Nordic Pulp & Paper Research Journal 2021; 36(2): 214–226 **DE GRUYTER**

**Chemical pulping**

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# The impact of using different wood qualities and wood species on chips produced using a novel type of pilot drum chipper

https://doi.org/10.1515/npprj-2019-0096
Received November 20, 2020; accepted February 14, 2021; previously published online March 3, 2021

**Abstract:** Resource-efficient wood chipping for forest-industrial processes demands large fractions of accept chips and small fractions of small-sized material, such as pin chips and fines. In Kraft pulping, a narrow distribution of wood chip thickness is important for even impregnation and for making high-quality pulp. Using newly developed forest-industrial drum-chipping technology, the investigation covered wood of varying moisture content, frozen versus unfrozen wood, and the use of different wood species. Using conventional techniques for analyzing wood chip dimensions, fast-grown spruce wood with high moisture content gave 4.2 % pin chips and fines, which was less than half of the fractions obtained with spruce wood with lower moisture content. A comparison between frozen and unfrozen pine resulted in slightly thinner and shorter chips for the frozen wood, but in both cases accept yields of up to ~85 % were achieved. A comparison of different tree species (aspen, birch, pine, and spruce) resulted in larger accept fractions (~90 %) for the hardwood species, even though the average length of these wood chips was as low as 17 mm. The results provide a first indication of how basic wood log properties affect the yields of accept chips and small-sized material when using modern industrial drum-chipping technology.

**Keywords:** drum chipper; frozen wood; moisture content; tree species; wood chips.

## Introduction

Most forest-industrial processes, i. e. processes in the pulp and paper industry and in wood-based biorefineries, are based on wood chips. The objective of wood chipping is to produce a high yield of wood chips that have a suitable quality for processing using digesters and refiners, regardless of season, weather conditions, and variations in feedstock composition. Although wood chip quality is of utmost importance both for the pulp yield in chemical pulping and for subsequent process steps, very little research is devoted to investigations of new forest-industrial wood chipping technology and factors that influence wood chip quality. A common definition of high wood chip quality is that the chips consist of a low fraction of overthick chips, pin chips, and fines, and that they are uniform with regard to bulk density and moisture content (Hartler and Stade 1977, Uhmeier 1995, Hartler 1996). Uniformity with respect to length and thickness is also important. The definitions of length, thickness, and width of a wood chip are indicated in Figure 1. High wood chip quality results in pulp with high and uniform quality, whereas low wood chip quality results in low-quality pulp, or even costly operation disturbances (Hartler and Stade 1977, Hartler 1996). More specifically, a high fraction of wood chips of too small dimensions results in poor yields and pulp of lower strength (Hartler 1996). A high fraction of overthick chips increases the fraction of reject (shives) (Hartler 1996), as the thickness affects impregnation in Kraft pulping and poor impregnation results in uncooked pieces of wood.

Wood chippers in the pulp and paper industry of today are typically disc chippers (Brännvall 2009). However, an inherent problem with disc chippers is that they have an uneven velocity across the disc, as the

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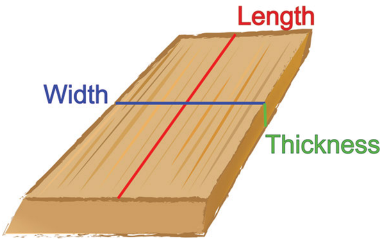

**Figure 1:** Schematical image of wood chip indicating the orientation of fibers in relation to length, width, and thickness.

velocity is lower at the center than at the periphery. Using a novel drum-chipping technology described in previous papers, promising results have been achieved with regard to wood chips for both Kraft pulping (Gard Timmerfors et al. 2020) and sulfite pulping (Gard Timmerfors and Jönsson 2019). Drum chippers have a uniform velocity across the drum and can therefore generate more uniform wood chips with relatively low fractions of pin chips and fines (Gard Timmerfors et al. 2020).

When wood chippers are operated in the forest industry, the feedstock will often exhibit large variations with regard to moisture content and temperature. The moisture content of the wood logs will depend on growth conditions, logging period, and the handling of the wood logs before they reach the industry (Hart 2009). Even if the time between harvest and transport to industry is minimized, temporary weather phenomena, for example drought, will affect the moisture content of logs and wood chips (Marrs 1989, Hart 2009, Sfeir et al. 2021). Wood with a dry-matter content over 70 % will give increased amounts of pin chips and fines (Brännvall 2009). Furthermore, there is a difference between wood harvested and handled during winter and summer seasons. In Nordic regions, the wood will typically be frozen during chipping in the winter, but unfrozen during the summer season. During winter, the interior of a log might still be frozen even if the outer part thawed during handling. Although the effects of temperature variations on wood chipping to a large extent remain to be elucidated, earlier studies on disc chipping of softwood have indicated that low temperatures make the wood more brittle (Hernández et al. 2014). That would make the influence of high cutting speeds (such as at the periphery at the disc) more pronounced, resulting in more small-sized material, pin chips and fines, and less large-sized material. Studies of disc chippers and mechanical testing furthermore show that whereas the moisture content would be most important at sub-zero temperatures (< 0 °C), the basic density would be more important at higher temperatures (Hartler and Stade 1977, Hartler 1996, Hernández et al. 2014). Industrial experience indicates that frozen wood will give rise to thinner wood chips and increased fractions of pin and fines, and that this increase of pin chips and fines will be higher at higher disc velocities (Brännvall 2009).

Another factor that will affect the wood chip quality is the variation among the wood species that are used as feedstock for pulping operations. Wood density and mechanical behavior can vary between species, between trees of the same species, and within the same tree. There are some previous studies of the impact of tree species and ring orientation on wood chip quality (Twaddle 1997), such as the thickness of the wood chips (Figure 1) and effects of the angle between annual rings and cutting knife for loblolly pine, southern red oak, shagbark hickory, and sweetgum. Chipping in a laboratory test bed indicated that the thickness, which increased with wood chip length (Figure 1), was dependent on the tree species. The variation of the angle between annual rings and knife was most important for wood of southern red oak. An angle between annual rings and knife edge of 0° resulted in thicker wood chips than an angle of 90°. Thus, there was a variation between species but also within a single species, depending on the microstructure of the wood (Twaddle 1997). The importance of the inherent mechanical variation in the wood material itself was also observed in a study of Norway spruce log cracking (Hellström et al. 2008).

The aim of this study was to investigate how wood quality, such as moisture content and freezing state, and wood species affect the quality of wood chips produced using the novel industrial drum-chipping technology. Although chipping is an important area for the pulp and paper industry, forest-industrial chipping is covered by relatively few studies. There are some basic comparisons between the new drum-chipper technology and conventional disc-chipper technology in the literature (Gard Timmerfors et al. 2020), but this is the first study addressing the effects of wood quality on chips produced using the new drum-chipper technology.

The focus area of this work is forest-industrial wood chipping for the pulp and paper industry. This is different compared to chipping or particle size reduction for the bioenergy sector, where there are several recent studies regarding the properties of the raw material (Abdallah et al. 2011, Spinelli et al. 2011, Spinelli and Magagnotti 2012). There are differences with regard to chipping techniques, standards, and definitions (Abdallah et al. 2011). For example, the moisture content is critical for the impregnation process in chemical pulping, and too low moisture content will cause problems (Hartler and Stade 1977). In contrast, dry wood chips (or particles) are advantageous in the bioenergy sector, as less water needs to be vaporized during combustion. Yet another type of chipping occurs at sawmills, where chipper-canters are used to convert residual portions of wood logs to wood chips (Cáceres et al. 2015, Pfeiffer et al. 2015, Curti et al. 2018). Such wood chips are typically used in the pulp and paper industry, but the chipping process is different and affects only the outer portions of the wood logs rather than whole wood logs as in forest-industrial wood chipping with disc chippers and drum chippers.

