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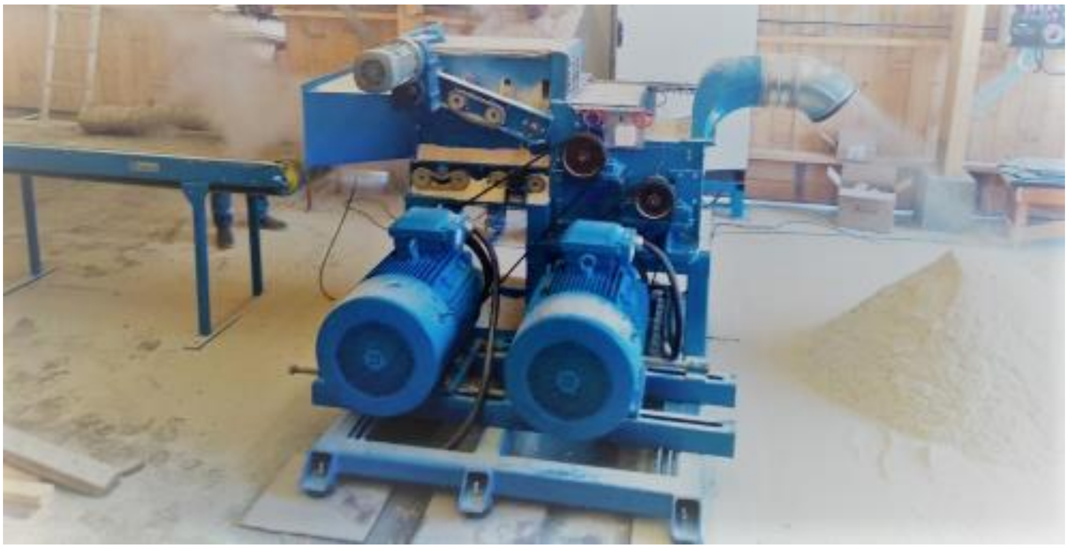
Department of Forest Biomaterials and Technology

Wood powder production with a novel milling technology

- Analysis of specific energy consumption and of the product's bulk properties

Tobias Holdo



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Wood powder production with a novel milling technology - Analysis of specific energy consumption and of the product's bulk properties

Produktion av träpulver med en ny malningsteknik

- Analys av specifik energiåtgång och produktens bulkegenskaper

Tobias Holdo

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Abstract

The interest for lignocellulose biomass has grown strongly in the last decades due to its potential to substitute fossil fuels. Pre-processing of biomass is often needed to enable utilization of its full potential. A common pre-processing step is milling where the biomass is fractionated into wood powder usable for e.g. wood powder combustion. There are a number of problematic factors affecting the utilization of wood powder, such as blockings and bridging, as a result of low density and elongated and irregular particle shapes.

The aim with this study was to, for a novel milling technology, determine and evaluate the specific energy consumption, wood powder bulk- and flow properties together with a comparison of the results from a hammer mill.

This study was carried out by milling of logs and collecting data from wood powder samples. Data from a log mill and a hammer mill's energy consumption, wood powder density and wood powder flowability was collected.

The results show that the log mill consumed least energy, when the blade rotation speed was low in combination with high moisture content and high feeding speed. The wood powder's tapped densities had an interval of 190-320 kg/m^3 respectively 150-260 kg/m^3 for the loose density. The Hausner ratio had an interval of 1.22-1.32, indicating a good to medium-good flowability.

The conclusions are that the log mill's specific energy consumption decreases with increasing moisture content, increasing moisture content decreases the tapped- and loose density and that the Hausner ratio is showing promising results.

Keywords: Log mill, hammer mill, tapped density, loose density, hausner ratio, biomass, flowability.

Sammanfattning

Intresset för lignocellulosarik biomassa har ökat de senaste åren på grund av dess potential att substituera fossila bränslen. Förbehandling av biomassa är ofta en nödvändig åtgärd för att möjliggöra dess fulla potential. Ett vanligt processteg är att mala biomassan till pulverform lämpad för exempelvis pulverförbränning. Det finns ett antal problematiska faktorer som påverkar användningen av träpulver var av blockeringar och överbyggnad, som ett resultat av låg densitet och heterogena partiklar, påverkar flödet vid utnyttjande av träpulver.

Syftet med studien var att, för en ny malningsteknik, bestämma och utreda den specifika energiåtgången och träpulvrets bulk- och flödesegenskaper samt att jämföra dessa med resultat från en hammarkvarn.

Studien utfördes genom att mala stockar och att samla in data från proverna av det producerade träpulvret. Datamaterial från stock- och hammarkvarnens energiåtgång, träpulvrets densitet samt träpulvrets flödesbarhet samlades in.

Resultaten visade att stockkvarnen förbrukade minst energi när klingornas rotationshastighet var låg i kombination med hög matningshastighet och hög fukthalt på råmaterialet. Träpulvrets kompakterade densitet hade intervallet 190-320 kg/m^3 respektive 150-260 kg/m^3 för den lösa densiteten. Hausner ratio hade ett intervall på 1.22–1.32, vilket indikerar en bra till måttligt bra flödesbarhet.

Slutsatserna är att stockkvarnens specifika energiåtgång minskar med ökad fukthalt, ökad fukthalt sänker den kompakterade- och lösa densiteten samt att Hausner ratio uppvisar lovande resultat.

Nyckelord: Stockkvarn, hammarkvarn, kompakterad densitet, lös densitet, hausner ratio, biomassa, flödesbarhet.

Preface

This master's thesis is a part of the PhD-project "Multi-blade size reduction of wood for industrial processes and its influence in the forest-to-industry supply chain".

I would like to express my gratitude to Sylvia Larsson, my supervisor at SLU, for extraordinary engagement and flexibility during the course which made this work possible.

Thank you Atano Kumar Das (PhD-student) for the good cooperation and your dedication to the project. I believe your structured way of working was one of the keys to success.

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Tobias Holdo

Umeå, 2020-01-20

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1 Introduction

The interest for lignocellulose biomass has grown strongly in the last decades due to its potential as a substitute for fossil fuels. Biomass was the fourth largest energy source on a global scale 2017 after coal, oil and natural gas, contributing with approximately 10 % of the global primary energy supply (IEA 2018).

The biomass resource in Sweden amounts to 23.5 million hectares of productive forest land of which 40 % is ready for thinning. Approximately 67 % of this thinning forests has not yet reached the final felling age (Nilsson & Cory 2018). In these early thinnings, biomass can be harvested and utilized as fuel for bioenergy production along with harvest residues from final fellings. Early thinning operations also provides necessary silviculture measures, generating better stand conditions for the remaining trees (Skogsstyrelsen 2017).

Lignocellulose biomass can be converted into two main types of energy products: electrical/heat energy and transport fuel (McKendry 2002a). To utilize biomass bulk solids in an efficient way, pre-processing to create a type of biomass such as powders or biomass with more suitable bulk characteristics is often needed (Barletta, Poletto 2013). A common pre-processing step is milling, which thereby create wood powders usable for e.g. powder combustion or gasification (Falk 2013; Gil & Arauzo 2014).

There are a number of problematic factors affecting the utilization and use of wood powder and other biomass products. Feeding and flowability issues, such as blockings and bridging, as a result of low density and elongated and irregular particle shapes cause variation in feeding. These issues reduces throughput and causes downtime which in the end affects the profitability (Falk et al. 2015; Salehi et al. 2019).

In this study, a novel milling technology was utilized for production of wood powder directly from logs. The largest difference between the log mill and conventional mills is the possibility to, in one step, produce fine powder from logs. The conventional methods require several treatment steps before pulverization: chipping, drying, (pelleting) and/or milling (Obernberger & Thek 2010). Pre-studies from the PhD-project “Multi-blade size reduction of wood for industrial processes and its influence in the forest-to-industry supply chain” have shown that the novel mill technology is promising for tailoring of particle size and shape for obtaining narrow particle size distribution.

