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Productivity and fuel consumption for mobile comminution equipment when chipping forest biomass

Produktivitet och bränsleförbrukning för olika maskintyper vid flisning av stamved, grot och stubbar

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Förord

Detta arbete presenterar en metaanalys av de sönderdelningsstudier som genomfördes av Skogforsk under forskningsprogrammen Effektivare SkogsbränsleSystem 2007–2010 och 2011–2015 samt de studier som genomförts fram till 2020 i andra skogsbränsleprojekt.
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Författarna

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Summary

In 2017, 22% of the woody biomass harvested in EU28 was used for energy production, and low-value forest biomass is seen as a key resource in mitigating climate change. The use of logging residues and small trees from thinning is still far from its maximum sustainable potential due to low supply chain profitability. The cost structure for the biomass supply of these assortments is dominated by costs of comminution and road transports, which are dependent on each other, and operational analyses to find efficient supply systems are of the utmost importance. A prerequisite for these analyses is reliable data on the performance of comminution equipment (chippers and grinders) and the trucks used. Our aim was to provide functions for estimating productivity, fuel consumption and energy efficiency for comminution equipment, based on equipment type, feedstock and the type of chips produced. The results show general differences between the machine types, given the same engine size. Disc chippers are more productive and more fuel and energy efficient compared to drum chippers and hammermills when chipping stemwood, but lose efficiency and produce low-quality chips when chipping logging residues or small trees. Drum chippers are more versatile and produce acceptable chips from all uncontaminated feedstocks, but fuel consumption is slightly higher. Hammermills can handle all feedstocks, including stumps, but fuel consumption is high. A comparison of drum chippers and hammermills indicates a difference in the effect of engine power on the two machine types, which is logical.

Keywords: Biomass, Chipper, Crusher, Hammermill, Wood chips, Logs, Logging Residue, Stump

Sammanfattning

Under 2022 använde svenska värmeverk, kraftvärmeverk och skogsindustrin 17,1 TWh flis från stamved, grot och träddelar för energiändamål. Detta är den högsta förbrukningen av biobränslen från skogen sedan 2014. Trots denna utveckling finns en betydande potential att ytterligare öka utnyttjandet av skogsbränslen på ett hållbart sätt. Under 2022 användes 9,7 TWh grotflis, och i SKA22 bedömer Skogsstyrelsen att potentialen för grot från föryngringsavverkning är 24 TWh årligen fram till 2035. Då de skogliga biobränslena huvudsakligen har svenskt ursprung, utgör de en strategisk del av den svenska energiförsörjningen.

En huvudanledning till att potentialen inte utnyttjas är att lönsamheten i försörjningskedjan från skog till energianvändare är låg. De främsta orsakerna till den låga lönsamheten är höga hanteringskostnader och det relativt låga värdet på den producerade biomassan. I Sverige betalades ett högre pris för primära skogsbränslen under 2011 än under åren fram till 2022 på grund av konkurrens från andra bränslen, till exempel återvunnet trä och hushållsavfall. Därefter har energipriserna ökat snabbt på grund av den europeiska energisituationen. Kostnaderna i försörjningskedjan domineras av sönderdelnings- och transportkostnader, vilka ofta är beroende av varandra.

Det har genomförts många studier av olika typer av sönderdelningsutrustning, dels av flishuggar som använder vassa verktyg för att hugga virket till flis, dels av krossar som slår sönder virket till krossflis. Flishuggarna kan delas upp i trum- och skivhuggar, medan det finns en uppsjö av olika tekniska lösningar för krossar. Även om ett flertal sammanställningar av de publicerade studierna gjorts för att ta fram generella funktioner för produktiviteten hos olika typer av sönderdelningsutrustning, så utgör olikheter i hur den producerade mängden flis mätts i de inkluderade studierna en källa till osäkerhet.

Under perioden 2009 till 2016 genomförde Skogforsk en serie tidsstudier av sönderdelningsutrustning med en standardiserad metod där den producerade mängden flis vägdes och fukthaltsbestämdes. Vid studierna mättes även maskinernas bränsleförbrukning. Genom att lägga ihop datamaterialet från dessa studier kan en metaanalys av generella prestations- och bränsleförbrukningssamband göras. Utifrån dessa insamlade data kan energiinnehållet i den producerade flisen beräknas, vilket möjliggör analyser av energieffektiviteten i sönderdelningen, det vill säga hur stor del den förbrukade energin i sönderdelningen utgör i relation till energin i den producerade flisen.

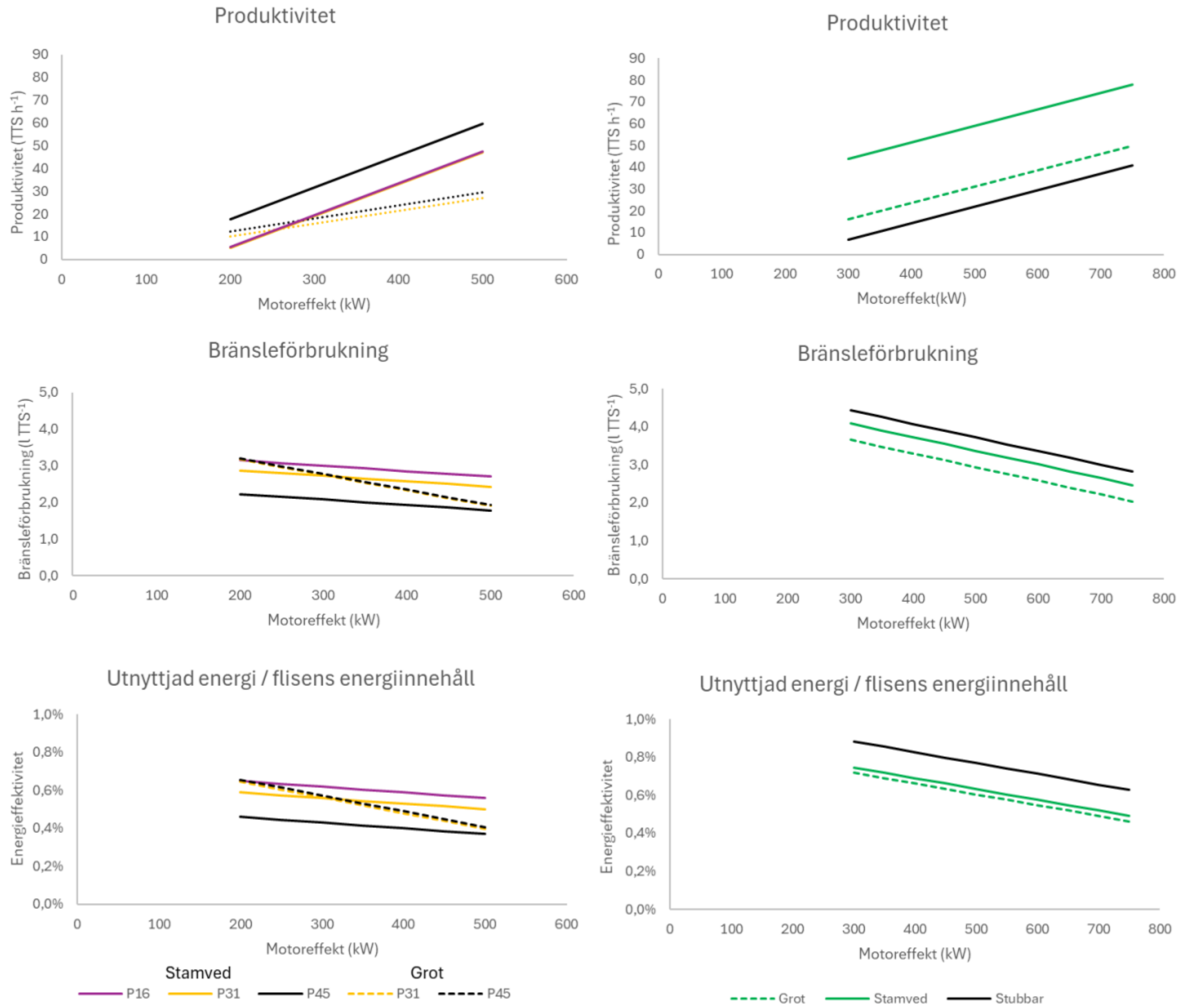
Syftet med studien var att presentera funktioner för att beräkna produktivitet, bränsleförbrukning och energieffektivitet för professionell sönderdelningsutrustning baserat på typ av sönderdelningsutrustning, råvara och målfraktionen för den flis som produceras. Resultaten kan användas för benchmarking av sönderdelningsutrustning och systemanalyser av skogsbränsleförsörjning.