Three series of experiments were conducted addressing moisture content, frozen vs. unfrozen wood, and different wood species. With regard to different wood species, four wood species commonly occurring in Nordic forests were investigated: Norway spruce, Scots pine, downy birch, and Eurasian aspen. Forest land covers 69 % of Sweden, an area corresponding to 23.5 million ha (Skogsdata 2018). The standing volume consists mainly of Norway spruce (40.8 %), Scots pine (39.0 %), and birch (12.4 %) (Skogsdata 2018). Among broad-leaved trees, aspen (1.6 %) is second after birch (together with alder) (Skogsdata 2018). Thus, the selection of wood species represents the two most common types of softwood (spruce and pine) and the two of the most common types of hardwood (birch and aspen).

The wood chips were produced using a pilot drum chipper described in a previous paper (Gard Timmerfors and Jönsson 2019). The evaluation of the wood chips was performed using SCAN-CM, a series of manual industrial standard methods (Scandinavian Pulp, Paper and Board Testing Committee's series of test methods for chemical and mechanical pulps and wood chips), and using a ScanChip analyzer. The SCAN-CM standard methods have been widely used in industry. The ScanChip analyzer is an optical system for rapid analysis of wood chips, and advantages include larger sample size and automation. The wood with different moisture content was also analyzed with regard to its chemical composition and performance in a standard Kraft cook, to detect potential damage caused by wood rot, which would make the comparison difficult. Analysis of the chemical composition could reveal if there were other fundamental differences than the moisture content. Investigations in this area will provide a better understanding of the impact of wood quality and wood species in the production of chips for pulping and biorefinery processes.

# Materials and methods

## Wood logs

The study consisted of three sets of experiments, performed under different time periods and using different sets of wood logs. The three experimental series were focused on moisture content, frozen wood, and different wood species, respectively.

In the first experimental series, debarked and unfrozen wood logs of Norway spruce (*Picea abies*) were used. The diameter of the logs were in the range 10–14 cm. There were six logs in total. Each log originated from a separate tree. There were two logs from fast-growing trees from wet conditions and growing in the outer part of the forest with plenty of nutrition and sunlight resulting in wood with a high moisture content (HMW, high moisture wood). There were two logs from dryer conditions and growing inside the forest resulting in wood that was a little dryer than an average wood log used in industry. This wood was referred to as MMW (medium moisture wood). Finally, there were two logs from very dry trees growing inside the forest and selected for visually appearing as dry (LMW, low moisture wood). Felling and debarking was made manually.

Studies of the difference between frozen and unfrozen wood were performed using debarked wood logs of Scots pine (*Pinus sylvestris*). The diameter of the logs were in the range 10–15 cm. Five logs were used, and each log originated from a separate tree. Each log was separated into two halves. One half was chipped in its unfrozen state and the second half was put into a plastic cover and before chipping it was kept outdoors for seven days in temperatures ranging between −3 °C and −15 °C. When it was possible to distinguish top and bottom parts of wood logs, they were evenly distributed among the frozen and unfrozen assortments to avoid any bias.

Studies of the difference between tree species were conducted using a third set of logs. The tree species were Eurasian aspen (*Populus tremula*), downy birch (*Betula pubescens*), Scots pine, and Norway spruce. There were at least 12 logs of each species. The logs were debarked manually and chipped while frozen.

## Wood chipping

The wood logs were chipped using a pilot-scale drum chipper of novel design, constructed by Multi Channel Sweden AB (Bredbyn, Sweden). The drum of the pilot chipper had a diameter of 3 m, a width of 20 cm, and was equipped with 16 knives. For all three sets of experiments, the knife angles (α = 2.2°, ε' = 30°) were adjusted to be suitable for production of wood chips of an average thickness of around 4 mm. Definitions of knife angles and T dimension of the chipping process, and studies of the relationship between chip size and knife angles have been previously reported (Gard Timmerfors and Jönsson 2019, Gard Timmerfors et al. 2020) and the feeding system has been described (Gard Timmerfors and Jönsson 2019). The logs are placed manually on the in-feed system and are fed into the chipper at approx. 0.9 m/s (400–450 rpm). The system is designed so that the velocity is a little lower than the velocity of the wood logs pulled in by the chipper, as the feeding system should not pull or push the wood log.

For the first and the second series of experiments, the logs where chipped separately and all wood chips were collected. For all three series, the fractions were mixed and downsized according to SCAN-CM 41:94 (sampling) method prior to conducting tests that required a small sample size (bulk density, thickness distribution, size distribution, and moisture content).

In the first series of experiments, the drum velocity was 30 m $s^{-1}$. The T dimension was adjusted for a setting length of 23 mm (SL23) (T = 12 mm).

In the second series of experiments, half wood logs were chipped at different velocities. For each velocity, one half of each log was chipped in frozen state and the other half in unfrozen state. The velocities were 27 m $s^{-1}$, 30 m $s^{-1}$, and 33 m $s^{-1}$. The T dimension was adjusted for a setting length of 26 mm (SL26) (T = 14 mm).

In the third series of experiments, wood logs of each tree species were chipped under winter conditions and using two different setting lengths. The drum velocity was 30 m $s^{-1}$ and the T dimension was adjusted for setting lengths of 23 mm (SL23) (T = 12 mm) and 19 mm (SL19) (T = 10 mm). During chipping, a sample amounting to 40–80 L was collected for characterization (wood chip dimensions, bulk density, and moisture content). The wood chips were collected by holding a 125 L polyethene bag after the 5 m long scraper conveyor of the pilot chipper, in a similar manner as described in the SCAN-CM 41:94 method in which a bucket is used for the collection procedure. The sample was taken when the third wood log reached the chipper to get a mixture of wood chips from the second and the third, and sometimes the fourth wood log.

## Characterization of wood chips

Manual analyses of wood chips were performed using the standard methods SCAN-CM 39:94 (dry-matter content), SCAN-CM 46:92 (bulk density), SCAN-CM 47:92 (thickness and thickness distribution), and SCAN-CM 40:01 (size distribution). For each assortment, the analyses were repeated 3–4 times. In addition, some of the samples were analyzed using a ScanChip image analysis system (PulpEye, Örnsköldsvik, Sweden, and Iggesund Tools, Iggesund, now ANDRITZ) located in the Metsä Board Husum mill (Husum, Sweden). The ScanChip analyzer provides average values and distribution of length, thickness, and width (Figure 1), for 30–50 % of the wood fragments (wood chips and particles) in a sample. The samples were inserted manually into the ScanChip analyzer. The ScanChip analyzer automatically measures the dimensions of wood chips and particles, and calculates the mass fractions according to the SCAN standard system (oversized, overthick, large accept, small accept, pin chips, and fines as defined in Table 1).