1.1 Wood Powder – current and future use

The applications for wood powder biomass is wide and the potential for industrial use is increasing. One of the advantages regarding wood powder is the possibility for retrofitting of coal- and oil boilers, requiring few modifications of the fossil boiler to work as a powder boiler (Marks, Mattsson & Wallin 2005). Combustion of wood powder is usually not associated with problems if the powder is homogeneous, containing a lot of fine particles (particle size<1 mm) and has a suitable moisture content. The density of wood powder is approximately 200 kg/m3 leading to relatively low transport capacity compared to other lignocellulose biomass products. Wood powder it therefore, as a final product, often transported to the industries in the shape of pellets that have a bulk density of 550-700 kg/m3 (Lehtikangas 1999).

In the future, biomass and wood powder may, to a great extent, be used in existing and new applications to substitute fossils and thereby reduce climate impact. To substitute fossils, smart and profitable biomass systems and feedstock are required not competing with e.g. production of food crops (Yuan et al. 2008). One company that has started to substitute fossils in a creative way is Skanska AB, heating material for asphalt production with wood powder as a fuel instead of oil. Skanska has concluded that conversion from oil to wood powder is profitable and their goal is to change the heating technology and feedstock for all their asphalt industries (Bioenergi 2018).

1.2 System description

In this study, two systems for wood powder production are compared: the new log mill system and a traditional hammer mill system, as a part of the wood pellet production chain. The number of process steps differs between the systems but the final product is wood powder for both of them (Figure 1).

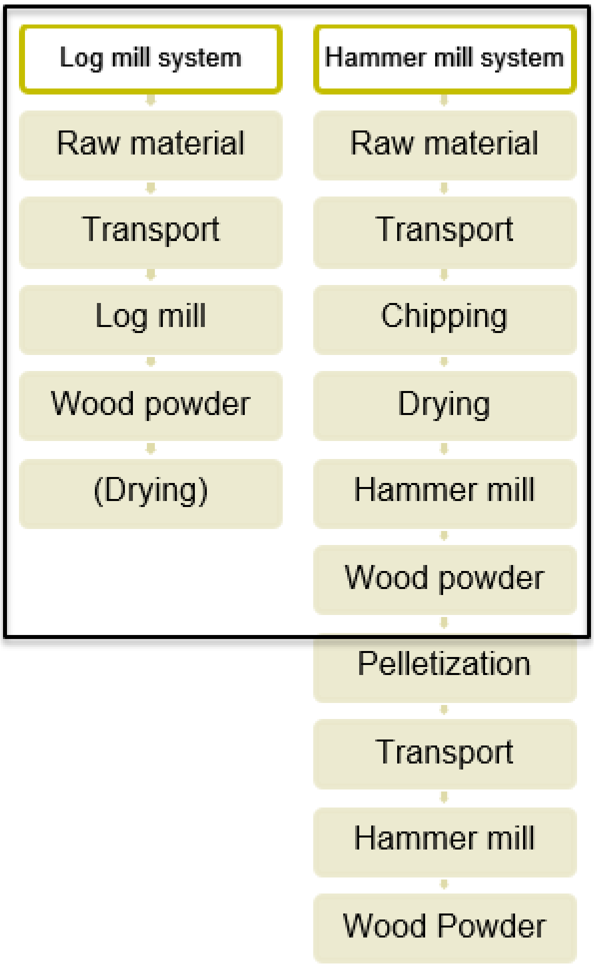

Figure 1. The two milling processes on a general industrial scale. The black colored frame delimited the compared systems in this study.

1.3 Log mill system

1.3.1 Raw material

The log mill was developed for milling of logs but the Kling Mill Company (2019) concludes that a wider array of material can be processed, including materials with large particle size as well as with relatively high moisture content. Fresh logs have an initial moisture content of approximately 50 % (Lehtikangas 1999), which causes problems such as bridging and clogging/blockings if a conventional mill is used (Obernberger & Thek 2010).

1.3.2 Transport and storage

The most common way to transport logs and biomass in Sweden is with truck and if the transport distance is large, a terminal is often used for inter mediate storage of the biomass (logs and chips) before further transport to downstream customers (Trafikanalys 2015). There exists a couple of different types of trucks though the most common type today is the 64-ton truck (von Hofsen 2019). Bulk density during transporting and storage have a large effect on the transport- and storage costs (McKendry 2002b). The raw bulk density for logs of Scots pine are approximately 800 kg/m³ (Hájek 2003).

Storage of feedstock close to the industry generates a higher delivery precision and access to feedstock. In storage, microbial degradation is much slower for non-processed biomaterial, such as logs, compared to particulate biomaterials, such as wood chips. Consequently, log handling is a much less “a hot system”, than handling and storage of particulate biomass (Lehtikangas 1999).

1.3.3 Milling and drying

The location of the log mill can be in connection to the industry, reducing steps in the wood powder production chain due to the lack of need for pre-processes such as chipping, pelletizing and/or drying. During the milling step, feedstock is processed into wood powder by two multi-blade rollers. If fresh logs are set to be used as feedstock, a drying process is necessary afterwards to obtain a proper moisture content e.g. for powder combustion or pellet production (Lehtikangas 1999). The industrial log mill system includes a drying process and a cyclone attachment which fractionates the powder, recycling larger particles through the mill, to obtaining as much of the biomass as possible and to insure homogeneity (Klingmill 2019).

1.4 Hammer mill system

1.4.1 Raw material

The hammer mill system, including the chipping process, is commonly the first steps in the pellet production chain if feedstock with large particle size distribution is utilized. The most frequent feedstock for production of biomass pellet is sawmill residues, such as wood shavings, sawdust and wood dust, though feedstock such as log-wood and wood chips are also utilized (Lehtikangas 1999; Obernberger & Thek 2010). Pellet production requires a feedstock with suitable characteristics, which generates restrictions on the raw material such as initial particle size and moisture content. The particle size is a vital factor when producing ∅ 6 mm pellet, the target particle size for the feedstock is 4 mm. The particle size is important, not only for the milling process, but also for the user requirements. Moisture content is affecting the process behavior and energy consumption which leads to a need of drying. Raw material with a moisture content above 15 % requires drying before milling and pelletizing (Obernberger & Thek 2010). Bulk density is an important factor, both for storage and transport, and it varies between 200-350 kg/m^3 for both sawdust and wood chips (Strömberg & Herstad-Svärd 2012).

1.4.2 Drying and milling

The most common industrial biomass drying technologies are tube or drum dryers where the material is dried at a temperature of 60-90 Celsius (Obernberger & Thek 2010).

The most frequently used mill types are hammer- and cutting mills. Previous studies have shown that hammer mills generate a more homogenous wood powder with smaller particles than cutting mills. Feedstock with smaller particle size leads to a higher conversion efficiency when used as fuel (Obernberger & Thek 2010).

1.5 Energy consumption and flow properties

1.5.1 Energy consumption

Log mill system

There is a lack of studies investigating energy consumption for multi-blade mills, such as the log mill, utilizing logs to produce wood powder. The log mill's construction is somewhere more similar to the construction of a roller mill, if compared to a hammer mill. A roller mill uses cylindrical rollers to mill/crush the feedstock into fractionated particles and the mill is more energyeffective when pulverizing wet feedstock compared to dry (Karinkanta et al. 2018). Besides moisture content, particle size is another important factor when milling. Godin et al. (2016) concludes that milling of feedstock with large particle size consumes more energy compared with feedstock containing small particle size.

Milling of feedstock to a fine fractionated wood powder generates an advantage of lower energy consumption during the drying stage. Drying of large particles, such as wood chips, are slower compared with small particles generating a higher moisture content in the particle-center requiring more energy during drying. In such cases, storage to balance the moisture content might be required. This problematic effect is less of a concern for e.g. saw dust resulting in reduction of energy and time needed for a dry feedstock (Obernberger & Thek 2010).

Hammer mill system

The two major energy consuming processes in the hammer mill system, as a part of the pellet production chain, are the drying- and milling processes. Drying is the largest energy consumer, requiring roughly 1,200 kilowatt hours per ton of evaporated water. The drying step corresponds to approximately 93 % of the total energy consumption when sawdust is used as feedstock and the milling process, using a hammer mill, correspond to 1.4 % (Obernberger & Thek 2010).

When a hammer mill is used, the energy consumption depends on three main factors: moisture content, particle size difference between the ingoing feedstock and the milled product and the material itself (Temmerman, Jensen & Hébert 2013). To minimize energy consumption, feedstock moisture content should not exceed 25 % (Oyedeji et al. 2016). The screen size has a large effect on the energy consumption, consuming more energy if the screen size is small (Rezaei et al. 2016).