Resultaten visar att skivhuggar är mer produktiva och mer bränsle- och energieffektiva jämfört med trumhuggar och krossar med samma motoreffekt vid flisning av stamved. Däremot tappar skivhuggarna i effektivitet och producerar flis av låg kvalitet vid flisning av grot och träddelar. Trumhuggarna är mer mångsidiga och producerar godtagbar flis från alla oförorenade skogsbränslen, även om bränsleförbrukningen är något högre vid flisning av stamved. Krossarna kan hantera alla typer av material, inklusive förorenade material som exempelvis stubbar, men bränsleförbrukningen är hög. Det analyserade materialet är dock så obalanserat att närmare analyser per maskintyp behövs.

För trumhuggar ökar produktiviteten när man producerar en grövre flis från stamved, det vill säga rötved, massaved eller träddelar (Figur 1), samtidigt som bränsleförbrukningen per producerat ton minskar. Detta förbättrar energieffektiviteten, det vill säga relationen mellan förbrukad energi och producerad energi minskar. Dessa samband återfinns inte vid sönderdelning av grot, antagligen eftersom fraktionsfördelningen i den producerade grotflisen beror mer på egenskaperna hos den grot som sönderdelas än av trumhuggens

konfiguration. Generellt ger trumhuggar med en högre motoreffekt en något lägre bränsleåtgång per ton Ts än de med en lägre motoreffekt, vilket minskar andelen av energin i flisen som åtgår för flisningsarbetet.

De studerade krossarna hade en högre motoreffekt än huggarna, vilket är nödvändigt då mer energi åtgår för att krossa skogsbränslet till flis än för att hugga det. Krossarna hade en klart högre produktivitet vid krossning av stamved (rötved, massaved eller träddelar) än vid krossning av grot eller stubbar. Även om produktiviteten vid krossning av stamved och grot är relativt likvärdig med den för trumhuggar är bränsleåtgången avsevärt högre (Figur 1). För skogsbränslen som förorenats med mineraljord är dock krossar det bästa alternativet, då trumhuggarnas prestation sjunker och bränsleförbrukningen ökar när knivarna blir slöa.



Figur 1. Produktivitet, bränsleförbrukning och energieffektivitet för trumhuggar (vänster kolumn) vid flisning av grot och stamved till olika flisfraktioner, samt för krossar (höger kolumn vid flisning av grot, stamved och stubbar.

Det insamlade materialet var för litet för att ta fram funktioner för skivhuggarna. Även här ökade produktiviteten kraftigt då motoreffekten ökade. Vid flisning av rundved var produktiviteten hög, liksom fliskvaliteten. Produktiviteten var avsevärt lägre vid flisning av grot eller träddelar, och den producerade flisen höll inte en acceptabel kvalitet.

Fukthalten i det flisade materialet påverkade inte trumhuggarnas produktivitet nämnvärt och ingick därför inte i produktivitetsmodellerna. Däremot ökade bränsleförbrukningen med ökande fukthalt. Detta har, tillsammans med det faktum att den tillgängliga energin i den producerade flisen minskar med fukthalten, negativ effekt på energieffektiviteten. Den ökade bränsleförbrukningen kan vara en effekt av hur fukten påverkar skärkrafterna när flisen kapas, men också av det enkla faktum att fuktigare flis är tyngre och därför kräver mer energi för att slungas ut från maskinen. Det kan vara värt att notera att de flesta material som studerades hade lagrats, och att vedegenskaperna för ett fuktigt lagrat material inte är likvärdiga med egenskaperna för färsk ved med samma fukthalt.

Trädslagsblandningen i det flisade materialet påverkade varken produktiviteten eller bränsleförbrukningen nämnvärt. Detta beror förmodligen på två saker: 1) Mängden flis/skogsbränsle mättes i ton TS, vilket till stor del eliminerar effekten av olika veddensiteter, och 2) Det mesta av det flisade materialet utgjordes av blandningar dominerade av tall och gran med en viss inblandning av asp och björk. Andra lövträd var sällsynta i det studerade materialet.

I arbetsrapporten återfinns funktioner för att beräkna produktivitet, bränsleförbrukning och energieffektivitet för trumhuggar och krossar baserade på ursprungsmaterial, producerad flisfraktion, motoreffekt och fukthalt.

Introduction

Global and regional agreements have been made to increase the long-term use of low-value forest biomass for energy (IEA 2013; European Commission 2015), as this biomass is seen as a key resource in mitigating climate change. In 2017, 22% of the woody biomass harvested in EU28 was used for energy production in households and by the energy sector, with the remaining 78% used in forest (wood based) industries (Malico et al. 2019). A large proportion of the roundwood used in the forest industries becomes by-products, e.g. bark, used for energy production.

Forest fuels are divided into primary forest fuels, i.e. forest biomass harvested for energy use, and secondary fuels, i.e. forest industry by-products. In Sweden, the largest sources of primary forest fuels used in heat and power production are logging residues, i.e. tops and branches, and small trees. Biomass from these two sources accounted for 10.2 TWh of fuel delivered to the energy industry in 2018 (Anon. 2020b). The forestry sector delivers a further 4.8 TWh of primary forest fuel in the form of low-quality logs from ordinary harvesting operations to the energy sector. As in the rest of Europe (Verkerk et al. 2011; Diaz-Yanez et al. 2013), the use of logging residues and small trees is still far from its maximum sustainable potential, which is estimated to 44.5 TWh after consideration of ecological and environmental restrictions by the Swedish Forest Agency (Anon. 2015). In Sweden, this is partly explained by low profitability in the supply chain (Björheden 2017).