## Carbohydrate analysis

Accept chips (large and small accept, as defined in Table 1) sorted out using the SCAN-CM 40:01 (size distribution) method from the three wood chip fractions HMW, MMW, and LMW were dried in a ventilated oven for at least 24 h at around 40 °C. The drying continued until the mass was constant to assure that the chips were completely dry. The chips were then milled using a Wiley mill. The carbohydrate content of the powdered wood samples was determined by MoRe Research (Örnsköldsvik, Sweden) using the SCAN-CM 71:09 procedure.

## Kraft cooking and pulp analysis

Standard Kraft cooking of the three wood chip assortments with different moisture contents was made in the pilot digester facility of MoRe Research. Each assortment was treated and analyzed according to a standard Kraft batch cooking procedure developed by MoRe Research using the following procedure: A sample of 2 kg (dry weight) of wood chips was divided into two 1 kg (dry weight) fractions. Each fraction was inserted into a basket, and put into a pilot reactor together with cooking liquid. The liquid-to-wood ratio was 3.8 L cooking liquor per kg dry weight wood chips. The effective alkali charge was 22 %. The pilot digester was heated, and then the following temperature profile was used: 40 min heating 122–132 °C, 5 min heating 132–156 °C, 70 min 156–158 °C, and 125 min 158–160 °C. The reactor was cooled down and the pulp was washed using deionized water. For calculation of the pulp yield by weighing, one

**Table 1:** Data for Norway spruce wood chips produced using unfrozen wood logs with different moisture content (SL23, velocity 30 m s$^{-1}$).[a]

| **Parameter/fraction** | **Def.**[b] | **LMW** | **MMW** | **HMW** |
|---|---|---|---|---|
| SCAN standard[c] | | | | |
| Dry matter (%) | | $78.7 \pm 0.9^{***}$ | $61.3 \pm 3.3$ | $41.9 \pm 3.5^{***}$ |
| Bulk density (kg m$^{-3}$) | | $111 \pm 7^{***}$ | $128 \pm 6$ | $128 \pm 19$ |
| Thickness (mm) | | $5.4 \pm 0.4^{**}$ | $4.9 \pm 0.2$ | $5.7 \pm 0.1^{***}$ |
| Oversized (%) | > Ø45 | $0.3 \pm 0.5$ | $0.8 \pm 0.6$ | $2.7 \pm 0.4^{***}$ |
| Overthick (%) | > //8 | $10.7 \pm 2.3$ | $9.0 \pm 1.6$ | $13.7 \pm 1.1^{***}$ |
| Large accept (%) | > Ø13 | $60.5 \pm 8.3$ | $59.9 \pm 3.5$ | $65.1 \pm 2.0^{***}$ |
| Small accept (%) | > Ø7 | $19.8 \pm 4.6$ | $17.0 \pm 2.9$ | $14.3 \pm 0.6^{**}$ |
| Pin chips (%) | > Ø3 | $7.5 \pm 3.7$ | $10.5 \pm 1.3$ | $3.5 \pm 0.5^{***}$ |
| Fines (%) | < Ø3 | $1.1 \pm 0.9^{**}$ | $2.8 \pm 0.9$ | $0.7 \pm 0.2^{**}$ |
| Total accept[d] (%) | | $80.4 \pm 3.9$ | $76.9 \pm 1.4$ | $79.4 \pm 1.6$ |
| ScanChip analyzer[e] | | | | |
| Length (mm) | | 21.1 | 21.1 | 20.6 |
| Width (mm) | | 19.9 | 20.3 | 20.0 |
| Thickness (mm) | | 4.4 | 4.0 | 4.2 |
| Oversized (%) | > Ø45 | < 0.1 | 0.2 | 0.4 |
| Overthick (%) | > //8 | 10.4 | 7.9 | 10.4 |
| Large accept (%) | > Ø13 | 60.3 | 61.8 | 61.8 |
| Small accept (%) | > Ø7 | 21.9 | 22.9 | 20.9 |
| Pin chips (%) | > Ø3 | 9.1 | 6.7 | 5.7 |
| Fines (%) | < Ø3 | 1.2 | 0.6 | 0.8 |
| Total accept[d] (%) | | 82.2 | 84.7 | 82.7 |
| Carbohydrate composition[f] | | | | |
| Arabinan (mg g$^{-1}$) | | 11 | 11 | 12 |
| Galactan (mg g$^{-1}$) | | 11 | 16 | 20 |
| Glucan (mg g$^{-1}$) | | 412 | 442 | 423 |
| Xylan (mg g$^{-1}$) | | 51 | 53 | 54 |
| Mannan (mg g$^{-1}$) | | 111 | 100 | 108 |
| Kraft cooking results[g] | | | | |
| Yield (g g$^{-1}$) | | 46.3 | 47.8 | 47.3 |
| Reject (%) | | 0.31 | 0.45 | 0.47 |
| Viscosity (ml g$^{-1}$) | | 1060 | 1110 | 1090 |
| Kappa number | | 24.1 | 24.2 | 24.7 |
| ISO brightness (%) | | 36.3 | 34.3 | 36.4 |
| Fibre length (mm) | | 2.02 | 2.23 | 1.83 |

[a] LMW, low moisture wood; MMW, medium moisture wood; HMW, high moisture wood. Average values and standard deviations for size fraction distribution calculated using SCAN-CM 40:01 or using automated chip analyzer.

[b] Definition: Ø, screen hole diameter in mm; //, screen slot distance in mm.

[c] Significant differences (*t*-test) compared to MMW wood chips are indicated: $^{***}p \le 0.01$; $^{**}0.01 < p \le 0.05$; $^{*}0.05 < p \le 0.1$. Calculation of average values and standard deviations: dryness, SCAN 39:94; bulk density, SCAN-CM 46:92; thickness distribution, SCAN-CM 47:92.

[d] Sum of large and small accept chips.

[e] Average values for length, thickness, and width calculated using automated chip analyzer.

[f] Values for carbohydrate composition according to SCAN-CM 71:09 (equivalent to anhydrous sugar).

[g] Values for pulp quality using ISO 302:2004, ISO 5351:2010, ISO 2470-1:2016, ISO 16065-2:2007.

of the fractions was dried in an oven at 105 °C for at least 16 h or until the mass was constant. The other fraction was added to 60 L of water in a tank equipped with a stirrer, and the material was defibrated by mixing for 3 min at a speed of 1440 turns min$^{-1}$. The material was passed through a laboratory screener with 0.15 mm screen slots (Lorentzen & Wettre, Stockholm, Sweden). The reject fraction was determined by weighing the dried residue from the screener and dividing this amount with the calculated dry-weight of the wood chips used for the analysis. The rest of the material, the pulp, was centrifuged to a dry content of 25 %, disintegrated with a mechanical homogenizer, and sampled. The sample was dried in an oven at 40 °C for 18–24 h and analyzed according to ISO 5251 (viscosity), ISO 302 (Kappa number), ISO 2470 (brightness), and ISO 16065-2 (fiber length).

## Results and discussion

Industrial wood chipping typically imply the handling of wood logs with different moisture content under different temperatures, and often involves a mixture of wood species. Earlier studies of the effects of temperature and wood species on wood chip quality have been made using traditional disc chippers or specially designed laboratory set-ups (Hernández et al. 2014, Twaddle 1997). In this study, we evaluated the effects of basic feedstock variations on wood chip quality when using a newly developed drum-chipping technology.