The energy consumption increases with moisture content when a hammer mill is used for both wood chips and wood pellets. The energy consumption also increases with different particle size distribution between ingoing feedstock and final product, consuming more energy if the difference is large. Milling of wood chips consumes 5-200 watt-hour per kilo when the feedstock has a moisture content of 0-25 %. Increment of moisture content from <10% to around 20-25 % increases the energy consumption four-fold when using pine as feedstock (Temmerman, Jensen & Hébert 2013.

The energy consumption for milling of pellets, with a moisture content of 0-15 %, varies between 1.4-18 Wh/kg. Pellets is by its nature dryer, compared to wood chips as a result of the pre-treatment steps, which decreases the energy consumption during the final milling stage (Temmerman, Jensen & Hébert 2013).

1.5.2 Biomass bulk flow properties

One of the largest problems due to wood powder bulk properties is poor flowability as a result of low density. The Hausner ratio, the relation between tapped- and loose density, is a measurement indicating the flowability of a powder (Geldart, Harnby & Wong 1984). Previous studies have been carried out to examine the Hausner ratio of wood powder and Falk at al. (2015) concludes that the Hausner ratio for wood powder of Norway spruce, milled by a hammer mill, is 1.56. Furthermore, Falk (2013) found that a wood powder with a greater number of small particles decreases the bulk density for both tapped- and loose density, generating a higher Hausner ratio, which is in line with what Rezaei et al. (2016) found in their study.

The log mill's possible advantage compared with conventional mill types is its possibility to mill a log, independent of moisture content, to a homogeneous small-sized powder (Klingmill 2019). Wood powder flow characteristic complications such as blockings, bridging and downtime are less of a problem for a homogeneous wood powder containing high amount of fine particles (Paulrud, Mattsson, & Nilsson 2002).

1.6 Aim

The aim for this study is to, for a novel log milling technology:

i. Determine the effects of moisture content, feeding speed and blade rotation speed on the specific mill energy consumption.

ii. Analyze resulting wood powder bulk properties, assessed by the Hausner ratio.

iii. A comparison of the specific energy consumption and the bulk properties for the milling process of the log mill system and the chipping- and milling processes of the hammer mill system, from feedstock to dry wood powder.

Framing of a questions for the log mill system:

-What are the effects of:

i. Log moisture content, log feeding speed and blade rotation speed,

on

ii. Specific milling energy consumption,

iii. Wood powder bulk density,

iv. Hausner ratio?

2 Material and Method

This study was a part of the PhD-project “Multi-blade size reduction of wood for industrial processes and its influence in the forest-to-industry supply chain”. The experimental work was performed at Biomass Technology Center (BTC), Swedish University of Agricultural Sciences, Umeå, Sweden.

2.1 Materials

2.1.1 Log mill system

The log mill was delivered by the company Klingmill AB, Torshälla, Sweden. Stems of Scots pine (Pinus sylvestris L.) was gathered from an early thinning site in Vindeln, North-East Sweden. The logs were stored at BTC approximately 1 ½ month before experimental start. To gain a homogenous feedstock, 27 logs were subjectively selected with restrictions of diameter interval 10-14 cm (top to but-end) and stem-form. Logs with as little defects (branches, knots and lop-sided) as possible were selected, sorted by their form, from no visual defects. All experimental logs were taken from the same part of the log (but-end), barked manually with a barking knife, and cut to approximately 1.7 meters in length (Figure 2).

Figure 2. Left: Experimental logs during storage. Right: Manual debarking of logs. (Photo: Atanu kumar das)

Log length and diameter was measured both with and without bark to gain full control over the log size. The diameter was measured at the but-end, in the middle and at the top with a cross-caliper, generating a mean diameter for every point of measurement. Wood disks with a thickness of two centimeters were cut off from the log to measure basic density and initial moisture content, calculated as wet basis (w.b). The wood disk for moisture content was cut off from the top and dried in a drying cabinet at 105° C until the moisture content was constant. The wood disks was used to determine the initial moisture content of the logs.

The logs that required pre-drying were dried in a drying cabinet at 30° C and weighed in time intervals until the desired moisture content was obtained. Before milling, disks with a two centimeter thickness were cut off to obtain material for microstructural analysis (which was a part of the PhD-project). Logs with a final length of 151-161 cm were used as feedstock when milling.

2.1.2 Hammer mill system

The feedstock for the hammer mill system amounted to 20 stems of Scots pine with a diameter interval of approximately 14-17 cm (top to but-end). The logs were debarked manually and had the same origin and length, as for the log mill system. The logs were chipped to a chip size of 1.9-16 mm and dried at 105 °C over night generating a moisture content of 7 % (w.b). For practicality, three of the logs were chosen to work as representative logs for measuring energy consumption during the chipping process. A hammer mill (Vertica Hammer Mill DFZK-1, Bühler AG, Uzwil, Switzerland) with the screen size of 2 mm and engine effect of 55 kilowatt was used for milling the wood chips into wood powder.

2.2 Methods

2.2.1 Log mill system

The log mill is a pilot prototype containing feeding conveyors and rotating multi-blades (Figure 3). The conveyor system feeds the mill with logs and the rotating blades mill them into wood powder (Klingmill 2019). There are two engines powering the rotating blades with an effect of 55 kW each.

Figure 3. Left: Feeding conveyors. Centre: Multi-blade roller. Right: Profile view of the mill and its two multi-blade rollers. (Photo: Tobias Holdo)

Pre-trials were performed to examine how the mill worked and to find its limitations such as speed capacity related to moisture content. These limitations worked as the extremes in the model design. Resulting wood powder from the pre-trials was used to practice the sampling procedure. The bulk density tests and the Hausner ratio measurement were also practiced to examine if the amount of powder was enough and to make sure that the tests were possible to perform.

The 27 chosen experimental logs were milled as soon as possible after the drying process and the power required was logged with the computer program Easyview. The wood powder was collected in plastic bags by a sawdust extractor connected to the mill. The plastic bag was drained of powder on a plastic sheet straight from above into a cone-shaped pile. The sampling method was the coning and quartering method where the cone of powder was divided into four segments (Figure 4). It is a suitable sampling technique when the sample size is large and no sample divider is available (Alakangas 2014). Two of them were used for the bulk density tests and the other two were used in the PhD-project.

Figure 4. The wood powder sampling process, "The coning and quartering method". (Photo: Tobias Holdo)

The wood powder was poured into trays and placed in the drying cabinet at 105 °C over night to generate a constant moisture content. The weight of the powder was taken before and after drying, to obtain the ingoing moisture content. The quarter for moisture content was merged with the quarter for bulk density after weighing to gather the amount of powder needed to perform each of the bulk density analysis.

To simulate the log mill system for industrial use, including a cyclone attached to the mill, the wood powder was sieved in a two-step process with the sieve size of 8.00 mm and 3.15 mm to remove oversized particles (Figure 5). The weight of the removed particles was taken and bulk density tests and Hausner ratio calculations were performed again on the screened wood powder.

Figure 5. Left: Sieve size 8.00 mm. Centre: Sieve size 3.15 mm. Right: Sieve table (Photo: Tobias Holdo)

2.2.2 Hammer mill system

The electric power required for the chipping process was logged with Easyview in the same way as the experimental logs for the log mill system. The amount of wood chips generated from the three logs were used to calculate the specific energy consumption (kWh/ton). The wood chips from the three representative logs were merged with the rest of the wood chips generated from the remaining 17 logs, before hammer milling. The electric power required for the hammer milling process was also logged with Easyview and the produced wood powder was collected with plastic bags. The electric power required for the chipping and milling processes were merged together as one, seen as the electric power required for the hammer mill system.

The sampling method of the wood powder was the same as for the log mill system (Figure 4). The samples were poured into trays and placed in the dry cabinet at 105 °C over night to gain, an overall, similar moisture content. The dry wood powder was handled the same way as for the log mill system. The powder was screened with the same sieve size (8.00 & 3.15 mm) and the bulk density tests and the Hausner ratio analysis were carried out the same way.