Supply chain economy

The main causes of low profitability in the supply chain are high handling costs and the relatively low value of the produced biomass. In Sweden the price paid for primary forest fuels in 2011 was higher than the prices paid in the subsequent years until 2022 (Anon. 2024), due to competition from other fuels, e.g. recycled wood and household waste, and has thereafter increased rapidly due to the European energy situation. The operational costs for the supply of residues are dominated by comminution (48 SEK/m^3) and road transport costs (41 SEK/m^3), while the costs for small tree operations are dominated by felling costs (43 SEK/m^3), followed by comminution (41 SEK/m^3) and road transport costs (41 SEK/m^3) (Brunberg 2016). Similar cost structures can be found in e.g. Australia (Ghaffariyan et al. 2013) and Finland (Hakkila 2004; Routa et al. 2013), which is not surprising given the similarities in the supply chains (Diaz-Yanez et al. 2013). Efforts have been made to improve cost efficiency in supply systems (Ghaffariyan et al. 2017). Costs for comminution and road transports dominate the cost structure of the biomass supply for both logging residues and small trees. Furthermore, the efficiency of these work tasks are inter-dependent (Bradley et al. 1976; Asikainen 1995; Eliasson et al. 2017), operational analyses to find efficient supply systems adapted to local conditions are of the utmost importance.

A requirement for these system analyses is sufficient and reliable data on the performance of comminution equipment (chippers and grinders) and the trucks used. This data can be divided into two parts, data on the performance per effective work hour and data on delays that occur (Spinelli & Visser 2009; Belbo & Vivestad 2018). Currently, much data is available on chipper and grinder performance (e.g. Liss 1987; Asikainen & Pulkkinen 1998; Aman et al. 2011; Jernigan et al. 2013; Spinelli et al. 2013; Nuutinen et al. 2014; Kuptz & Hartmann 2015; Laitila & Nuutinen 2015; Laitila & Routa 2015; Magagnotti et al. 2015; Zamora-Cristales et al. 2015), but the quantity of chips produced has been measured in many different ways (Eliasson et al. 2018) and conversion to a common unit is often difficult. As shown by Eliasson et al. (2018), the unit used may affect the result and, to further complicate matters, machine settings may influence the measurement of the chips in some cases (Spinelli & Magagnotti 2012; Eliasson et al. 2015). Despite these difficulties, relevant results presenting basic productivity relationships have been produced, based on reviews of published studies (Spinelli & Magagnotti 2014; Bergström & Di Fulvio 2019).

It is probably better to base these kinds of meta-studies on machine studies carried out using the same approaches and measurement methods. In the *Efficient Forest Fuel Supply Systems* research programmes, Skogforsk carried out a series of performance studies of mobile comminution equipment: drum chippers (Eliasson & Nordén 2009; Eliasson & Picchi 2010; Eliasson et al. 2011; Eliasson et al. 2013; Eliasson et al. 2014a; Eliasson & Johanneson 2014a; Eliasson & Johanneson 2014b; Eliasson et al. 2014b; von Hofsten 2015; Eliasson 2016; Eliasson & von Hofsten 2016; von Hofsten et al. 2016; Eliasson & von Hofsten 2017a; Eliasson & von Hofsten 2017b; Prinz et al. 2018), disc chippers (Eliasson et al. 2011; Eliasson et al. 2012a; Eliasson et al. 2012b) and grinders (Eliasson & Granlund 2010; Eliasson et al. 2012c; Fogdestam et al. 2012; Anerud et al. 2016). In these studies, productivity and fuel consumption, as well as a number of influencing parameters, were measured in the same way (Eliasson 2014), enabling us to use the data to make general models for fuel consumption and productivity.

Aim

The aim of this study was to present functions for estimating productivity, fuel consumption and energy efficiency for professional comminution equipment based on equipment type, feedstock and the type of chips produced. Results could be used in benchmarking and system analysis of chip supply systems.

Material and methods

In the *Efficient Forest Fuel Supply Systems* research programmes and in other, later research programmes, Skogforsk has examined comminution equipment in commercial operations in a standardised way since 2009. A total of 24 machines have been investigated in 25 separate studies (Table 1). These studies are characterised by large quantities of produced chips per replicate; a guidance has been that a replicate should provide the chipper with at least half an hour of work. Depending on the size of the machine and the chip transport vehicles, between 3 and 50 oven dry tonnes (odt) of chips were produced in a replicate.

Machine and material parameters

In each study, machine parameters, classifications of the biomass before chipping, and the quality of the chips produced were measured. Data was collected on the following machine parameters:

Power – Engine power in kW for the engine powering the chipper/grinder

Parts driven – The parts of the machine powered by the engine, e.g. All parts = Chipper + chip extraction + loader, Chipper + chip extraction, or Chipper only. Of these options, ‘All parts’ is most common, followed by ‘chipper + chip extraction’. However, to simplify analyses, this parameter was simplified to a binary parameter were *Parts driven* either equals ‘All parts’ or ‘Not all parts’.

Machine type – In four classes, disc, open drum, closed drum chippers and crushers, where open and closed drum chippers are merged into drum chippers for some analyses.

Extraction – Conveyor, fan, accelerator, or disc. Fan implies a machine with a bottom sieve and augers that feed the chips to a fan that throws the chips through a extraction tube; accelerator is a drum chipper where the drum throws the chips into the extraction tube, where it is further accelerated by the accelerator to generate the necessary throw length; and disc is a disc chipper with blades on the back of the disc that throw the chips through the extraction tube.

Sieve size – mesh size in mm for the bottom sieve if the machine has one.

It is important to note that some of these parameters are confounded with one another, e.g. disc extraction only occurs for disc chippers, and that a parameter may affect another, e.g. sieve size will affect the chip size distribution.

Table 1. Number of studied machines and their engine power by machine type.

Machine type	No of machines	Engine power (kW)		
		Mean	Minimum	Maximum
Disc	4	642	130	932
Closed drum	11	404	157	787
Open drum	7	345	246	571
Crusher	3	589	360	783

The material parameters were:

Species composition – a rough estimate of the species composition. Particularly for logging residues, assessing the species composition accurately can be difficult.

Material type – Logs, tree sections with limbs, logging residues (branches and tops). In most analyses, logs and tree sections were combined into stemwood.

Moisture content (M) – moisture content wet basis.

Chip quality is expressed by the *chip size distribution*, classified according to SS-EN 15149-1 into P-classes. Chip sampling intensity for determining the chip size distributions varied within the analysed material, but in most studies one chip sample was taken per replicate. In studies where a large amount of biomass (>30 odt) was chipped per replicate, more than one sample may have been taken per replicate. In other studies, with many replicates per treatment but smaller amounts of biomass per replicate (3-10 odt), chip samples were not taken from all replicates within a treatment. This resulted in two parameters for the chip size class: 1) *Min P-class* which equals the actual P-class or the minimum noted P-class if sampling intensity differed from one sample per replicate, and 2) *Max P-class* which equals the actual P-class or the maximum noted P-class if sampling intensity differed from one sample per replicate.

Time and fuel consumption studies

All time studies of the chipping work were performed as comparative time studies with snap back timing (Bergstrand 1987). Time was recorded with Allegro hand-held computers equipped with Skogforsk SDI software. The work of the machines was usually split into 8-10 non-overlapping work elements, of which five (*Boom out*, *Grip*, *Boom in & feeding*, *Adjustment*, and *Chipping)* represent effective chipping work. All measured times for each load were totalled per work element and divided by the quantity of produced chips to obtain time (s) per unit of produce. In this analysis, the time for the elements *Boom out*, *Grip*, *Boom in & feeding*, *Adjustment*, and *Chipping*, were summarised into *Effective chipping time*. For each load, chipper productivity per effective hour was then calculated as the quantity of produced chips divided by the *Effective chipping time*. *Complementary times*, e.g. the elements *Move with load*, *Unloading*, *Move empty*, and *Landing work*, and delay times were not included in the current analyses. All productivity calculations were based on effective chipping time and not the gross time used by the machines, to enable a fair comparison of the chipping units regardless of the kind of carrier/trailer on which they were mounted or the type of operation they were used for.