### Effects of growth conditions and moisture content

In the first series of experiments, chipping behavior for trees grown under different conditions – resulting in wood with different moisture content, was evaluated for the settings SL25 and drum velocity 30 m $s^{-1}$. The wood logs could be divided into three categories depending on the moisture content (Table 1). The dry-matter contents of the wood chips were, approximately, 80 % for LMW, 60 % for MMW, and 40 % for HMW. The differences were statistically significant ($p \leq 0.01$).

Moisture content was expected to affect the bulk density. The bulk density of LMW wood chips was around 110 kg $m^{-3}$, which was significantly ($p \leq 0.01$) lower than the value for MMW (Table 1). The average wood chip thickness, as determined by using the SCAN method, varied between 4.85 and 5.70 mm, but the differences did not follow any particular trend with regard to dry-matter content (Table 1).

The fraction of oversized wood chips increased with increasing moisture content, and the value for HMW, 2.7 %, was significantly ($p \leq 0.01$) higher than the values for LMW and MMW (Table 1). The overthick fraction was in the range 9–14 %, with HMW exhibiting a significantly higher value. This agrees with the values for average thickness, where HMW also exhibited the highest value and MMW the lowest. HMW showed a significantly ($p \leq 0.01$) higher value for large accept, ~65 %, whereas LMW and MMW both had values around 60 %. Conversely, the fraction of small accept increased with decreasing moisture content (Table 1). The combined effect of this was that there was no significant difference between the assortments with regard to total accept, which was in the range 77–80 % (Table 1).

With regard to the small-sized fractions, pin chips and fines, HMW consistently showed the lowest values (Table 1). For fines, the value for LMW was significantly lower ($p \leq 0.05$) than that for MMW. The combined fraction of pin chips and fines was 8.6 % for LMW, 13.3 % for MMW, and 4.2 % for HMW. These values can be compared with the estimated acceptable range for pin chips and fines in digesters after screening, which is 8–11 % (Hartler 1996). The relatively high fraction of pin chips and fines observed for LMW agrees with the observation that wood with a dry-matter content over 70 % gives increased fraction of pin chips and fines (Brännvall 2009).

In summary, the SCAN size-fraction analysis showed that for large-sized fractions, such as oversized, overthick, and large accept, HMW always exhibited the highest values. In agreement with this, HMW always exhibited lower values than the others for small-sized fractions, such as small accept, pin chips, and fines. In all but two cases, differences between LMW and MMW were not statistically significant even at $p \leq 0.1$ (Table 1).

The average values for length, width, and thickness, as determined using the ScanChip analyzer, are shown in Table 1, whereas the size distribution behind the average values is shown in Figure 2. Although the average length was similar (Table 1) and most of the wood chips had a length in the range 17–25 mm (Figure 2A), the distribution curves indicated differences as the peaks were not superimposed (Figure 2A). With decreasing chip moisture content, the peak of the distribution curve shifted slightly towards greater length (Figure 2A). The average width and distribution curves for width were similar for all assortments (Table 1, Figure 2A), although the peak for LMW shifted somewhat towards greater width (23–24 mm). The range of the average thickness determined using the ScanChip analyzer, 4.0–4.4 mm, was somewhat lower than the range determined using the SCAN method (Table 1). Similar results have been obtained in previous studies in which both the SCAN method and ScanChip analyzer have been used (Gard Timmerfors and Jönsson 2019, Gard Timmerfors et al. 2020). The reason for that is that in the SCAN method the thickest part of the chips determines how the chip is sorted, whereas the ScanChip analyzer determines the average thickness and disregards chips with too big variation. For both methods, the average thickness was smallest for MMW. These chips had smaller average thickness, larger fractions in the range 1–3.5 mm, and smaller fractions that were thicker than 4 mm (Figure 2B).

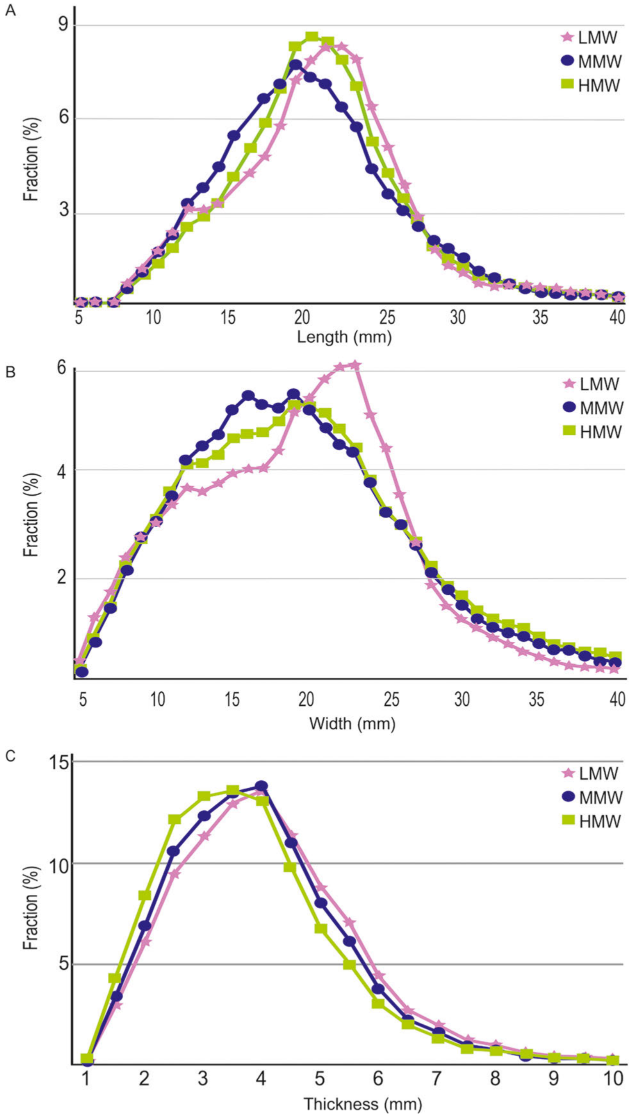

**Figure 2:** Analysis of size distribution of wood chips with different moisture content using the ScanChip analyzer. The figure shows the fractions of wood chips as a function of (A) length, (B) width, and (C) thickness: LMW, solid pink line, filled star (★); MMW, length and thickness, solid blue line, filled circles (●); HMW, length and thickness, solid green line, filled squares (■).

Compared to the SCAN method, size-fraction determination using the ScanChip method typically gave more similar values. A reason for that could be that the ScanChip analysis covered the whole sample, whereas the SCAN method was restricted to a 10-L sample size even if it was repeated four times for each assortment. Nevertheless, the ScanChip analyzer indicated a trend for the combined fraction of pin chips and fines, which was 10.3 % for LMW, 7.3 % for MMW, and 6.5 % for HMW. Thus, both the SCAN method and the ScanChip analyzer indicate that chipping of high moisture content assortments produces less small-sized material.

The carbohydrate composition was analyzed to check for potential differences caused by different growth conditions, different genetic background, and attacks by wood-degrading fungi, as differences in the contents of major constituents, such as carbohydrate and lignin, could potentially affect chipping and cooking results. The fractions of some hemicellulosic constituents, viz. galactan and xylan, were higher in wood with higher moisture content (Table 1). The glucan content, which probably reflects the cellulose content, was highest for MMW, followed by HMW, and LMW. The combined fraction of carbohydrate was slightly larger for MMW, which contained 62.2 % carbohydrate compared to 59.6 % for LMW and 61.6 % for HMW. MMW also had a slightly higher fraction of glucan than LMW and HMW. This could possibly indicate that MMW had slightly higher levels of cellulose, something that potentially could affect yield and viscosity during Kraft pulping.

