased when the annual operating hours of the chipper unit increased (Table 1). The operating hour cost of the tractor-powered semi-

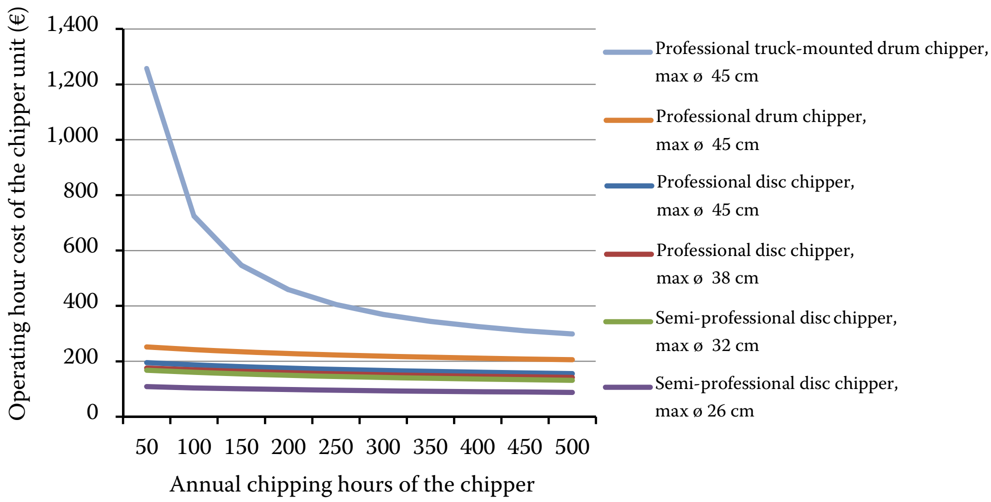

Fig. 2. The operating hour cost of the chipper as a function of its annual chipping hours

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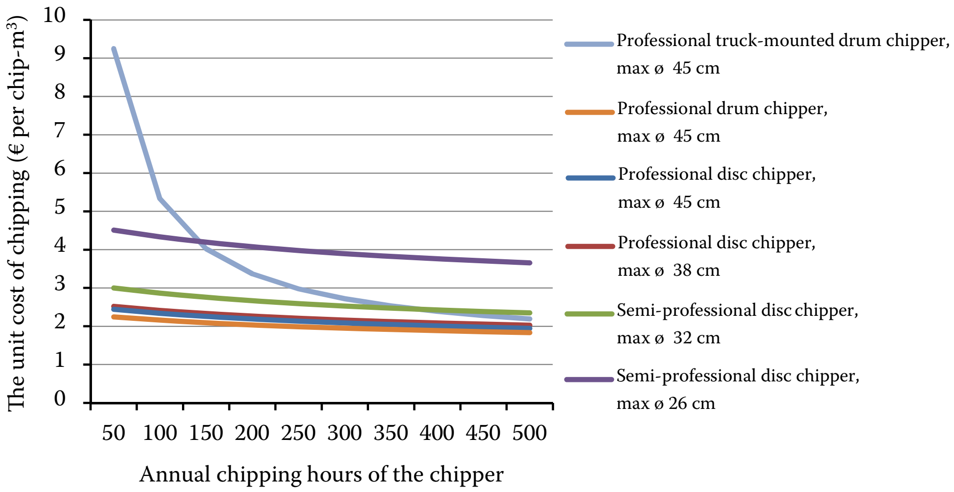

Fig. 3. The unit cost of chipping as a function of the chipper's annual operating hours

professional chipper units was in a range between €87.8 – €168.8; for the tractor-powered professional chipper units, the hourly costs were €141.9 to €251.4 (Fig. 2 and Table 1). For the truck-mounted professional drum chipper, the operating hour cost changed steeply in a range between €298.4 and €1,257.6 (Fig. 2). The operating hour cost was highest mainly due to the high investment cost and because the truck-mounted chipper cannot be used for other purposes, unlike the tractor. Low annual equipment use increases the share of fixed cost per operating hour, especially when the annual operating hours and produced chip volumes are low.