Fuel consumption of the engine that powered the chipper and the engine powering the carrier, including the hydraulic loader, was measured by topping up the fuel tanks after each load using an accurate fuel gauge. Fuel consumption per produced quantity of chips (oven dry tonnes) was used in the analyses to compensate for differences between trailer loads. However, fuel consumption could not be measured independently of fuel consumed during complementary work times for all machines, so a variable *Parts driven* was introduced in the analyses.

In most cases, chip mass was measured using certified scales at wood terminals and heating plants; however, in one case, the loader scale of the timber truck delivering the wood was used, and in another, masses according to the machine scale on the chipper were used and corrected in relation to the total mass from the certified scale at the heating plant (Eliasson et al. 2018). Samples were taken from the chips produced in each replicate to determine moisture content and, in most cases, to determine chip size distribution. When many replicates were made using the same machine settings for the same material, the number of chip size distribution samples was reduced.

Calculations and statistical analysis

Energy efficiency was calculated as the ratio between the energy in the fuel consumed by the machine and the accessible energy in the produced chips or hog fuel. Diesel fuel volume was converted to input energy in J by its energy content, 9.8 MWh per m^3 = 35.68 GJ m^{-3} (Anon. 2020a). The accessible energy (h_{net}) per oven dry tonne (odt) in the produced wood fuel was calculated according to Anonymous (1999), using Eq.1:

$$h_{net} = (h\_eff \times (1 - A/100) \times (1 - M/100) - 0.678 \times M/100)/(1 - M/100) \quad (Eq. 1)$$

where h_eff= 5.33 MWh/odt, ash content A = 1% for logs, 2.5% for logging residues and 5% for stumps, and M = moisture content percentage.

Analyses involved descriptive analysis and general linear models (GLM) in SAS. In the GLMs, *Power* and *Moisture content* were treated as continuous variables (covariates) and all other parameters were treated as class variables (fixed factors). Care was taken to avoid using confounded or partially confounded variables in the same analysis. Most analyses were only performed for drum chippers, since a) they are the dominating machines for the material, and b) the grinders and disc chippers in the material are confounded by extraction method.

Results

All machine types

Observed productivity and fuel consumption of the machines varied according to material and machine type (Table 2). The crushers were all hammermills and the only machine type used for comminution of stumps, so stumps were excluded from all analyses except for the separate analyses for crushers. When used for chipping logging residues, and in two cases when chipping tree sections, disc chippers did not produce material of acceptable quality, which in this case means a high proportion of chips longer than 100 mm even when the machines were set to produce P45 chips.

Table 2. Average productivity and fuel consumption, minimum and maximum engine power for the machines, and the number of replicates (N) for each machine and material combination.

	Hammermill	Disc chipper	Closed drum chipper	Open drum chipper
Productivity (odt h^{-1})				
Residues	38.2	7.9	20.9	25.1
Logs	80.2	73.7	59.9	46.6
Stumps	23.8			
Tree sections		62.5	30.5	28.1
Fuel consumption (l odt^{-1})				
Residues	2.6	1.7	2.0	2.5
Logs	2.4	1.7	1.7	2.5
Stumps	3.7			
Tree sections		2.7	2.0	2.6
Engine power Min-Max (kW)				
Residues	456-783	130-130	265-426	246-450
Logs	783-783	130-932	397-787	571-571
Stumps	360-783			
Tree sections		932-932	157-787	246-450
N				
Residues	7	3	81	23
Logs	3	21	26	2
Stumps	10			
Tree sections		5	32	38

GLMs of productivity (Table 3) explain most of the variability in the data set, but interactions and imbalanced data make interpretation of the models difficult. The power used for chipping, the covariate *Power* and the factor *Parts driven*, are the primary variables explaining productivity. Factors different to those included in the model clearly influence productivity but cannot be added to the analysis due to the imbalances in the dataset.

The models for fuel consumption (FC) and energy efficiency (EE), on the other hand, are logical and easier to interpret, but only explains 36% and 44% of the variation (Table 4). They can be modelled as:

$$FC\ or\ EE = Intercept + Parts\ driven + Material + Machine\ type + C_M \times M - C_P \times Power \quad (Eq.2)$$

where the parameter estimates for Intercept, Parts driven, Material, Machine type C_M and C_P can be found in table 5. Fuel consumption increased with increasing *M* and decreasing *Power*, and is, on average, 0.56 l higher for machines where the engine powers the chipper, base machine and all other systems, compared to when it only powers the chipper and some other system (Table 5). As expected, disc chippers were the most fuel-efficient machine type, while crushers used most fuel per odt chips produced (Table 6). However, due to the imbalances in the dataset interactions between *Power* and *Machine type* or *Material* could not be included in the models.

Table 3. GLM model for productivity (R2 = 0.80) including all machine types.

Source	DF	Type III SS	F Value	Pr > F
Parts driven	1	1711.5	15.07	0.0001
Material	1	2174.0	19.14	<.0001
Machine type	3	656.2	1.93	0.1261
Machine type × Material	3	3469.9	10.18	<.0001
Power	1	51121.0	450.06	<.0001

Table 4. GLM model for fuel consumption per oven dry tonne (R2 = 0.364) and for energy efficiency (R2 = 0.440), all machine types.

		Fuel consumption			Energy efficiency		
Source	**DF**	**Type III SS**	**F Value**	**Pr > F**	**Type III SS**	**F Value**	**Pr > F**
Parts driven	1	11.15	32.92	<.0001	0.00004186	41.67	<.0001
Material	1	0.04	0.11	0.7405	0.00000118	1.18	0.2789
Machine type	3	6.10	6.00	0.0006	0.00002278	7.56	<.0001
M	1	3.35	9.89	0.0019	0.00002150	21.41	<.0001
Power	1	1.49	4.40	0.0374	0.00000441	4.39	0.0376

Table 5. Parameter estimates for the GLM model for fuel consumption presented in Table 4

	Fuel consumption		Energy efficiency	
Parameter	**Estimate**	**Pr > |t|**	**Estimate**	**Pr > |t|**
Intercept	1.369	<.0001	0.0021875010	0.0003
Parts driven All	0.563	<.0001	0.0010921494	<.0001
Parts driven Not all	0.000	.	0.0000000000	.
Material Logging residues	0.031	0.7405	0.0001727232	0.2789
Material Stemwood	0.000	.	0.0000000000	.
Machine type Crusher	0.364	0.0950	0.0008062661	0.0323
Machine type Disc	-0.481	0.0019	-0.0008807154	0.0010
Machine type Closed drum	-0.170	0.1832	-0.0002741470	0.2137
Machine type Open drum	0.000	.	0.0000000000	.
C_M	0.0224	0.0019	0.0000568187	<.0001
C_P	-0.0005	0.0374	-0.0000008857	0.0376

Table 6. Least square means for fuel consumption (l/odt) and for energy efficiency (J/J) based on the GLM in Table 4, for a machine where all parts of the chipper are driven by the same engine, an engine power of 400 kW, and material with an M of 40% wet basis. Means under the same heading followed by the same letter within columns are not significantly different.

Machine type	Fuel consumption	Energy efficiency
Hammermill	3.01c	0.0052
Disc chipper	2.16a	0.0035
Closed drum chipper	2.47ab	0.0041
Open drum chipper	2.64bc	0.0044

Three subsets were selected based on the machine type used for comminution to enable better analyses where more factors could be taken into account.