The pulp yield varied slightly between 46.3–47.8 % (Table 1). The viscosity and the kappa number were similar. For MMW, the ISO brightness was slightly lower than for LMW and HMW, whereas the fiber length was longer.

It remains a possibility that other differences than the moisture content affect the results of the study presented in Table 1 and Figure 2. For example, wood from trees with a higher age might be associated with longer fiber length, lower brightness, and higher pulp yields. Future studies are needed to resolve how differences in age affect wood chip quality and subsequent Kraft pulping when using the new drum- chipping technology.

## Effects of chipping frozen wood at sub-zero temperatures

In the second series of experiments, the settings SL26 and the drum velocities 27, 30, and 33 m $s^{-1}$ were used to investigate the effect of wood being frozen or unfrozen when chipping. Between these assortments, there were only small differences in dry-matter content (46–56 %) and average thickness (5.1–5.5 mm), as determined using SCAN standard methods (Table 2).

According to the SCAN standard method, the fractions of oversized wood chips were ≤1.3 %. There were no significant differences between fractions of oversized wood chips from frozen and unfrozen logs when chipped at the same velocity (Table 2). The fractions of overthick chips were in the range 6.9–11.2 %. In most cases, there were no significant differences between unfrozen and frozen

**Table 2:** Data for wood chips produced using frozen and unfrozen wood logs of Scots pine and settings SL26.[a]

| **Parameter/fraction** | **Def.**[b] | **27 m s$^{-1}$** | | **30 m s$^{-1}$** | | **33 m s$^{-1}$** | |
|---|---|---|---|---|---|---|---|
| | | **Unfrozen** | **Frozen** | **Unfrozen** | **Frozen** | **Unfrozen** | **Frozen** |
| SCAN standard[c] | | | | | | | |
| Dry matter[d] (%) | | 46 ± 1 | | 56 ± 3 | | 52 ± 1 | |
| Thickness[d] (mm) | | 5.2 ± 0.1 | 5.1 ± 0.1 | 5.1 ± 0.1 | 5.5 ± 0.1*** | 5.2 ± 0.3 | 5.2 ± 0.3 |
| Oversized (%) | > Ø45 | 0.4 ± 0.1 | 0.9 ± 1.2 | 1.3 ± 1.3 | ND[f] | 0.5 ± 0.3 | 0.5 ± 0.7 |
| Overthick (%) | > //8 | 8.6 ± 1.8 | 9.2 ± 1.4 | 11.2 ± 0.8 | 10.5 ± 1.3 | 6.9 ± 1.8 | 10.0 ± 1.5* |
| Large accept (%) | > Ø13 | 71.2 ± 3.4 | 72.4 ± 0.5 | 60.5 ± 3.0 | 72.9 ± 1.3*** | 63.7 ± 7.8 | 64.5 ± 0.8 |
| Small accept (%) | > Ø7 | 14.3 ± 2.0 | 12.0 ± 0.3 | 16.0 ± 1.0 | 11.4 ± 0.2*** | 17.6 ± 2.6 | 15.8 ± 0.5 |
| Pin chips (%) | > Ø3 | 4.5 ± 1.2 | 4.5 ± 0.4 | 8.0 ± 1.5 | 4.1 ± 0.2*** | 8.7 ± 2.7 | 7.4 ± 0.5 |
| Fines (%) | < Ø3 | 0.9 ± 0.4 | 1.0 ± 0.2 | 2.9 ± 0.6 | 1.0 ± 0.1*** | 2.5 ± 0.9 | 1.7 ± 0.2 |
| Total accept[e] (%) | | 85.5 ± 4.4 | 84.4 ± 0.4 | 76.6 ± 2.4 | 84.3 ± 1.1*** | 81.4 ± 5.3 | 80.3 ± 1.3 |
| ScanChip analyzer[e] | | | | | | | |
| Length (mm) | | 25.5 | 24.0 | 25.2 | 24.1 | 24.9 | 24.6 |
| Width (mm) | | 22.9 | 22.3 | 22.1 | 23.0 | 21.5 | 21.7 |
| Thickness (mm) | | 4.8 | 4.3 | 5.0 | 4.6 | 4.8 | 4.6 |
| Oversized (%) | > Ø45 | 0.3 | 0.1 | 0.1 | ND[d] | 0.2 | 0.2 |
| Overthick (%) | > //8 | 10.1 | 7.2 | 12.1 | 8.4 | 10.5 | 9.3 |
| Large accept (%) | > Ø13 | 69.2 | 69.7 | 64.9 | 72.0 | 62.4 | 63.5 |
| Small accept (%) | > Ø7 | 15.9 | 17.2 | 15.2 | 14.2 | 18.2 | 18.8 |
| Pin chips (%) | > Ø3 | 4.1 | 5.0 | 6.0 | 4.7 | 6.9 | 6.9 |
| Fines (%) | < Ø3 | 0.6 | 0.8 | 1.6 | 0.8 | 1.9 | 1.2 |
| Total accept[g] (%) | | 85.0 | 86.9 | 80.1 | 86.2 | 80.5 | 82.3 |

[a] Average values and standard deviations for size fraction distribution calculated using SCAN-CM 40:01 or using automated chip analyzer.
[b] Definition: Ø, screen hole diameter in mm; //, screen slot distance in mm.
[c] Significant differences (t-test) comparison between frozen and unfrozen pine for each velocity: $^{***}p \le 0.01$; $^{**}0.01 < p \le 0.05$; $^{*}0.05 < p \le 0.1$.
[d] Average values and standard deviations for dryness (SCAN 39:94) and thickness distribution (SCAN-CM 47:92).
[e] Not detected.
[f] Sum of large and small accept chips.
[g] Average values for length, thickness, and width were calculated using automated chip analyzer.

wood. The fraction of large accept chips was always larger for frozen compared to unfrozen wood, when values for the same velocity are compared. At 30 m s$^{-1}$, this difference was significant ($p \le 0.01$). The trend was the opposite for small accept chips; there was always a larger fraction of small accept for the unfrozen wood (Table 2), and at 30 m s$^{-1}$ the difference was significant ($p \le 0.01$). With regard to the fraction of total accept, the differences between large and small accept cancelled each other, and there were no significant differences between frozen and unfrozen wood. The fraction of total accept was in the range 76.6–85.5 %, and the highest values (84.4–85.5 %) were achieved at a velocity of 27 m s$^{-1}$ (Table 2). Comparing frozen and unfrozen wood, there were no clear trends for the fractions of pin chips (4.1–8.7 %) and fines (0.9–2.9 %). The lowest values for pin chips (4.5 %) and fines (0.9–1.0 %) were achieved at the velocity 27 m s$^{-1}$, resulting in combined fractions of pin chips and fines being only 5.4–5.5 %.