Unit costs (€/chip-m^3) take into account both chipping productivity (Fig. 1) and the operating hour cost of the chipper (Fig. 2). This is essential information for comparing chipper alternatives with a different productivity and fixed and variable costs. In this study, the unit costs of chipping were lowest for the tractor-powered professional chipper units (Fig. 3). For the professional drum chipper, the unit cost of chipping was in a range between €1.8 and €2.2/chip-m^3 (Fig. 3). For professional disc chippers, the unit cost was in a range between €1.9 and €2.4/chip-m^3 (max. ø 45 cm) and €2.0 and €2.5/chip-m^3 (max. ø 38 cm) (Fig. 3). For the truck-mounted professional drum chipper, the unit cost of chipping increased rapidly in a range between €2.2 and €9.2/chip-m^3. For semi-professional chippers, the unit cost was in a range between €4.5 and €3.7/chip-m^3 (max. ø 26 cm) and €3.0 and €2.3/chip-m^3 (max. ø 32 cm) (Fig. 3).

To reach a cost level below the cost of outsourced chipping (€4.0/chip-m^3), the annual chipping hours of the professional truck-mounted drum chipper should be above 150 h; with a semi-professional disc chipper (max. ø 26 cm) the annual chipping hours should be at least 250 h (Fig. 3). Expressed as an annual volume of produced chips, the break-even point was reached at 6,000 chip-m^3 for the semi-professional disc chipper and at 20,400 chip-m^3 for the professional truck-mounted drum chipper (Fig. 4). Due to low chipping productivity, the unit costs of chipping were highest almost invariably for the small (max. ø 26 cm) semi-professional chipper, although the professional truck-mounted chipper showed higher units costs for low annual chipping hours (Fig. 3). The cost difference for the tractor-powered professional chippers was approximately €1.9 per chip-m^3 and about €1.4 per chip-m^3 compared with the bigger semi-professional chipper powered by a 150 kW tractor (Fig. 3). The high capacity of the professional chippers (Figs 1 and 4) enables the expansion of a chipping entrepreneurship business in future without the requirement of extra investment in machinery. The wide intake opening of professional chippers also enables the efficient chipping of large-diameter fuel logs. A weakness is the investment costs: they are relatively high for a professional chipper and a powerful tractor or truck.

The profitability of the chipper investment

To get a positive NPV, the break-even point was 152 annual chipping hours for the tractor-powered drum chipper, 175 h and 186 chipping hours for the

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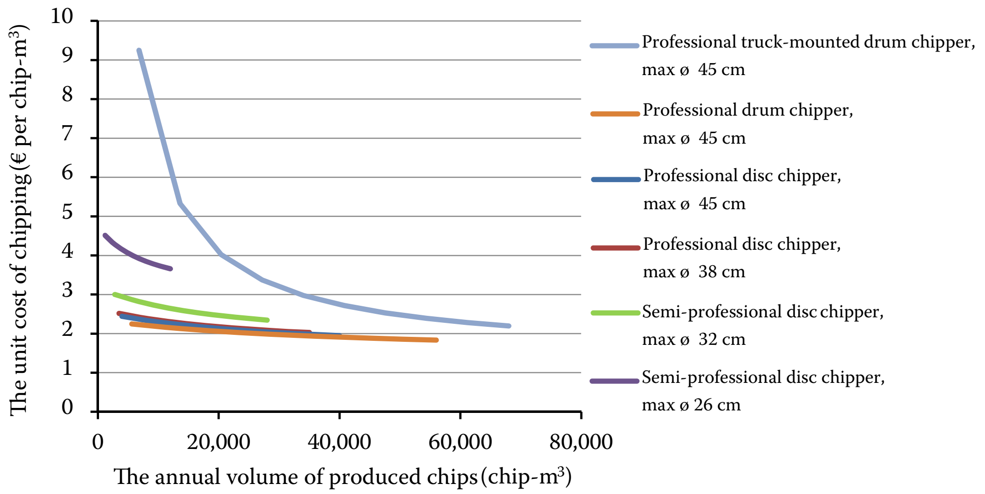