Drum chippers

As for all machines, *Power* explains most of the variability for drum chipper productivity, but *Parts driven*, *Material group* and the chip quality (*Min P-class*) produced also play a significant role (Table 7). Drum chipper productivity can be modelled as:

$$Productivity = Intercept + Parts\ driven + Material \times Min\ Pclass + C_P \times Power \times Material \quad (Eq.3)$$

where the parameter estimates for Intercept, *Parts driven*, *Material*, *Min Pclass* and C_P can be found in table 8. When the engine powers only the chipper, productivity is 3.5 odt per effective hour higher, although the difference is not significant, compared to chippers where all parts of the machine are driven by the engine (Table 8). Productivity for logging residues is significantly lower and increase less with increasing engine power than for stemwood as long as chips in the P45-class are produced (Table 9, Figure 1). For stemwood productivity is higher when P45 chips rather than P31 chips are produced (Table 9).

Fuel consumption and energy efficiency were significantly affected by the same variables as the productivity, with the addition of feedstock moisture content (Table 10) and can be modelled as:

$$FC\ or\ EE = Intercept + Parts\ driven + Material \times Min\ Pclass + C_M \times M + C_P \times Power \times Material \quad (Eq.4)$$

where the parameter estimates for Intercept, *Parts driven*, *Material*×*Min P-class,* C_M and C_P can be found in table 11. Moisture content was positively correlated to both fuel consumption and energy efficiency, while engine power was negatively correlated to both fuel consumption and energy efficiency (Table 11, Figure 2 & 3). Average fuel consumption varied between 1.94 and 2.95 l odt^{-1} depending on *Material group* and chip size produced (Table 12). This means that the energy used for chipping is 0.4 to 0.6% of the energy in the produced chips.

Table 7. GLM model for drum chipper productivity (R2 =86.1%).

Source	DF	Type III SS	F Value	Pr > F
Parts driven	1	250.7	3.81	0.0524
Material × Min P-class	4	2896.3	11.00	<.0001
Power l	1	10400.8	158.01	<.0001
Power × Material	1	2366.1	35.95	<.0001

Table 8. Parameter estimates for the GLM model for drum chipper productivity.

Parameter	Estimate	Pr > |t|
Intercept	-7.04	0.0243
Parts driven - All	-3.48	0.0524
Parts driven – Not all	0	.
Material × Min P-class Residues P31	9.15	0.1062
Material × Min P-class Residues P45	11.51	0.0210
Material × Min P-class Stemwood P16	-12.17	<.0001
Material × Min P-class Stemwood P31	-12.58	<.0001
Material × Min P-class Stemwood P45	0	.
C_P Material = Residues	0.0570	<.0001
C_P Material = Stem	0.1406	<.0001

Table 9. Least square means for the productivity (odt (effective hour)$^{-1}$) for a machine where all parts of the chipper are driven by the same engine, and with an engine power of 400 kW. Means under the same heading followed by the same letter within row or by the same Greek letter within columns are not significantly different.

	Productivity	
Min P-class	**Logging residues**	**Stemwood**
P16		35.3α
P31	23.2aα	34.9bα
P45	25.5aα	47.4bβ

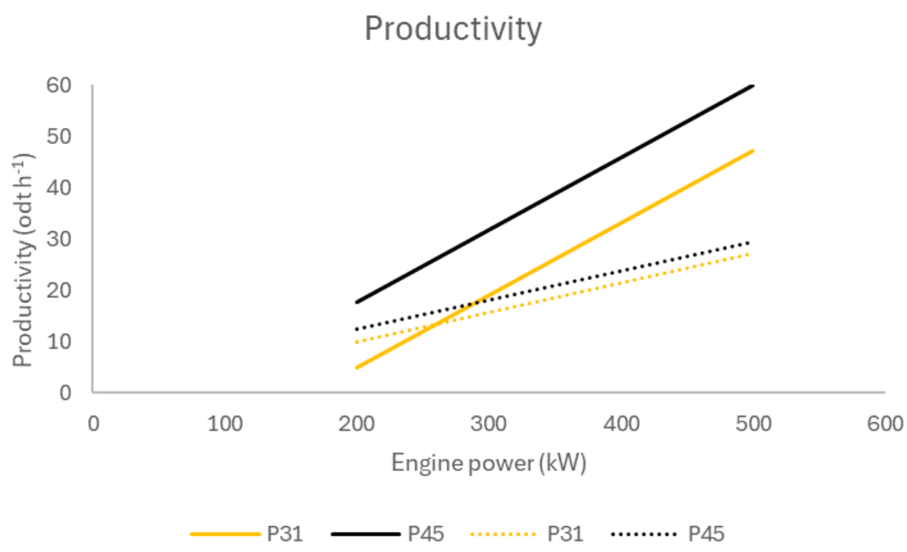


Figure 1. Productivity when chipping stemwood (solid lines) and logging residues (dashed line) into P31 or P45 size chips using a drum chipper where the engine powers the chipper, loader and base machine.

Table 10. GLM explaining Fuel consumption (R2=58.9%) and Energy efficiency (R2=60.9%).

Source	**DF**	**Type III SS**	**F Value**	**Pr > F**
Fuel Consumption				
Parts driven	1	4.22	23.68	<.0001
Material group × Min P-class	4	10.65	14.94	<.0001
M	1	2.27	12.73	0.0005
Power	1	5.97	33.51	<.0001
Power × Material	1	1.96	11.02	0.0011
Energy efficiency				
Parts driven	1	0.00001784	23.88	<.0001
Material group × Min P-class	4	0.00004375	14.64	<.0001
M	1	0.00001829	24.47	<.0001
Power	1	0.00002331	31.18	<.0001
Power × Material	1	0.00000734	9.82	0.0021

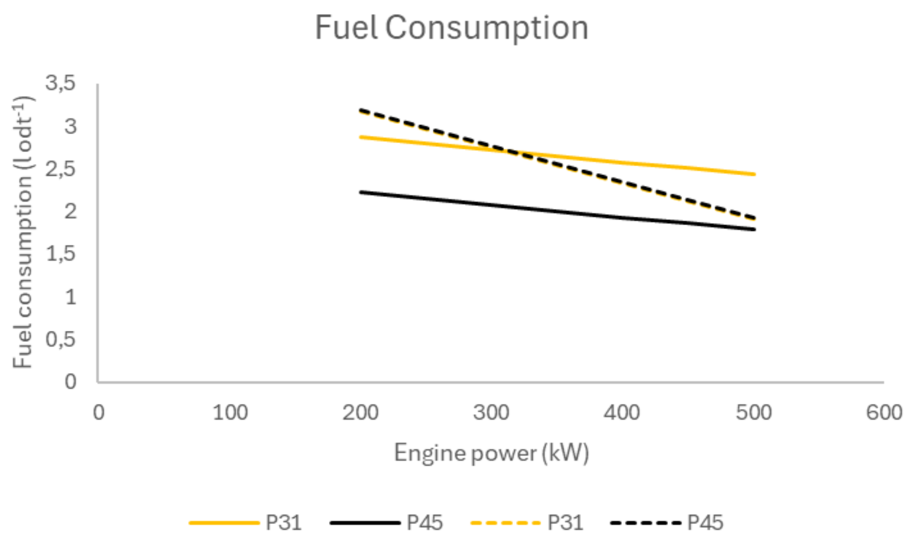


Figure 2. Fuel consumption when chipping stemwood (solid lines) and logging residues (dashed line) with a moisture content of 40% into P31 or P45 size chips using a drum chipper where the engine powers the chipper, loader and base machine.