The average values for length, width, and thickness, as determined using the ScanChip analyzer are shown in Table 2, whereas the size distribution behind the average values is shown in Figure 3. The average length was in the range 24.0–25.5 mm, and slightly lower for frozen than for unfrozen wood (Table 2). This slight length difference is also seen in Figure 3A, which shows that the frozen wood exhibited higher values than unfrozen wood in the range 10–22 mm and lower values in the range 25–35 mm. The average width was similar (21.5–23.0 mm) and there was no difference between frozen and unfrozen wood (Table 2). The average thickness determined using the ScanChip analyzer (4.3–5.0 mm) was somewhat lower than the corresponding values obtained with the SCAN method (5.1–5.5 mm) (Table 2). The ScanChip data point towards a slightly lower average thickness for frozen wood, which is also supported by thickness distribution data in Figure 3C showing larger fractions of wood chips below 4 mm for frozen wood and smaller fractions above 4 mm. This obser-

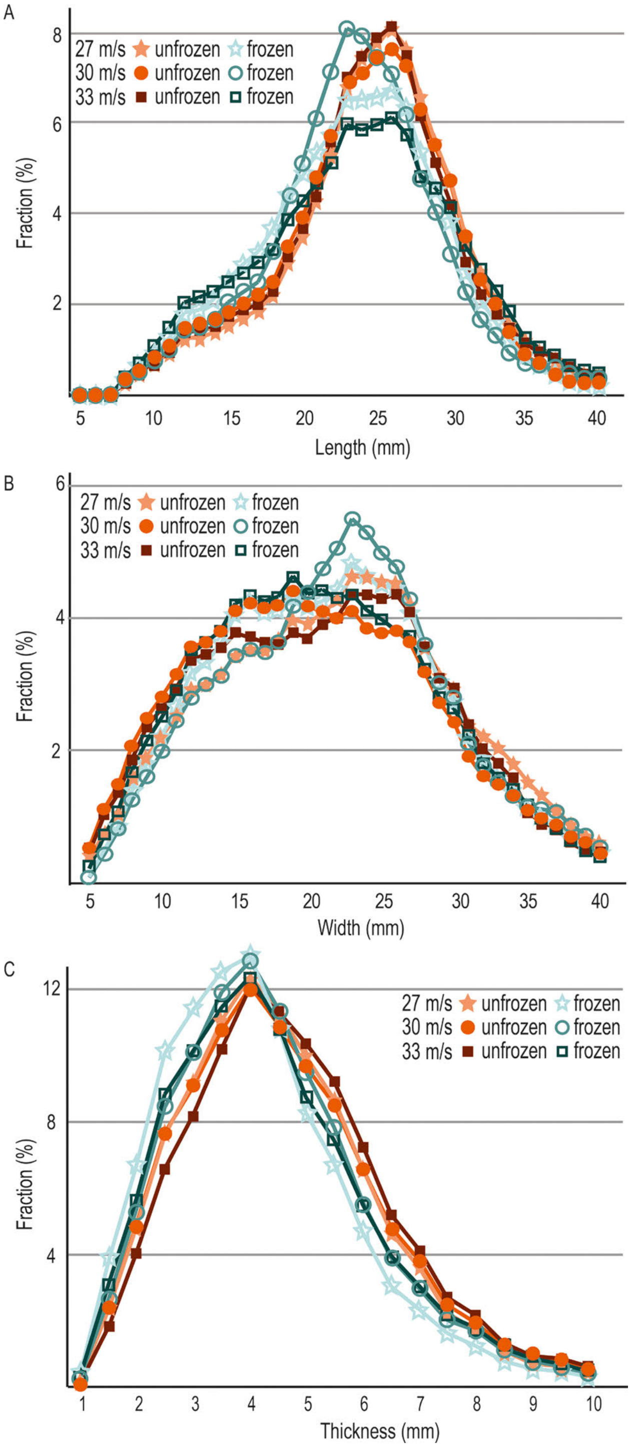

**Figure 3:** Analysis of size distribution of wood chips with different moisture content using the ScanChip analyzer. The figure shows the fractions of wood chips as a function of (A) length, (B) width, and (C) thickness: 27 m s$^{-1}$, unfrozen wood logs, solid light orange line, filled star (★); 27 m s$^{-1}$, frozen wood logs, solid light turquoise line, open star (☆); 30 m s$^{-1}$, unfrozen wood logs, solid orange line, filled circles (●); 30 m s$^{-1}$, frozen wood logs, solid turquoise line, open circles (○); 33 m s$^{-1}$, unfrozen wood logs, solid dark orange line, filled squares (■); 33 m s$^{-1}$ frozen wood logs, solid dark turquoise line, open squares (□).

vation agrees with ScanChip data showing slightly larger fractions of overthick wood chips for unfrozen logs (Table 2). As for the SCAN method, the ScanChip analyzer did not show any clear differences between frozen and unfrozen wood for pin chips and fines.

Hernández et al. (2014) reported on changes in the mechanical properties of frozen black spruce, which could affect length and thickness distribution. Hartler (1996) observed that the pin chip fractions in industrial wood chip samples were almost twice as high when the temperature was −15 °C compared to +15 °C. There was also a trend for the fractions of fines, which were higher during cold conditions in February than during warm conditions in May (Hartler 1996). Surprisingly, our data do not show larger fractions of pin chips and fines for frozen wood compared to the unfrozen. More studies are needed to understand if this is due to the use of different wood-chipping technologies in different studies or to other factors. An increase of the fractions of pin chips and fines during winter could possibly be due to more wear on the knives when more sand and small stones get stuck on wood logs because of the frost, as less sharp knives would result in increased fractions of pin chips and fines. Alternatively, this result could be a consequence of that this study was based on drum-chipping technology rather than disc-chipping technology. Biological variation, such as regarding the occurrence of knots, might also play a role, as has been observed previously in studies based on chipping-canters (Grubii et al. 2019).

## Effects of using different wood species

In the third series of experiments, the settings SL25 and SL19 were used with a drum velocity of 30 m s$^{-1}$ to investigate chipping of trees from four different wood species, viz. aspen, birch, pine, and spruce (Table 3). The dry-matter content was in the range 42–53 %. Within the same setting length, the average thickness, as determined by using the SCAN method, was higher for the hardwood species than for the softwood species (Table 3). The average bulk density was in the range 126–149 kg m$^{-3}$. Within the same setting length, birch always exhibited the highest value (Table 3). This can be related to the relatively high basic density of birch wood (480–550 kg m$^{-3}$) compared to many other wood species, such as quaking aspen (350–400 kg m$^{-3}$), Norway spruce (380–390 kg m$^{-3}$), and Scots pine (390–420 kg m$^{-3}$) (Ek et al. 2009).