Fig. 4. The unit cost of chipping as a function of annually produced fuel chip volume

tractor-powered disc chippers (max. ø 45 cm and ø 38 cm), 272 chipping hours for the truck-mounted drum chipper, and 286 chipping hours for the tractor-powered semi-professional (max. ø 32 cm) disc chipper (Fig. 5). The NPV of the smaller semi-professional disc chipper (max. ø 26 cm) was always negative, with a given range for the annual chipping hour of between 50 and 500 hours (Fig. 5).

The break-even points for the positive NPV, expressed as an annual volume of produced chips (Fig. 6), were 13,000 and 14,000 chip-m^3 for the tractor-powered disc chippers (max. ø 38 cm and ø 45 cm), 16,000 chip-m^3 for the tractor-powered semi-professional disc chipper (max. ø 32 cm), 17,000 chip-m^3 for the tractor-powered drum chipper, and 37,000 chip-m^3 for the truck-mounted drum chipper (Fig. 6). The NPV of the smaller semi-professional disc chipper (max. ø 26 cm) was always negative (Fig. 6) within the given range for the chipper's annual capacity (1,200–12,000 chip-m^3).

The key finding is that below an annual chipping demand of 13,000 chip-m^3, outsourced chipping is economically a feasible choice. From the investment perspective, a tractor-powered professional disc chipper with an intake opening of 38 cm was assessed to be the most profitable chipper choice when the annual chipping volumes were above 13,000 chip-m^3 and below 35,000 chip-m^3 (Fig. 6). The larger professional disc chipper (max. ø 45 cm) with a higher productivity (Fig. 1) was the second most profitable choice if the annual chipping volumes were between 14,000 and 40,000 chip-m^3 (Fig. 6). The third feasible choice was the tractor-powered drum chipper with a demand for pro-