Table 11. Parameter estimates for the GLM models for drum chipper fuel consumption (l odt^{-1}) and energy efficiency (J J^{-1}) presented in Table 10.

	Fuel consumption		Energy efficiency	
Parameter	**Estimate**	**Pr > |t|**	**Estimate**	**Pr > |t|**
Intercept	1.228	<.0001	0.0019	0.0004
Parts driven - All	0.519	<.0001	0.0011	<.0001
Parts driven – Not all	0	.	0	.
Material × Min P-class Residues P31	1.495	<.0001	0.0029	<.0001
Material × Min P-class Residues P45	1.514	<.0001	0.0030	<.0001
Material × Min P-class Stem P16	0.923	<.0001	0.0019	<.0001
Material × Min P-class Stem P31	0.647	<.0001	0.0013	<.0001
Material × Min P-class Stem P45	0	.	0	.
C_M	0.0194	0.0005	0.000055	<.0001
C_P Material = Residues	-0,00422	0.0011	-0.00000828	0.0021
C_P Material = Stem	-0.00147	0.0011	-0.00000297	0.0021

Table 12. Least square means for fuel consumption (l odt^{-1}) and for energy efficiency (J J^{-1}) for a machine where all parts of the chipper are driven by the same engine, an engine power of 400 kW, and material with an M of 40% wet basis. Means under the same heading followed by the same letter within row or by the same Greek letter within columns are not significantly different.

	Fuel consumption		Energy efficiency	
Min P-class	**Logging residues**	**Stemwood**	**Logging residues**	**Stemwood**
P16		2.86α		0.0059α
P31	2.33aα	2.58aα	0.0048aα	0.0053aα
P45	2.35aα	1.93bβ	0.0049aα	0.0040bβ

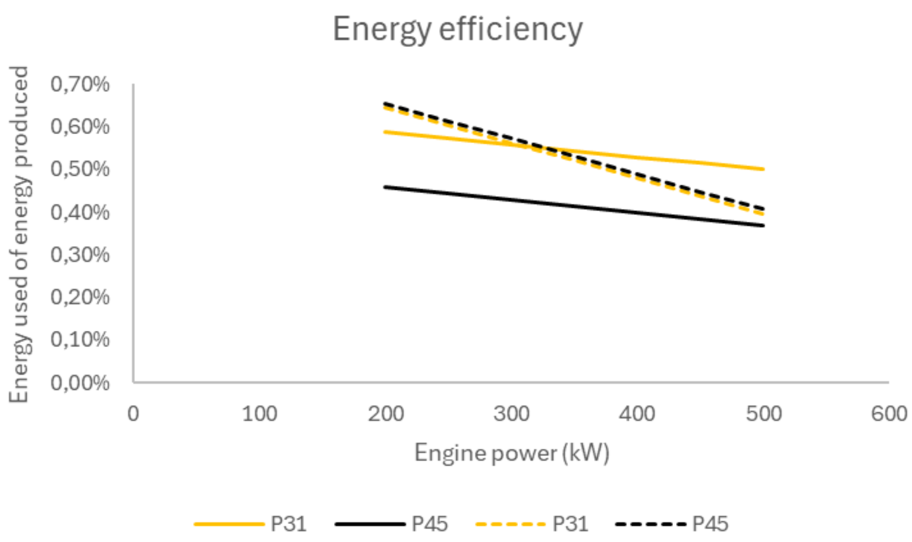


Figure 3. Energy efficiency (the energy used by the chipper in relation to the energy in the chips produced) when chipping stemwood (solid lines) and logging residues (dashed line) with a moisture content of 40% into P31 or P45 size chips using a drum chipper where the engine powers the chipper, loader and base machine.

Disc chippers

The data in Table 13 for disc chippers is limited, as only three different machine types were studied, so more parameters are confounded with each other and the models cannot be as elaborate. The engines of the large and very large disc chippers powered everything, while the loader feeding the small machine was powered by the forwarder engine and not the chipper engine. Both for logging residues and spruce tree sections from thinning, the disc chippers produced chips with an unacceptable proportion of particles longer than 100 mm, but for large-diameter hardwood tree sections chip quality was almost as high as for logs. The large disc chipper had higher productivity and lower fuel consumption than the very large machine, but this is partly an effect of the larger chip size produced.

Table 13. Productivity (odt h^{-1}) and fuel consumption (l odt^{-1}) for the three sizes of disc chipper studied. Means within a column followed by the same letter are not significantly different.

Material	Machine size	P class	Productivity	Fuel consumption
Logs	Small	P45	11.3a	1.66a
Logs	Large	P45	86.5d	1.55a
Logs	Very large	P31	72.0c	2.33b
Tree sections - Hardwood	Very large	P31	68.4bc	2.40b
Tree sections - Spruce	Very large	>P100	53.6b	3.06c
Logging residues	Small	>P100	7.9a	1.68a

Crushers

Crusher data is limited, and all the studied machines were hammermills. In all cases but one the loader feeding the hammermill is powered by an engine separate engine. A simple model with just *Material group* and *Power* as variables explains 96% of the variation in productivity and 92% of the variability in fuel consumption (Table 14).

$$Productivity, FC\ or\ EE = Intercept + Material + C_P \times Power \quad (Eq.5)$$

where the parameter estimates for Intercept, *Material* and C_P can be found in table 15. A comparison of the parameter estimates in Tables 15 and 8 shows that the necessary power increase to increase productivity by one odt of chips is 73% higher for hammermills than for drum chippers.

Average fuel consumption is higher for hammermills compared to drum chippers, and varies between 3.3 and 4.1 l odt-1 depending on *Material group* (Table 16) to which should be added the fuel used by the loader feeding the machine. This corresponds to a energy use by the hammermill of 0.66 to 0.83% of the energy in the produced hog fuel.

Table 14. GLMs explaining Productivity (R2= 96%), Fuel consumption (R2=92%) and Energy efficiency (R2=91%) for the studied hammermills.

Source	DF	Type III SS	F Value	Pr > F
Productivity				
Material group	2	2411.3	53.85	<.0001
Power	1	2722.9	121.62	<.0001
Fuel consumption				
Material group	2	2.427	20.12	<.0001
Power	1	6.101	101.13	<.0001
Energy efficiency				
Material group	2	0.00001119	23.33	<.0001
Power	1	0.00001560	65.03	<.0001

Table 15. Parameter estimates for the GLM models for hammermill productivity (odt h^{-1}), fuel consumption (l odt^{-1}) and energy efficiency (J J^{-1}) presented in Table 14.

	Productivity		Fuel consumption		Energy Efficiency	
Parameter	**Estimate**	**Pr > |t|**	**Estimate**	**Pr > |t**	**Estimate**	**Pr > |t**
Intercept	-15.6	0.0010	5.52	<.0001	0.0105425834	<.0001
Material - logging residues	9.1	0.0015	-0.78	<.0001	-0.0016502787	<.0001
Material - stemwood	37.1	<.0001	-0.35	0.0763	-0.0013637143	0.0020
Material - stumps	0.0	.	0.00	.	0.0000000000	.
C_P	0.075	<.0001	-0.0036	<.0001	-0.0000056785	<.0001

Table 12. Least square means for productivity (odt $^{h-}1$), fuel consumption (l odt^{-1}) and energy efficiency (J J^{-1}) for a hammermill with either an engine power of 400 kW or the average engine power in the material (589 kW). Note that the engine usually does not power the loader. Means under the same heading followed by the same letter within columns are not significantly different.