2.2.3 Factors and responses

Factors

The model factors were moisture content, feeding speed and blade rotation speed. Moisture content was decided with the restriction of a clear difference between the different settings. Hence, the decided moisture content of the feedstock was thought to represent a feedstock of a realistic industrial use. The moisture content was calculated as the wet basis (w.b) moisture content (Eq.1).

$$MC_w = \frac{W_W}{W_t} * 100 \tag{1.}$$

MC_w was the moisture content (w.b), W_w was the weight (g) of water and W_t was the total weight (g) of the material.

Responses

Response variables were specific energy consumption (kWh/ton), tapped- and loose bulk density (kg/m^3) and the Hausner ratio (-). The effect (Ws and kWs) for the log mill, the hammer mill and the chipping process was logged with the program Easyview, converted into Excel, and calculated as the specific energy consumption, idle power excluded. The idle power was calculated as a mean value from the 10 seconds before the milling and chipping processes started. Then energy consumption from the hammer mill and the chipping process were merged together, considered as one system and calculated as the specific energy consumption (Eq.2).

$$\mathrm{E} = \frac{E_t - E_i}{M_{dry}} \tag{2.}$$

E was the specific energy consumption (kWh/ton), E_t was the total energy consumption (kWh), E_i was the idle power (kWh), and M_{dry} was the dry mass of wood powder (ton).

Bulk density was measured using a cylindrical vessel of 5.4 liters. When measuring loose bulk density, the vessel was filled to its width until overfilling and then dropped from the height of 15 cm. The vessel was refilled and the process was repeated three times and then the leftover powder was leveled off. The weight of the wood powder was taken and the process was repeated for every sample.

Tapped bulk density was measured using a frame mounted on the cylindrical vessel increasing the total volume with 1.4 liters. The vessel was overfilled and shaken with a sieve shaker for 10 minutes with the amplitude of

1.5 mm (Figure 5). Later, the frame was removed and the weight was taken after the leftover powder had been leveled off.

This type of bulk density measurements have been used earlier in previous studies. Salehi et al. (2019) examine the bulk density of wood chips and used the same method, with some modifications, fitting their needs. The bulk density (BD) was calculated by the mass (m) of the wood powder divided by the volume (V) of the vessel Eq.3.

$$BD = \frac{m}{V} \tag{3.}$$

Furthermore, the bulk density was used to calculate the flowability by the Hausner ration (HR) which is the relationship between final tapped density (D_T) and loose bulk density (D_L) Eq.4.

$$HR = \frac{D_T}{D_L} \tag{4.}$$

The ratio between tapped- and loose density was calculated for screened wood powder and compared to the values Geldart, Harnby & Wong (1984) concludes as “good or bad” values for powders when analyzing the flowability. A Hausner ratio below 1.25 indicates a good flowability and a value above 1.4 indicates a bad flowability. Values between 1.25 and 1.4 can have characteristics from both groups.

2.2.4 Experimental design

For evaluation of the responses: specific energy consumption, tapped- and loose bulk density and the Hausner ratio, a three factor two-level full factorial design with one mid-point was performed in full triplicates as a screening design - rendering 9 different settings and 27 experiments in total (Appendix 1).

The statistical program used to analyze the data was MODDE (version 11.0.1). This program provides software for setting up and evaluating experimental designs, and thereby characterize the behavior of a system (Mäkelä 2017). The statistical method for modelling was Multiple Linear Regression (MLR), which is suitable when there is one response variable and two or more explaining variables (Tai & Machin 2014). MLR is helpful when investigating a correlation between independent and dependent variables (Peter et al. 2017). In this study, the response variables were dependent and the factors independent (Table 1). The model design was:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon \qquad (5.)$$

Table 1. *Explanation of the model*

Variables	**Explanation**
y	**Response variable**
β_0	**Overall mean**
$\beta_1 x_1$	**Main effect of moisture content (%)**
$\beta_2 x_2$	**Main effect of feeding speed (m/s)**
$\beta_3 x_3$	**Main effect of blade rotation speed (m/s)**
$\beta_{12} x_1 x_2$	**Interaction effect of moisture content (%)**
$\beta_{13} x_1 x_3$	**Interaction effect of feeding speed (m/s)**
$\beta_{23} x_2 x_3$	**Interaction effect of blade rotation speed (m/s)**
ε	**Residual**

A MLR-model with the factors and their interactions was created for each response variable and if there were significant interactions, the effect of the factors depends on the level of the other factors (Eriksson et al. 2008). The residuals for using MLR was evaluated and the analysis was considered to be suitable. The MLR-models were evaluated by using the coefficient of multiple determination (Q^2) according to Segerström & Larsson (2014). The Q^2-value expresses how much of the variance in the response variable that can be predicted. The interval of Q^2 is 0-1 and if the coefficient is 1 or close to, the predictive power of the model is high. The Q^2-value is fairly similar to the coefficient of determination (R^2) but the difference is that R^2 continues to increase with number of factors included in the model, which Q^2 does not (Eriksson et al. 2008). To create the best (highest Q^2) and simplest (lowest number of factors) model, non-significant factor and interactions were excluded as well as experiments considered as outliers when examine the residuals in MODDE.

The statistical significance of the models were tested through the analysis of variance (ANOVA). ANOVA in experimental design is especially suited for analyzing interactions between factors in an experiment (Smalheiser 2017). The statistical significant tests were carried out at a confidence interval of 95 %.

3 Results

Results and analysis models for the three measured responses: Energy consumption (kWh/ton), bulk densities, tapped and loose (kg/m^3) and Hausner ratio of resulting wood powder are presented below.

3.1 Energy consumption

3.1.1 Log mill system

The energy consumption of the log mill system varied between different production settings according to the following (see also Appendix 1):

- 74-270 kWh/ton – idle power included
- 62-220 kWh/ton – idle power excluded

The contour surface plots show the impact of different factors on the specific energy consumption (kWh/ton) of the log mill system. The specific energy consumption decreased with increasing moisture content for all blade rotation speed combinations. The blue-colored areas in the contour plots show the most energy-effective factor settings, i.e. at the lowest blade rotation speed, highest feeding speed, and the highest log moisture content within the range of the design (Figure 6).

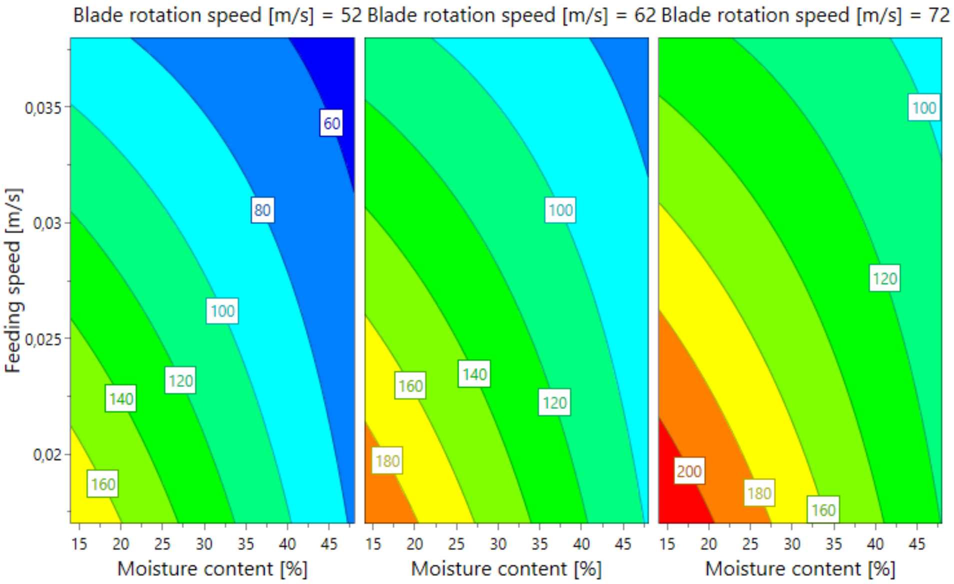

Figure 6. Modelled specific energy consumption (kWh/ton) of the log mill system. Contour surface plots of energy consumption vs. blade rotation speed (m/s), feeding speed (m/s) and moisture content (%). The values in the contour surface plots presents the energy consumption (kWh/ton).

A significant (p=0.000) MLR-model for specific energy consumption was built from the following factors: moisture content, feeding speed, blade rotation speed and the interaction of moisture content and feeding speed, that all had a significant impact. The coefficient plot expresses the regression coefficients and a coefficient was significant if the interval did not include zero (Figure 7). The model explained 87 % (R^2=0.87) of the variation with a model predictability of 81 % (Q^2=0.81).