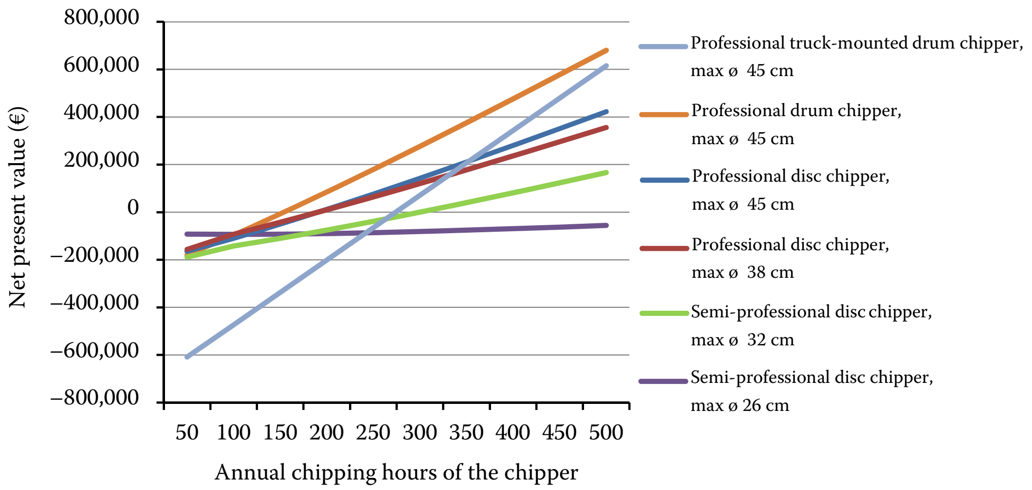

Fig. 5. Net present value as a function of the chipper's annual chipping hours

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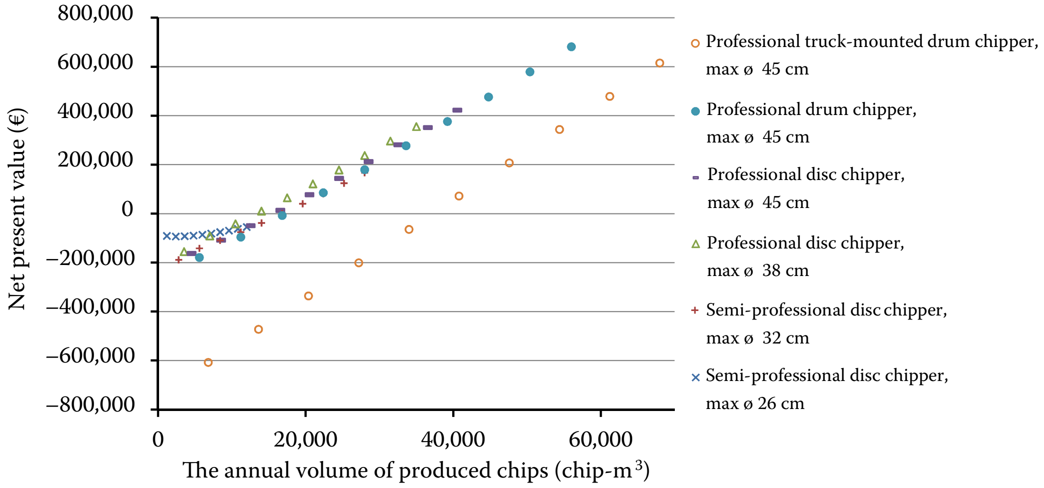

Fig. 6. Net present value as a function of the annual volume of produced chips

duced chips from 17,000 chip-m^3 to 56,000 chip-m^3. The truck-mounted drum chipper was an economically feasible choice if the annual demand for fuel chips was within a range between 56,000 and 68,000 chip-m^3.

DISCUSSION AND CONCLUSIONS

Decision analysis in economic theory shows that the decision-making process is based on an objective, punctual analysis of the investment and its possible outcomes, but also on the investor's subjective perspective (Virlics 2013). The dimensions and properties of the material to be chipped, the quality requirements for fuel chips, and the annual chipping volumes are the key criteria for the selection of a suitable chipper technology. Furthermore, initial investment, operating costs, and the cost of outsourced chipping are the key elements for comparing the profitability of investment alternatives. To calculate a cost per unit of product (e.g. €/chip-m^3), a productivity estimate is also needed.

The operational cost depends on all the incurred expenses when the chipper unit is actually operating. Conversely, the capital cost depends on the initial investment, the economic service life of the chipper unit, and the interest rate charged on borrowed capital; it is incurred whether or not the machine is working (Nurminen et al. 2009; Ackerman et al. 2014; Spinelli et al. 2017). The investment risk exists because it is uncertain that the cost of the investment will be recovered and a profit gained (Virlics 2013). Risk and uncertainty is subjectively perceived, and it involves psychological and emotional factors (Virlics 2013).

In our study the cost of outsourced chipping was defined as €4.0/chip-m^3. It is obvious that the chipper investment is less feasible if the market price of chipping will decrease e.g. due to tightening competition on the open market. In our cost analyses the risk of entrepreneurship was defined to be 5% of the total annual costs. With tractor-powered professional chippers, the increase of the risk margin to 10% or 15% could increase chipping cost by 0.06 € and 0.12 € per produced chip-m^3. Similarly, if the risk margin is removed (0%), the unit cost of chipping is 0.06 euros lower per produced chip-m^3. Thus, the impact of risk margin is rather nominal to the unit cost of chipping, but rather affects the result of the financial year.