Within the same setting length, the fractions of oversized and overthick wood chips were always higher for hardwoods than for softwoods (Table 3). Although this was

**Table 3:** Data for wood chips produced using frozen wood logs of different tree species (SL23 or SL19 using velocity 30 m $s^{-1}$).[a]

| Parameter/fraction | Def.[b] | SL23 | | | | SL19 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Aspen | Birch | Pine | Spruce | Aspen | Birch | Pine | Spruce |
| SCAN standard[c] | | | | | | | | | |
| Dry matter (%) | | $49 \pm 1^{***}$ | $48 \pm 1^{***}$ | $48 \pm 1^{**}$ | $42 \pm 1$ | $52 \pm 1^{***}$ | $53 \pm 2^{***}$ | $44 \pm 1^{***}$ | $43 \pm 1$ |
| Thickness (mm) | | $5.0 \pm 0.5^{**}$ | $4.7 \pm 0.2^{**}$ | $4.5 \pm 0.2^{***}$ | $4.1 \pm 0.2$ | $3.9 \pm 0.2^{**}$ | $3.8 \pm 0.2^{**}$ | $3.6 \pm 0.2$ | $3.2 \pm 0.5$ |
| Bulk density (kg $m^{-3}$) | | $126 \pm 2^{***}$ | $138 \pm 5^{**}$ | $131 \pm 2^{***}$ | $135 \pm 2$ | $138 \pm 2^{**}$ | $149 \pm 2^{***}$ | $136 \pm 2$ | $137 \pm 2$ |
| Oversized (%) | > Ø45 | $1.3 \pm 1.8$ | $1.7 \pm 1.8$ | $0.2 \pm 0.4$ | $0.3 \pm 0.4$ | $0.7 \pm 0.7^{*}$ | $0.1 \pm 0.2$ | ND[d] | ND |
| Overthick (%) | > //8 | $12.9 \pm 0.8^{**}$ | $8.0 \pm 1.0^{*}$ | $5.3 \pm 1.3$ | $5.2 \pm 1.3$ | $4.0 \pm 0.7$ | $3.6 \pm 0.8$ | $2.7 \pm 1.2$ | $3.1 \pm 0.9$ |
| Large accept (%) | > Ø13 | $68.3 \pm 2.9$ | $54.8 \pm 3.4$ | $74.8 \pm 1.9^{*}$ | $54.8 \pm 15.7$ | $70.1 \pm 1.2^{***}$ | $67.6 \pm 0.6^{***}$ | $47.6 \pm 5.7$ | $36.2 \pm 6.9$ |
| Small accept (%) | > Ø7 | $11.4 \pm 2.7^{**}$ | $23.7 \pm 0.4$ | $13.2 \pm 0.8^{*}$ | $24.2 \pm 8.2$ | $20.3 \pm 0.6^{***}$ | $23.1 \pm 0.3^{***}$ | $35.2 \pm 3.5^{*}$ | $39.3 \pm 2.7$ |
| Pin chips (%) | > Ø3 | $5.1 \pm 1.8^{*}$ | $10.3 \pm 0.6$ | $5.4 \pm 0.6$ | $13.4 \pm 8.8$ | $4.3 \pm 0.3^{**}$ | $5.0 \pm 0.2^{**}$ | $12.9 \pm 2.9$ | $19.0 \pm 4.8$ |
| Fines (%) | < Ø3 | $0.8 \pm 0.1^{***}$ | $1.6 \pm 0.6$ | $0.8 \pm 0.8^{*}$ | $2.1 \pm 0.2$ | $0.7 \pm 0.1$ | $0.6 \pm 0.1$ | $1.5 \pm 0.4$ | $1.5 \pm 1.4$ |
| Total accept[e] (%) | | $79.8 \pm 0.3$ | $78.5 \pm 3.8$ | $88.0 \pm 1.9^{*}$ | $79.1 \pm 7.8$ | $90.4 \pm 1.3^{**}$ | $90.7 \pm 0.7^{**}$ | $82.8 \pm 2.2^{*}$ | $75.5 \pm 4.4$ |
| ScanChip analyzer[f] | | | | | | | | | |
| Length (mm) | | 23.7 | 21.9 | 21.4 | 20.5 | 16.9 | 16.8 | 15.6 | 15.9 |
| Width (mm) | | 24.7 | 19.8 | 20.9 | 17.6 | 19.6 | 18.6 | 16.5 | 16.9 |
| Thickness (mm) | | 4.4 | 4.0 | 3.7 | 3.9 | 3.3 | 3.0 | 2.8 | 2.8 |
| Oversized (%) | > Ø45 | 0.51 | 0.3 | 0.3 | 0.2 | 0.4 | 0.1 | ND | ND |
| Overthick (%) | > //8 | 11.8 | 7.0 | 4.3 | 4.2 | 2.6 | 1.8 | 2.0 | 2.6 |
| Large accept (%) | > Ø13 | 67.5 | 58.2 | 66.5 | 43.6 | 57.0 | 50.8 | 31.5 | 31.9 |
| Small accept (%) | > Ø7 | 12.5 | 24.0 | 20.9 | 31.2 | 32.1 | 36.7 | 42.8 | 40.8 |
| Pin chips (%) | > Ø3 | 4.9 | 9.6 | 7.1 | 18.5 | 7.5 | 9.8 | 21.9 | 21.5 |
| Fines (%) | < Ø3 | 0.9 | 0.9 | 0.9 | 2.3 | 0.5 | 0.8 | 1.8 | 3.3 |
| Total accept[e] (%) | | 79.9 | 82.2 | 87.4 | 74.8 | 89.3 | 87.5 | 74.3 | 72.7 |

[a] Average values and standard deviations for size fraction distribution calculated using SCAN-CM 40:01 or using automated chip analyzer.

[b] Definition: Ø, screen hole diameter in mm; // screen slot distance in mm.

[c] Significant differences (*t*-test) compared to spruce wood chips at the same length setting (SL23 or SL19) are indicated: $^{***}p \le 0.01$; $^{**}0.01 < p \le 0.05$; $^{*}0.05 < p \le 0.1$. Average values and standard deviations for dryness (SCAN 39:94), bulk density (SCAN-CM 46:92), and thickness distribution (SCAN-CM 47:92).

[d] Not detected.

[e] Sum of large and small accept chips.

[f] Average values for length, thickness, and width calculated using automated chip analyzer.

not always statistically significant for the SCAN analysis, the same pattern emerged also for the ScanChip analysis (Table 3). That observation also agreed with the values for average thickness (Table 3), which were higher for hardwood species than for softwood species. The thickness distribution according to the ScanChip analyzer showed that chipping of aspen, in particular, resulted in larger fractions of thicker wood chips than the other species (Figure 4C). For all wood species, the setting SL19 showed a more narrow size distribution than SL23 (Figure 4).

For the Kraft pulping industry, the large size accept fraction is particularly important. A decrease of the average length of the wood chips might lead to a smaller fraction of large accept chips, due to an average smaller diagonal. Together with the thickness the diagonal will determine which slots the wood chips will pass defining the difference between large and small accept chips. For softwood species, pine and spruce, the fractions of large accept decreased and the fractions of small accept increased when the setting length was changed from SL23 to SL19 (Table 3). For the hardwood species, aspen and birch, there was no such trend (Table 3). For SL19 and according to the SCAN method, the approx. accept fractions for aspen and birch were: large accept 70 %, small accept 20 %, and total accept 90 %. The ScanChip analyzer showed similar results, although the fractions of large accept were somewhat lower and the fractions of small accept somewhat higher.