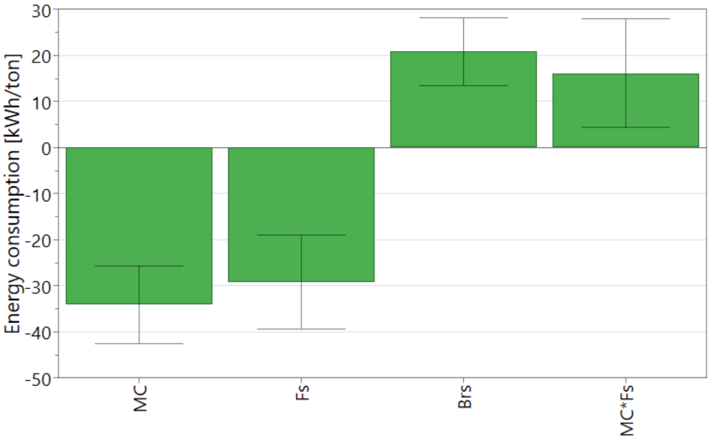

Figure 7. Effects for the scaled factors in the model for specific energy consumption. The y-axis displays the impact on specific energy consumption from each factor when varied from its lowest to its highest value when other factors are kept constant at their average value. MC=Moisture content, FS=Feeding speed, BRS=Blade rotation speed.

3.1.2 Hammer mill system

The energy consumption for the hammer mill system was (see also Appendix 2):

- 86 kWh/ton – idle power included
- 53 kWh/ton – idle power excluded

3.2 Wood powder bulk properties

3.2.1 Log mill system

The wood powder density intervals of the log mill system varied between different production settings according to the following (see also Appendix 1):

- 190-320 (kg/m^3) – tapped density
- 150-260 (kg/m^3) – loose density

The linear regression plots show the impact of moisture content on the wood powder densities of the wood powder from the log mill system. The tapped- and loose density increased with decreasing moisture content (Figure 8).

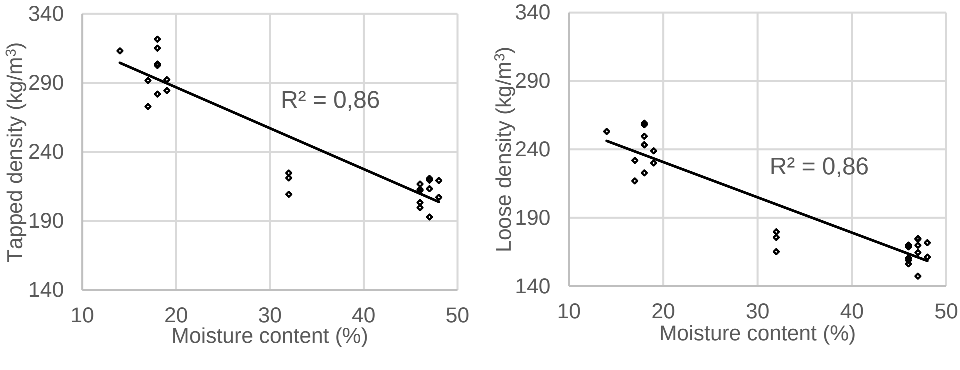

Figure 8. Modelled tapped- and loose density (kg/m^3) of the log mill system. LR-plots of tapped- and loose density vs. moisture content (%).

A significant (p=0.000) LR-model was built for tapped- and loose density respectively from the factor: moisture content, which had a significant impact. The model for tapped density explained 86% (R^2=0.86) of the variation in the data with a model predictability of 84 % (Q^2=0.84). The model for loose density explained 86 % (R^2=0.86) of the variation in the data with a model predictability of 84 % (Q^2=0.84). The density models had a lack of fit (tapped density (p=0.002) and loose density (p=0.007)) meaning that there was an error in the models.

3.2.2 Hammer mill system

The tapped- and loose density for the wood powder created by the hammer mill was (see also Appendix 2):

- 270 (kg/m^3) – tapped density
- 220 (kg/m^3) – loose density

The tapped- and loose densities were located in the higher part of the density interval for the log mill system.

3.3 Hausner ratio

3.3.1 Log mill system

The Hausner ratio of the wood powder, generated from the log mill system, varied between different production settings according to the following (see also Appendix 1):

- 1.22-1.32

The linear regression plot show the impact of the factor: moisture content of the log mill system. The Hausner ratio decreased with decreasing moisture content (Figure 9).

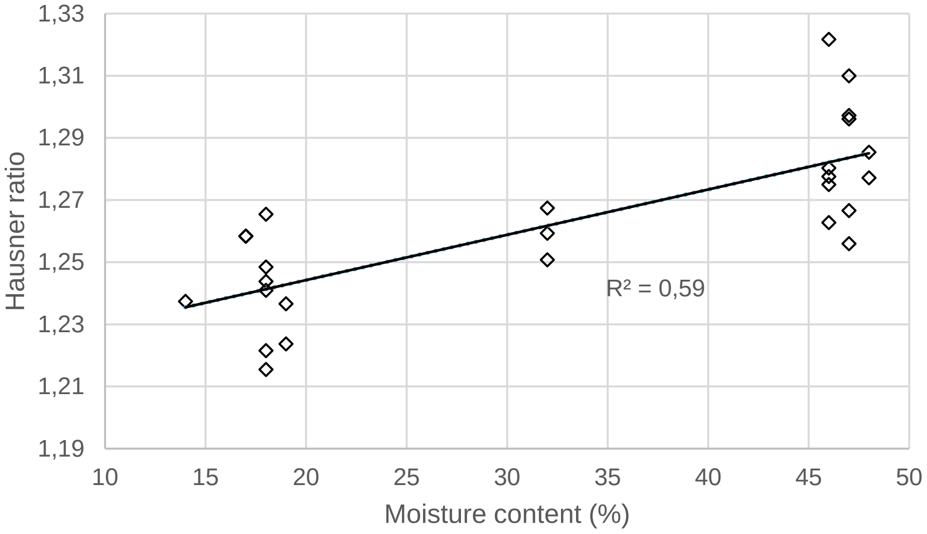

Figure 9. Modelled Hausner ratio of the log mill system. LR-plot of Hausner ratio vs. moisture content (%).

A significant (p=0.000) LR-model for the Hausner ratio was built from the factor: moisture content, that had a significant impact. The model explained 59 % (R^2=0.59) of the variation in the data with a model predictability of 52 % (Q^2=0.52).

3.3.2 Hammer mill system

The Hausner ratio for the wood powder created by the hammer mill was calculated to 1.23 which is in the lower section of the Hausner ration interval for the log mill system (see also Appendix 2).

4 Discussion

Discussion and comparison for the three measured responses: Energy consumption (kWh/ton), bulk densities, tapped and loose (kg/m^3) and Hausner ratio of resulting wood powder are presented below.

Results and comparison

4.1.1 Energy consumption

Log mill system

The specific energy consumption of the log mill system varied between 62-220 kWh/ton. The lowest energy consumption was generated at the, within the range of the design, lowest blade rotation speed, highest feeding speed, and the highest log moisture content. The MLR-model was significant for the specific energy consumption built on the factors: moisture content, feeding speed, blade rotation speed and the interaction of moisture content and feeding speed had a significant impact. The interaction effect showed that a low feeding speed in combination with low moisture content affect the energy consumption more compared to low feeding speed and high moisture content.

In previous studies on hammer milling of wood chips, energy consumption increases with moisture content (Temmerman, Jensen & Hébert 2013; Oyedeji et al. 2016). The results from log milling in this study show the opposite pattern that increasing moisture content decreases the energy consumption. The multi-blade roller construction differs significantly from that of a hammer mill. Mill types more similar to the log mill, have been shown to consume less energy when the feedstock is wet. Karinkanta et al. (2018)

concludes that the energy consumption for a roller mill decreases with increasing moisture content. The roller mill crushes the feedstock rather than milling it, and the construction is somewhat more similar to the log mill compared with the hammer mill.