Material	Productivity	Fuel consumption	Energy efficiency
At 400 kW			
Logging residues	23.5b	3.32a	0.0066a
Stemwood	51.5c	3.75ab	0.0069a
Stumps	14.4a	4.10b	0.0083b
At average power			
Logging residues	37.7b	2.65a	0.0055a
Stemwood	65.7c	3.08ab	0.0058a
Stumps	28.6a	3.43b	0.0072b

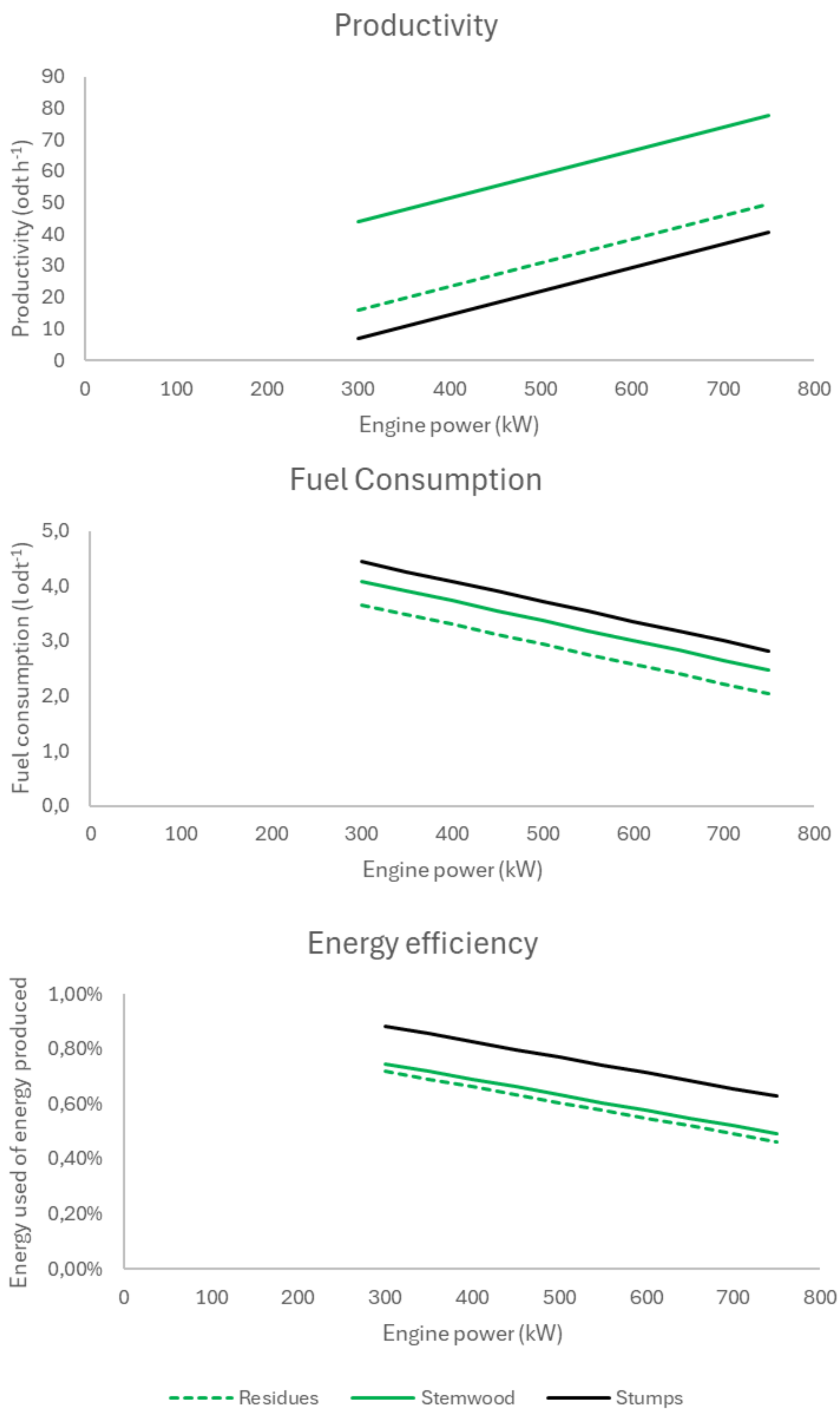


Figure 4. Productivity (odth^{-1}), fuel consumption (l odt^{-1}) and energy efficiency (J J^{-1}) for hammermills producing chips (hog fuel) from stemwood, logging residues, and stumps. Note that the engine usually is not powering the loader feeding the hammermill.

Discussion

Material

The analysed material derives from a set of studies carried out over a seven-year period, where the original intention was not to use the data for a meta-analysis, so the data is somewhat unbalanced. The data for drum chippers was based on many types of machines and feedstocks and can be considered the most reliable part of the material. For both disc chippers and hammermills, fewer machines were studied, and there are few replicates for some feedstocks. In the case of the disc chippers, there was a limited but acceptable amount of data for logs, while data for logging residues and tree sections was limited, as the machines did not produce an acceptable end product with these feedstocks. However, as the small disc chipper has a large influence on any linear models using *power* as a covariate, no such models were made. The situation is better for the crushers (Hammermills), but some caution is recommended when using the models in Table 15 due to the limited data.

The current study is based on the productive chipping/grinding work of the machines and no complementary work elements (e.g. transport times, relocation between sites), waiting times or delays were included. When using this data for predictions of gross productivity, consideration must be taken to expected complimentary work tasks and the normal delays in comminution work by applying delay factors representative for the work (Spinelli & Visser 2009; Belbo & Vivestad 2018).

All machines were well maintained and in good condition. Knife wear is known to have large effects on chipper performance (Nati et al. 2010; Facello et al. 2013b; Nati et al. 2014), so most of the chippers in the studies included in the database had sharp knives, to prevent knife condition impacting study results. The obvious exception is the observations from a study of the effects of knife wear (Nati et al. 2014), which are included in the database.

As all studies were carried out in commercial operations where large amounts of biomass are processed, the amount of material per individual loading cycle or the piece size of the material was not measured. Instead, we rely on the operator's experience of how much material to feed into the machine to utilise it at a high capacity without causing unnecessary delays. Experimental studies have shown that both piece size (Liss 1987; Spinelli et al. 2011; Assirelli et al. 2013; Di Fulvio et al. 2015) and the amount of material per loading cycle (Spinelli et al. 2011; Laitila & Routa 2015) affect productivity. This is partly the reason for the lower productivity for residues compared with stemwood, since the latter comprises larger pieces and, on average, gives a larger amount of material per loading cycle.

General results

The study shows general differences between the machine types. Given the same engine size, disc chippers are more productive and are more fuel and energy efficient compared to drum chippers and hammermills when chipping stemwood. However, due to their design, they lose efficiency and produce too low-quality chips when chipping logging residues or small trees from thinning. The increased productivity and efficiency is confirmed by experimental tests conducted under controlled conditions, and is attributed to the simpler design of disc chippers, in which the chipping and evacuation functions are combined into the same mechanism (i.e. the disc) (Spinelli et al. 2013).