In forest engineering, the estimation of maintenance and repair costs has been considered the most unpredictable cost element, because operating conditions, operator skills, repair and maintenance strategies, and machine qualities influence this cost (Nurminen et al. 2009; Ackerman et al. 2014; Dodson et al. 2015; Di Fulvio et al. 2017; Spinelli et al. 2019). Since the machinery is expensive and is essential for the entrepreneur, it needs to operate both in an economically feasible way and with few breakdowns. Owning the chipper unit for an extended period may lead to a low annual capital cost, but due to higher maintenance costs it might be better to replace the chipper unit with a new one instead of repairing it after a certain period. Unpredictable and unexpected machine breakdown means the entrepreneur is unable to carry out the

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work. Leasing the chipper for a shorter period may result in a more reliable operation, but the hourly cost may be higher.

It has been noted that the use of powerful and stable machinery in timber harvesting yields many advantages, because the alternative of downsizing inevitably leads to more frequent situations where the operator needs to use the machine close to its maximum capacity (Arlinger et al. 2014). This is unfavourable from the perspective of machine reliability and downtime, as well as ergonomics (Arlinger et al. 2014). In chipping, time consumption is inversely proportional to engine power and grapple load size in feeding (Spinelli, Hartsough 2001; Van Belle 2006; Spinelli, Magagnotti 2010; Ghaffariyan et al. 2013). Larger machines have higher engine power, which generally results in higher productivity if the conditions are suitable and the machine is managed properly (Laitila, Routa 2015). However, this does not necessarily mean that the unit cost (€/chip-m^3) will be lower, since the hourly costs of the chipper will also be higher. Chipping requires power, and entrepreneurs operating tractor-powered chipper units have observed that an underestimating of the chipping power requirement leads to transmission breakdowns, low productivity, and excessive fuel consumption (Spinelli, Magagnotti 2014). Interruptions are much less frequent with more powerful tractors (McCallum 1997).

The chipping cost is sensitive to transport logistics when chipping is done at the roadside landing. The fluctuation of interactions directly affects the degrees of utilisation of chippers and vehicles and the number of vehicles required (e.g. Mobini et al. 2011; Karttunen et al. 2012; Karttunen et al. 2013; Eriksson et al. 2014; Windisch et al. 2015; Eliasson et al. 2017; Väätäinen et al. 2017; Belbo, Vivestad 2018; Eliasson et al. 2018; Prinz et al. 2019). As the chipper is the most expensive machine in the fuel chip supply chain, it is unacceptable for an entrepreneur to spending around half their scheduled worktime on tasks other than chipping.

In our study, the chipping of delimbed stems was done at the heating plant or at the terminal. Centralised chipping makes it possible to work effectively and avoid the problems of 'hot systems' such as waiting and queuing at the landing, when chipping and long-distance transportation are independent of each other (Kärhä 2011; Eriksson et al. 2014; Wolfsmayr, Rauch 2014; Kühmaier, Erber 2018). When chipping at the heating plant or terminal, operating times and cost factors are much more constant and predictable compared with chipping operations at roadside landings, which justifies the static spreadsheet-based cost calculation approach applied in this study.

The results for the three tractor-powered professional chippers involved in the comparison were very close to each other. High chipping capacity and a wide infeed opening favours the drum chipper. However, the investment cost of a drum chipper is higher, and fuel consumption and service costs are somewhat higher compared with disc chippers. With tractor-powered chippers, the key to economic success is to find additional work for the powerful tractor (Akay 2005; Laitila, Väätäinen 2013) outside the hectic chipping season. The profitable running of truck-mounted drum chippers calls for high annual chipping volumes, and this chipper type is therefore a feasible choice for a professional chipping entrepreneur.

Semi-professional disc chippers offer lower investment costs, but their economic feasibility is rather poor. However, if an outsourced chipping service is unavailable and annual demand for fuel chips is low, entrepreneurs can consider an investment in a semi-professional chipper. This is especially the case if the entrepreneur can utilise existing applications such as a suitably powerful farm tractor or other second-hand machinery, which will greatly reduce the capital outlay for chipping equipment. This may be relevant for rural areas and remote communities, where the use of fuel chips for heating may be a new alternative to existing systems, typically based on imported fossil fuels.

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