The log mill's ability to mill wet feedstock to powder in an energy-effective way, compared to the hammer mill, is an important advantage for the subsequent drying process. Obernberger & Thek (2010) concludes that the drying process is the largest energy consumer in the pelletizing chain in which the hammer mill is commonly used. Furthermore, they conclude that smaller particles dry faster compared to larger particles. Since the pre-drying step is excluded in the log mill system, energy is saved if the drying step can be performed on material with smaller particle size. This can lead to a more economical production of wood powder.

Hammer mill system

The result from the hammer mill system showed that the specific energy consumption for chipping and milling logs with approximately 7 % moisture content (w.b.) consumed 54 kWh/ton, idle power excluded.

This energy consumption lies within the interval stated by Temmerman, Jensen & Hébert (2013). The hammer mill has a particular advantage due to energy consumption when milling feedstock with low moisture content compared to the log mill. However, the pre-drying step is essential when using a hammer mill (Obernberger & Thek 2010).

Oyedeji et al. (2016) found that the specific energy consumption for a hammer mill, screen size of 3.18 mm, consumes roughly 170-395 kJ/kg when using wood chips from loblolly pine with a moisture content of 13.6-50 % (w.b). When the specific energy consumption for the hammer mill in this study, 2 mm screen size, was converted, it resulted in 290 kJ/kg with feedstock moisture content 7 % (w.b). If the energy consumption for the hammer mill system in this study was set to follow the same pattern as for the hammer mill in the study by Oyedeji et al. (2016), the energy consumption might have increased fourfold or more if the feedstock had had the same moisture content as for the log mill system. If feedstock with similar moisture content would have been used as for the log mill, problems such as bridging and clogging/blockings would arouse and affect the wood powder production negatively.

4.1.2 Bulk density

Log mill system

The tapped bulk density interval was 190-320 kg/m^3 and the loose bulk density interval was 150-260 kg/m^3. The tapped- and loose density increased with decreasing moisture content. The LR-models were significant for modelling the densities when built on the factor: moisture content, which was the only factor with a significant impact.

There was a visual difference in the particle size distribution, generating a wood powder with finer particles when milling wet feedstock. The visual difference was given strength by the sieve size analysis data from the PhD-project showing that the share of particles <1 mm differed between wet- and dry milled feedstock with their different settings (Table 2).

Table 2. Average particle size <1 mm. WmF=Wet milled feedstock, DmF=Dry milled feedstock, MdF=Medium-dry milled feedstock. Settings: FS=feeding speed, BRS=Blade rotation speed

	FS=0.02 BRS=72 (m/s)	FS=0.04 BRS=72 (m/s)	FS=0.02 BRS=52 (m/s)	FS=0.04 BRS=52 (m/s)	FS=0.03 BRS=62 (m/s)
WmF (%)	94	91	85	90	-
DmF (%)	93	89	82	76	-
MdF (%)	-	-	-	-	86

Sieve size analysis showed that share of particles < 1 mm was higher for the wood powder created from wet feedstock for all experiments and might explain why the density for the powder from the wet feedstock was lower compared to that from dry feedstock. Falk (2013) concludes that a finer powder decreases the bulk density, which probably was the case in this study when the powder from the log mill was compared between the feedstock and with the powder from the hammer mill. Salehi et al. (2019) performed a density test with a similar approach as in this study, using wood chips from pine residues. They found that the tapped density for the wood chips, with the chip size 1.9-4.0 mm, had a tapped density of approximately 327 kg/m^3 respectively 340 kg/m^3 for the loose density. Their results implies that larger particles increases the density when compared to the densities generated from the log mills wood powder (<3.15 mm). Rezaei et al. (2016) found that the density of wood powder from a hammer mill, using pine wood chips, increased when the screen size was increased from 3.2 to 25.4 mm. This indicates that larger particles increases the density, and is in line with what this study has shown.

The density models had a lack of fit meaning that there was an error in the models. The error might, to some extent, have occurred as a result of the exclusion of the outlier density related data (N25), but was considered as a false error because the Q^2 and R^2 was still rather high in combination with a high reproducibility (>0.9) (Eriksson et al. 2008). To ensure the quality of the density tests, a new test for N25 was performed to exclude human error. No difference in the result was found and the error was therefore considered to be origin from the ingoing moisture content of the log or from incorrect settings in the switchboard. The exclusion of the density related data resulted in a tapped density model increment of R^2 from 0.70 to 0.86 and Q^2 from 0.65 to 0.84. Furthermore, the exclusion increased the R^2 for loose density from 0.70 to 0.86 and Q^2 from 0.64 to 0.84.

Hammer mill system

The bulk densities of hammer milled wood powder was 270 kg/m^3 for the tapped bulk density and 220 kg/m^3 for the loose bulk density. The density of the hammer milled wood powder was within the higher range of the log mill density interval. Visual analysis showed that the wood powder particles from the hammer mill had an elongated shape and that the particle size was larger compared to wood powder from the log mill. The particle size analysis from the PhD-project showed that the amount of particles <1 mm was 93 % which indicates that the hammer mill could produce nearly the same amount of fine particles <1 mm as the log mill (94 %).

The bulk density was higher for the hammer milled wood powder compared to the wood powder of the log mill at a similar particle size distribution. It is likely that the wood powder created by the hammer mill had more irregular and larger wood powder particles below the 1 mm interval and within the interval 1-3.15mm (smallest sieve size), but this has to be confirmed by future analysis. A higher density as result of larger particle size distribution is in line with what Falk (2013), Salehi et al. (2019) and Rezaei et al. (2016) have found.

4.1.3 Hausner ratio

The Hausner ratio for log milled wood powders varied between 1.22-1.32 and decreased with feedstock moisture content. The LR-model was significant when built on the factor: moisture content which was the only factor with significant impact.

When the interval of Hausner ratio was compared to Geldart, Harnby & Wongs (1984) values, the test indicated good (HR≤1.25) and medium good (HR=1.25-1.4) wood powder flow properties. The lowest (best) Hausner ratio was gained when the tapped- and loose density were high which implies that the best Hausner ratio is gained when the feedstock is dried before milling. Falk et al. (2015) found that spruce powder, created with a hammer mill, has a Hausner ratio close to 1.60 which, if compared to the result from the dry-milled feedstock in the study, indicates that the log mill can produce a powder with lower Hausner ratio, indicating a better flowability compared to a hammer mill.

On the other hand, the wood powder created by the hammer mill in this study resulted in a Hausner ratio of 1.23. This confirms the uncertainty of comparing the Hausner ratio between studies if the conditions are not the same. However, wood powder from some of the log mill experiments showed potential to have a better flowability (lower Hausner ratio), compared to the hammer mill experiment, though the difference was very small.

The uncertainty in the comparison of the Hausner ratio between studies arises from the lack of standard for the tapped density test, making it difficult to perform an accurate analysis. Santomaso, Lazzaro & Canu (2003) concludes that there is a lack of a single, reliably and widely used flowability test, mostly because the variation in granular materials and how the measuring results are handled. However, the results can still be a pointer if the flowability is good or bad between samples in a specific study.

Results from previous studies conclude that wood powder with less fines increases the density and improves the Hausner ratio (Rezaei et al. 2016; Salehi et al. 2019). However, the log mill powder characteristics for thermal conversion (gasification and combustion) might be better, as a result of larger amount of particles <1 mm and a more spherical particle shape. Lehtikangas (1999) recommends a homogeneous wood powder with fine particles (<1 mm) for powder combustion and for this application log mill wood powder have an advantage along the potential to save energy during the drying stage.

4.2 Practical implementations

The results from this study can be used for determination if the log mill can produce a wood powder with better bulk properties in an energy efficient way compared to conventional mills.

The potential to create a wood powder instantly from a log might only be profitable if there is a lack of competition with already existing feedstock for other products (Yuan et al. 2008). The log feedstock in this study can be classified as timber/pulp wood but this was considered as unimportant in this study. Future feedstock could be stems from pre-commercial thinnings and early thinning-sites containing a minor stem diameter interval with no competition from higher values, such as timber. Another potential feedstock for the log mill could be harvest residues, transported as bundles or as chips, milled at the industrial sites. The feedstock could potentially be milled without the debarking step, depending on the end user's demands regarding wood powder quality. The ethical aspect of not using mature wood for e.g. wood powder production and/or wood powder combustion could, to a larger extent, win the public opinion even more and increase the use of bioenergy.