Although short average chips length would result in abnormally large fractions of pin chips and fines, the high standard deviation for spruce and the setting SL23 made the results from the setting SL19 more easily interpreted (Table 3). In summary, the SCAN size-fraction analysis showed that for large-sized fractions, such as oversized and overthick chips, hardwoods exhibited higher values than softwoods. In agreement with this, hardwood ex-

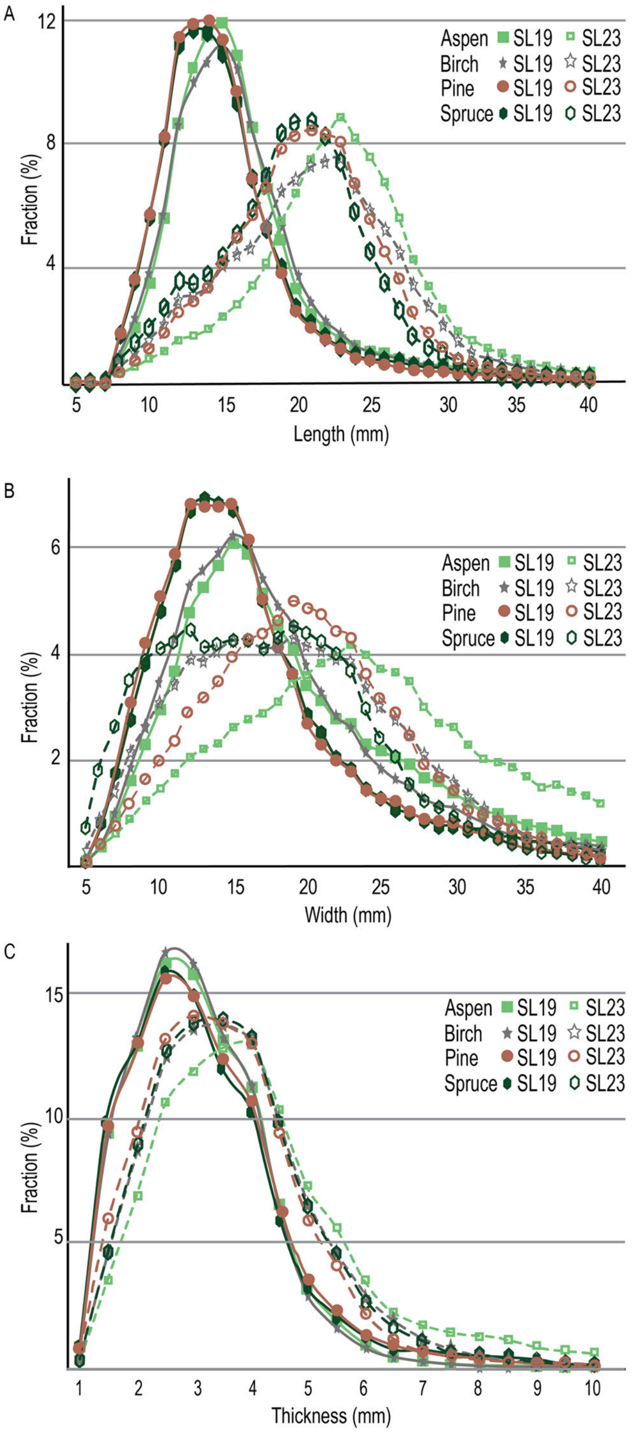

**Figure 4:** Analysis of size distribution of wood chips from different wood species using the ScanChip analyzer. The figure shows the fractions of wood chips as a function of (A) length, (B) width, and (C) thickness. Aspen, SL19, solid light green line, filled squares (■); aspen, SL23, dashed light green line, open squares (□); birch, SL19, solid gray line, filled star (★); birch, SL23, dashed gray line, open star (☆); pine, SL19 solid brown line, filled circles (●); pine, SL23, dashed brown line, open circles (○); spruce, SL23, solid dark green line, filled hexagon (⬢); spruce, SL23, dashed dark green line, open hexagon (⬡).

hibited lower values than softwood with respect to pin chips.

The average values for length, width, and thickness, as determined using the ScanChip analyzer, are shown in Table 3, whereas the size distribution behind the average values is shown in Figure 4. For each setting length, the values for average length were higher for the hardwoods than for the softwoods (Table 3). This is supported by Figure 4A. The figure also shows that the softwood species exhibited very similar length distribution whereas the hardwood species differed somewhat, especially for SL23, where the curve for aspen shifted towards longer lengths compared to the curve for birch.

Table 3 shows that for each setting, aspen wood chips always exhibited the largest average width. The details are shown in Figure 4B, which reveals that the width distribution was more even for SL19 than for SL23. For SL19, the width distribution of the softwoods were very similar, and distinctly different from the hardwoods (Figure 4B). As for length distribution of SL23, the curve for aspen shifted towards higher values compared to the curve for birch.

The average thickness determined using the ScanChip analyzer was somewhat lower than for SCAN method. However, the ScanChip values for average thickness agree with the SCAN method data in the sense that for each setting the chips from the hardwood species were thicker than the chips from the softwood species (Table 3). Such differences between the analysis methods have been noticed previously in this study. The distribution can been seen in Figure 4C. For SL19 the distribution was similar for the four wood species, although more narrow for the hardwoods. For SL23, birch, pine and spruce show similar distributions, whereas aspen differs somewhat (Figure 4C).

A comparison of wood chips using six length settings indicated that the average thickness of southern red oak wood chips was larger than that of loblolly pine wood chips (Twaddle 1997). This would agree with our results in the sense that hardwood gave thicker wood chips than softwood. Pine also exhibited smaller variation in thickness compared to three hardwood species (Twaddle 1997), but no similar trend is visible in our data (Figure 4C). As there were no measurements of the actual length of the wood chips or of the average size (Twaddle 1997) and as chipping technology and evaluation methods vary, the data in the two studies are difficult to compare.

## Conclusions

The investigation of different wood qualities and wood species using the novel type of drum chipper resulted in clear-cut differences with regard to the moisture content of the wood and with regard to comparison of different species of hardwood and softwood, whereas a comparison of frozen and unfrozen softwood resulted only in subtle differences. When fast-growing moist wood was chipped, the average thickness increased, which was also the case for dry wood logs. When hardwood and softwood were chipped using the same settings, the average thickness of hardwood chips was larger than that of softwood chips. Thus, in order to maintain the same thickness, the knife settings would need to be changed when changing between softwood and hardwood. Utilization of large quantities of dry wood or fast-growing moist wood would also require a change in knife setting in order to maintain the average thickness.

As expected, larger fractions of pin chips and fines were generated from drier wood qualities. In the comparison of different wood species, the fraction of pin chips and fines was low for hardwood species and particularly for aspen. Further studies will be needed to evaluate the optimal settings for each wood quality and wood species, and to understand if unexpected results, such as the absence of increase in the fractions of pin chips and fines for frozen wood, can be attributed to the new drum-chipping technology or to other factors. A direct comparison of the results of chipping of different segments of the same wood logs using traditional disc-chipping technology and the novel drum-chipping technology would be of interest. Studies of wood with structural differences, for example with regard to the occurrence of knots, would be of interest for understanding the formation of overthick and oversized wood chips. Future work is also needed to address potential effects of damage caused by rot and insects on wood chip quality, impregnation, and cooking.

**Acknowledgments:** We are grateful to Sten Häggström, Multi Channel Sweden AB, for help with wood chipping and for the supply of wood logs to the comparison of moisture content and frozen wood, and to Gunnar Kalén and Markus Segerström at the BTC of the Swedish University of Agricultural Sciences in Umeå for help with handling of wood logs used in the tree species comparison. We also want to thank Metsä Board Husum for access to their ScanChip system, and to Domsjö Fabriker AB for access to the wood yard.

**Funding:** This research was supported by the Swedish Energy Agency (P40512-1), Bio4Energy (https://www.bio4energy.se/), the Kempe Foundations, and the Industrial Doctoral School (IDS) of Umeå University.

**Conflict of interest:** The authors declare no conflicts of interests.

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