Drum chippers are more versatile, producing acceptable chips from all uncontaminated feedstocks but with a slightly higher fuel consumption. In contrast, hammermills can handle all feedstocks, including those contaminated with mineral soil, but with a comparatively high fuel consumption. A comparison of the individual functions for drum chippers and hammermills indicates a difference in the effect of power on the two machine types, which is logical. This did not show up in the analyses leading to the ANCOVA in Tables 3 and 4, as the material is not balanced enough to allow the introduction of an interaction between *machine type* and *power*.

Influencing factors and variables

The most important variable influencing the performance of the comminution machines is, as expected from literature (Papworth & Erickson 1966; Liss 1987) and machine manufacturers, the engine power of the machine. Increased engine power has a large positive effect on productivity, a small reduction effect on the fuel consumption per produced odt of chips, and thereby a positive effect on fuel efficiency. These are largely effects of the increased engine power, but also partly an effect of machine size, as there is a positive correlation between machine size and engine effect among the machines. It is important to note that we used the nominal engine power in our analyses and not the actual utilised power, as the engine load was not measured in the studies. Selecting a suitable engine load for the applicable work at hand can improve machine performance for a given nominal power (Spinelli et al. 2018).

Of the other factors used in the analyses, *Parts driven* and *Min P-class* reflect the machine design and machine settings in some way, and it is important to understand that the basic cause for the effects found may be attributed to some feature that is confounded by the analysed factor. In this respect *parts driven* is the most straightforward of these factors, since it describes how much of the machine is powered by the main engine powering the comminution device (disc, drum or rotor). For small and medium-sized machines, the main engine commonly powers all parts of the machine. For large machines used on terminals, the most common option is that the main engine only powers the chipper and extraction system.

The effect of *parts driven* on both productivity and fuel consumption is logical. A machine where the engine powers all auxiliary equipment, i.e. loader and extraction systems, should have less power available to power the chipping unit than one where only the chipping unit is powered by an engine of the same size. Productivity will therefore be lower and, as the engine needs the same amount of fuel, fuel consumption per odt will increase (cf. Papworth & Erickson 1966). In the analyses of drum chippers, it was noted that the effects of *parts driven* might be affected by the type of drum (open or closed) used in the machine. Due to limitations in the material, this could not be tested in this study, and merits further studies.

The main feature controlling chip size for all chippers is the cut length. For disc chippers, this is a combination of the distance from the disc surface to the tip of the knife and the angle between the disc and the log (Hartler 1986; Hellström 2010). For drum chippers, this is a combination of the distance between the drum or and the tip of the knife and the geometry between the drum centre and counter blade (Gard Timmerfors et al. 2020). However, depending on feedstock and the angle of the material in relation to the knife, there is always a risk of oversized chips that must be limited either by a sieve or piece breakers. The machines that use piece breakers to limit the quantities of oversized chips are either disc chippers or closed drum chippers.

For chip extraction, disc chippers use fan blades on the back of the disc, while closed drum chippers use the inertia of the drum and an accelerator after the piece breaker. Bottom sieves may be used by all type of machines except disc chippers, and for extraction these machines use either conveyors or augers beneath the screen that feed a fan. The large number of combinations of cut lengths and piece breakers/sieves made it difficult to use these settings in the analyses, so the chip size distribution of the produced chips, expressed as *Min P-class,* was used as a proxy for these chipper settings. This is a parameter that is easy to measure in chipper studies (and was measured as a quality parameter in our studies) but is not an ideal solution, since the chip size distribution is also influenced by the feedstock (Spinelli & Magagnotti 2012; Assirelli et al. 2013).

An added complication in the analyses was variations in chip sampling intensity for determining chip size distribution within the analysed material. In future studies, at least one chip sample should be taken per replicate to reduce this potential problem. For machines where large replicates are needed to obtain measurements of productivity and fuel consumption that are representative for commercial operations, multiple samples for chip size distribution will also be necessary in future studies. A procedure will also be needed for managing the situation where these samples show different P-classes within a replicate. In the results of the current study, the *Min P-class* recorded was used, as this explained more of the variation than the *Max P-class*.

Although P-class was used as a proxy for cut length and sieve sizes, our findings are in line with the results of previous studies of the effect of cut length (Eliasson et al. 2012a; Spinelli & Magagnotti 2012; Facello et al. 2013a; Di Fulvio et al. 2015) and sieve sizes (Nati et al. 2010; Röser et al. 2012; Eliasson et al. 2015). Productivity and chip size are shown to increase with increases in cut length or sieve mesh size, while fuel consumption per produced quantity of chips decreases.

Moisture content in the chipped material did not affect machine productivity significantly, so were not included in the productivity models. Fuel consumption increased with increasing moisture content, and this, together with the fact that the accessible energy in the produced chips decreases with moisture content, has a negative effect on energy efficiency. The increased fuel consumption might be an effect of how the moisture affects the cutting forces when the chips are cut (cf. Uhmeier 1995; Hellström 2010), but also of the simple fact that wetter chips are heavier so require more energy to be extracted from the machine. It is also important to note that most feedstocks studied had been stored, and that wet material is not equivalent to newly harvested material.

Some factors that influence productivity and fuel consumption were left out of the models, since they were too correlated with factors used. As an example, previous studies show that the extraction device (Twaddle & Watson 1992; Spinelli & Magagnotti 2012) and its settings (Spinelli et al. 2016; Eliasson & von Hofsten 2017a) affect chipper performance. In the current dataset, it seems that *extraction type* may have an impact on drum chipper performance, but all machines that used a conveyor for extraction had powerful engines and were only studied when chipping stemwood. This makes it difficult to explain whether the effect is due to the extraction device or an interaction between machine power and feedstock based on the current amount of data in the database. This highlights a need for further studies of the effects of extraction devices and settings where identical machines, except for the extraction device, are studied under identical conditions.

The species composition in the feedstock did not significantly affect productivity or fuel consumption, which is in line with earlier results (Spinelli et al. 2011; Eliasson et al. 2018), although many studies have shown differences (Spinelli et al. 2013; Kuptz & Hartmann 2015). This is probably for two main reasons: 1) The quantity of chips/hog fuel was measured in oven dry tonnes, which partly eliminates the effect of different material densities in the output (cf. Spinelli et al. 2011; Eliasson et al. 2018), and 2) most of the feedstock was mixed, where pine (*Pinus sylvestris*) and spruce (*Picea abies*) material were dominant, while hardwoods other than aspen (*Populus tremula*) and birch (*Betula pendula* & *B. pubescens*) were scarce in the mix. There were replicates where pure hardwood feedstock was comminuted, but they behaved no differently to other materials.

Use of results

The presented results on comminution equipment can be used as base data for simulations, optimisations and LCA analyses of chip supply systems, but also for benchmarking between machines and for more applied business decisions on, e.g., the choice of technology.

All financial calculations must be complemented by data on operational and technical delays (e.g. Spinelli & Visser 2009; Belbo & Vivestad 2018) and by statistics of service life, annual use and expected repair and maintenance costs (e.g. Spinelli et al. 2017; Spinelli et al. 2019). When using fuel consumption data and energy efficiency data, it is important to note that only productive work was modelled. Fuel consumption and energy efficiency figures presented here do not include the fuel used to relocate machines between sites and, if the chipped material is not transferred directly to the chip trucks by the chipper, the fuel needed to transport the chips to a reloading point and load them onto trucks.

Acknowledgement

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