The reduction of process step and the possibility of milling wet feedstock to a homogeneous wood powder is an advantage of the log mill system compared to the hammer mill system. The aim with biomass and biofuels are in many cases to substitute fossils to mitigate climate impact and because it is often more profitable to utilize e.g. wood pellets instead of oil for production of energy. The total amount of energy and fuels needed for producing of wood powder, when the total production chain is included, might be lower for the log mill system.

Another positive aspect is the log mill's possibility to reduce the energy consumption during the drying stage. As mentioned, the industrial log mill is supposed to have a cyclone attachment, recycling larger particles to the mill (Klingmill 2019), which would insure the quality of the wood powder even if the feedstock would be in particulate form before milling. The temperature of the wood powder, created by the log mill, reached approximately 20 ° C during the experiments with a surrounding temperature of approximately 0 ° C, and if a drying function would be added to/after the cyclone, the heath of the powder could be utilized to a larger extent, requiring less energy to dry the produced wood powder. Thereby, the energy needed to create a wood powder ready for e.g. combustion could be lowered.

4.3 Strengths and weaknesses in the study

4.3.1 Strengths

The experimental logs were well controlled (documented and measured) in this study. The sampling method was a well-known method used in previously studies and was concluded as “good enough” for this study. The logs were handled with care and was covered with plastics sheets to reduce risk of contamination. Milled samples were sealed in air-tight plastic bags before the density tests.

Energy consumption was calculated as the specific consumption, not including the idle power due to differences in the log mill settings and between capacities of the log mill and the hammer mill. Through this procedure a comparison between different settings and mills could be performed and more correct figures for energy consumption obtained. This approach has also been used in previously studies (Temmerman, Jensen & Hébert 2013; Oyedeji et al. 2016).

The bulk density analysis were initially carried out on non-sieved wood powders. However, to simulate industrial wood powder feedstock, analyses were remade on sieved samples. The decision was based on the possible effect from large, non-milled, sticks of particles (3.15-300 mm) and their likely impact on the bulk densities and flowability. In addition, sieving of wood powder facilitated comparisons with other studies due to a much narrower range in particle size.

4.3.2 Weaknesses

A couple of problems, related to the log mill, aroused during the milling section which can have affected the wood powder characteristics and the energy consumption. There was some downtime, milling- and feeding related problems, during several of the milling experiments. The capacity for the log mill’s two motors was 55 kW each, but the first motor performed the main milling. When the energy consumption exceeded the maximum power, the switchboard turned the mill of. This might have affected the resulting wood powder properties because the mill had to be restarted. The downtime also affected the energy consumption calculations and increased the error.

The aim was to have a three factor full-factorial design with one mid-point performed in full triplicates. However, one of the experiments was considered as an outlier (N25) and was excluded from the model, though the quality of the data set can still be considered to be high.

The results for tapped- and loose density and Hausner ratio, of the hammer mill system, were based on only one analysis each. If the samples had a lack of homogeneity, one single analysis could have a large impact on the results. A larger number of analysis might have had validated the result, but it was also a question of time and the hammer mill analysis were not the priority.

The evaluation of the flowability, based on the Hausner ratio, can be considered as uncertain because only one analysis was performed. When the Hausner ratio of the hammer milled wood powder was compared to results from previous studies, the result differed which made the analysis questionable. Because of visual difference in the particle size distribution of the hammer milled wood powder containing elongated particles and to analyze wood powder flowability, additional tests should be carried out. Angle of repose and compression ratio analyses can be better suited analyses for validating the wood powder flowability (Falk et al. 2015).

4.4 Further studies

The specific energy consumption is well documented in this study, though only for the log mill's milling process and the hammer mill processes (chipping and milling). If to compare and evaluate the total systems for wood powder production, energy consumption for drying etc. have to be taken in account. The idle power is not to be forgotten either, as a part of the total consumption contributing to the total consumption/cost.

Further studies are also needed to examine the flow properties of wood powder. The Hausner ratio, as a single test, might not be satisfying for determination of the flowability of wood powders.

4.5 Conclusion

The results from this study show that:

i. Specific energy consumption was affected by moisture content, feeding speed, blade rotation speed, and the interaction between moisture content and feeding speed. The lowest specific energy consumption was found in the slowest blade rotation speed (52 m/s) combined with high moisture content and high feeding speed.

ii. The moisture content was the only factor with significant effect on the wood powder densities and the Hausner ratio. Decreasing moisture content increased the tapped- and loose density resulting in an interval of 190-320 (kg/m^3) for the tapped density and 150-260 (kg/m^3) for the loose density. The Hausner ratio was improved with decreasing moisture content resulting in an interval of 1.22-1.32.

iii. The specific energy consumption for the log mill system was 62-220 (kWh/ton) depending on setting combination and the specific energy consumption for the hammer mill system was 53 kWh/ton. The wood powder densities of the hammer mill system were in the upper range of the log mill system's density interval and the hammer mill's Hausner ratio was in the lower range of the log mill system's interval.

References

Alakangas, E. (2014). Quality guidelines of wood fuels in Finland. Jyväskylä. Technical Research Centre of Finland. (Report, VTT-M-04712-15). DOI: https://doi.org/10.13140/RG.2.1.3290.3127

Barletta, D. & Poletto, M. (2013). An Assessment on Silo Design Procedures for Granular Wood Biomass. *AIDIC* (*The Italian Association of Chemical Engineerin*g), vol. 32. DOI: http://dx.doi.org/10.3303/CET1332369

Bioenergi. (2018). Skanska fortsätter byta från olja till biobränslen i asfaltverk. *Tidningen BIOENERGI*, 17 augusti. Tillgänglig: https://bioenergitidningen.se/bioenergi-i-industri/skanska-fortsatter-byta-fran-olja-till-biobransle-i-asfaltverk [2019-10-30]

Eriksson, L., Johansson, E., Kettaneh-Wold, N., Wikström, C. &Wold, S. (2008). *Design of Experiments: Principles and Applications.* 3. Ed. Umeå: Umetrics.

Falk, J. (2013). *Particle and feeding characteristics of biomass powders.* Umeå University, Department of applied physics and electronics. Master of engineering in energy technology. Master thesis. Available at: https://www.**diva**-portal.org/smash/get/diva2:627253/FULLTEXT01.pdf [2019-10-31]

Falk, J., Berry, R., Broström, M. & Larsson, S. (2015). Mass flow and variability in screw feeding of biomass powders — Relations to particle and bulk properties. *Powder Technology*, vol. 276, pp. 80–88. DOI: https://doi.org/10.1016/j.powtec.2015.02.023

Geldart, D., Harnby, N. & Wong, A.C. (1984) Fluidization of cohesive powders. *Powder Technology,* vol. 37, pp. 25-37. DOI: https://doi.org/10.1016/0032-5910(84)80003-0

Gil, M. & Arauzo, I. (2014). Hammer mill operating and biomass physical conditions effects on particle size distribution of solid pulverized biofuels. *Fuel Processing Technology*, vol. 127, pp. 80–87. DOI: https://doi.org/10.1016/j.fuproc.2014.06.016

Godin, B., Arimont, A., Temmerman, M. & Delcarte, J. (2016*). Influence of the Particle Size Distribution and Water Content on the Energy Consumption of Milling Sorghum and Bamboo.* ETA-Florence renewable energies. DOI: https://doi.org/10.5071/25thEUBCE2017-2BV.1.2

Hájek, B. (2003). *Utrustning för bestämning av träets densitet in-line*. Stockholm. Trätek. (Rapport, P 0302006). Tillgänglig: https://www.diva-portal.org/smash/get/diva2:1079726/FULLTEXT01.pdf [2019-10-21]

von Hofsen, H. (2019). *Skogsbrukets transport – och arbetsfordon (forestry vehicles for transport)*. Uppsala: Skogforsk. (Arbetsrapport, 1003-2019). Tillgänglig: https://www.skogforsk.se/cd_20190116112010/contentassets/f3058fbe108e47d88dc62de7ef7910ac/arbetsrapport-1003-2019.pdf [2020-01-07]

IEA. (2018). *Key World Energy Statistics 2019.* Paris: IEA. (Statistics report – 2019). Available at: https://www.iea.org/reports/key-world-energy-statistics-2019 [2019-09-19]

Karinkanta, P., Ämmälä, A., Illikainen, M. & Niinimäki, J. (2018). Fine grinding of wood – Overview from wood breakage to applications*. Biomass and Bioenergy*, vol. 113, pp. 31–44. DOI: https://doi.org/10.1016/j.biombioe.2018.03.007

Klingmill. (2019). *The KlingMill system*. Available at: http://klingmill.se/ [2019-10-21]

Lehtikangas, P. (1999). *Lagringshandbok för trädbränslen*. Uppsala: Sveriges lantbruksuniversitet.

Marks, J., Mattsson, J. & Wallin, F. (2005*). Träpulver i Torsångs värmecentral: (Slutrapport, STEM-projekt P11122-1 Konvertering av oljepannor mindre än 1 MW till eldning med träpulver)*. Borlänge: Högskolan Dalarna. Tillgänglig: https://www.diva-portal.org/smash/get/diva2:523165/FULLTEXT01.pdf

McKendry, P. (2002a). Review of Energy production from biomass (part 2): conversion technologies. *Bioresource Technology*, vol. 83, pp. 47–54. DOI: https://doi.org/10.1016/S0960-8524(01)00119-5

McKendry, P. (2002b). Review of Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, vol. 83, pp. 37–46. DOI: https://doi.org/10.1016/S0960-8524(01)00118-3

Mäkelä, M. (2017). Experimental design and response surface methodology in energy applications: A tutorial review. *Energy Conversion and Management*, vol. 151, pp. 630-640.
DOI: https://doi.org/10.1016/j.enconman.2017.09.021

Nilsson, P. & Cory, N. (2018). *Skogsdata 2018 – Aktuella uppgifter om de svenska skogarna från Riksskogstaxeringen. Tema: Riksskogstaxeringens kvalitetssäkringsarbete.* Umeå. Institutionen för skoglig resurshushållning. Tillgänglig: https://www.slu.se/globalassets/ew/org/centrb/rt/dokument/skogsdata/skogsdata_2018_webb.pdf [2019-10-20]

Obernberger, I. & Thek, G. (2010). *The pellet handbook : the production and thermal utilization of pellets*. London ; Earthscan.

Oyedeji, O., Fasina, O., Adhikari, S., McDonald, T. & Taylor, S. (2016). The effect of storage time and moisture content on grindability of loblolly pine (Pinus taeda L*.). European*

Journal of Wood and Wood Products, vol. 74(6), pp. 857–866. DOI: https://doi.org/10.1007/s00107-016-1070-x

Paulrud, S., Mattsson, J. & Nilsson, C. (2002). Particle and handling characteristics of wood fuel powder: effects of different mills. *Fuel Processing Technology*, vol. 76(1), pp. 23–39. DOI: https://doi.org/10.1016/S0378-3820(02)00008-5

Peter, S., Dhanja, J., Malik, V., Radhakrishnan, N., Jayakanthan, M. & Sundar, D. (2017). Quantitative Structure-Activity Relationship (QSAR): Modeling Approaches to Biological Applications. *Module in Life Sciences,* vol. 2, pp 661-676. DOI: https://doi.org/10.1016/B978-0-12-809633-8.20197-0

Rezaei, H., Lim, C., Lau, A. & Sokhansanj, S. (2016). Size, shape and flow characterization of ground wood chip and ground wood pellet particles. *Powder Technology*, vol. 301, pp. 737–746. DOI: https://doi.org/10.1016/j.powtec.2016.07.016

Salehi, H., Poletto, M., Barletta, D. & Larsson, S. (2019). Predicting the silo discharge behavior of wood chips - A choice of method. *Biomass and Bioenergy*, vol. 120, pp. 211–218. DOI: https://doi.org/10.1016/j.biombioe.2018.11.023

Santomaso, A., Lazzaro, P. & Canu, P. (2003). Powder flowability and density ratios: the impact of granules packing. *Chemical Engineering Science*, vol. 58(13), pp. 2857–2874. https://doi.org/10.1016/S0009-2509(03)00137-4

Segerström, M. & Larsson, S. (2014). Clarifying sub-processes in continuous ring die pelletizing through die temperature control. *Fuel Processing Technology*, vol. 123, pp. 122–126. https://doi.org/10.1016/j.fuproc.2014.02.008

Skogsstyrelsen. (2017). *Skogsbränslegallring*. Tillgänglig: https://www.skogsstyrelsen.se/bruka-skog/skogsbransle/skogsbranslegallring/ [2019-10-22]

Smalheiser, N. (2017). Data literacy : how to make your experiments robust and reproducible. London, England: Academic Press. DOI: https://doi.org/10.1016/B978-0-12-811306-6.00011-7

Strömberg, B. & Herstad-Svärd, S. (2012). Bränslehandboken 2012. Stockholm. Värmeforsk. (Rapport, 2012:1234). Tillgänglig: https://www.energiforsk.se/rapportsok/?q=A08-819 [2020-01-05]

Tai, B. & Machin, D. (2014). Multiple Linear Regression. I: John Wiley & Sons (Eds) .*Regression Methods for Medical Research*, vol. 1. Chichester: John Wiley & Sons, pp. 43–63. DOI: https://doi.org/10.1002/9781118721957.ch3 [2019-11-27]

Temmerman, M., Jensen, P. & Hébert, J. (2013). Von Rittinger theory adapted to wood chip and pellet milling, in a laboratory scale hammermill. *Biomass and Bioenergy*, vol. 56(C), pp. 70–81. DOI: https://doi.org/10.1016/j.biombioe.2013.04.020

Trafikanalys. (2015). *Skogens transporter – en trafikslagsövergripande kartläggning*. Stockholm. PM 2015:16. Tillgänglig: https://www.trafa.se/globalassets/pm/2011-

2015/2015/pm-2015_16-skogens-transporter---en-trafikslagsovergripande-kartlaggning.pdf [2019-20-22]

Appendix 1

Table A1. *The design matrix. Model factors: MC=Initial moisture content, FS=Feeding speed, BRS=Blade rotation speed. Response variables: TD=Tapped density, LD=Loose density, HR=Hausner ratio, SEC= Specific energy consumption, EC(I)=Energy consumption (idle power included)*

Exp. name	MC (%)	FS (m/s)	BRS (m/s)	TD (kg/m3)	LD (kg/m3)	HR (-)	SEC (kWh/t)	EC (I) (kWh/t)
N21	32	0.030	62	225	180	1.25	112	134
N6	46	0.020	72	212	160	1.32	138	165
N17	46	0.022	72	200	156	1.28	132	155
N24	48	0.022	52	207	161	1.29	83	98
N15	47	0.033	52	193	147	1.31	64	73
N7	17	0.037	72	273	217	1.26	120	147
N8	47	0.035	72	213	164	1.30	92	111
N23	18	0.023	52	282	223	1.27	103	133
N29	19	0.032	72	284	230	1.24	143	184
N25	15	0.038	52	206	157	1.31	94	111
N3	18	0.037	52	304	243	1.25	83	97
N19	47	0.035	72	221	174	1.27	90	104
N12	18	0.021	52	303	243	1.24	165	192
N22	32	0.029	62	221	176	1.26	84	104
N13	48	0.022	52	219	172	1.28	62	76
N30	46	0.037	72	217	170	1.27	80	87
N2	47	0.022	52	220	170	1.30	76	89
N28	47	0.017	72	219	175	1.26	101	132
N16	14	0.020	72	313	253	1.24	223	265
N1	18	0.021	52	315	258	1.22	133	157
N18	19	0.038	72	292	239	1.22	133	155
N4	46	0.034	52	213	169	1.26	73	83
N27	18	0.022	72	322	259	1.24	191	239
N5	17	0.021	72	292	232	1.26	219	265
N14	18	0.037	52	303	250	1.22	100	117
N26	46	0.035	52	203	159	1.28	78	90
N33	32	0.030	62	209	165	1.27	110	131

Appendix 2

Table A2. *Resulting values from the hammer mill system. MC=Initial moisture content, TD=Tapped density, LD=Loose density, HR=Hausner ratio, SEC= Specific energy consumption, EC(I)=Energy consumption (idle power included)*

	MC (%)	TD (kg/m3)	LD (kg/m3)	HR (-)	SEC (kWh/t)	EC(I) (kWh/t)
Chipping	41-47	-	-	-	8	11
Milling	7	270	220	1.23	45	75
Total	-	-	-	-	53	86