Effect of Chipper Knife Wear and Operating Parameters on the Dimensional Fractionation of Wood Chips in an Industrial Chemical Pulp Production Line – Case Study

Mariusz Reczulski

Dimensional uniformity of wood chips is essential for stable delignification, and knife wear in a disc chipper is the primary factor that deteriorates chip quality. In this study, changes in particle size distribution (PSD) of pine wood chips were examined at three points along an industrial chip-processing line, assessing the effects of knife sharpness, knife–anvil clearance, and transport and screening operations. Sharp knives combined with a narrow knife–anvil gap produced the lowest proportions of oversized and fine fractions, whereas progressive dulling significantly increased chip susceptibility to cracking during subsequent handling. The results indicated a need for more frequent knife maintenance and proper adjustment of the knife–anvil clearance to ensure stable chip quality under industrial operating conditions.

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Contact information: Centre of Papermaking and Printing, Lodz University of Technology, 93-005 Lodz, Poland; Corresponding author: mariusz.reczulski@p.lodz.pl

INTRODUCTION

The production of high-quality pulp depends strongly on the dimensional uniformity and structural integrity of wood chips fed into the digester. Chip geometry—particularly length and thickness—must remain within narrow tolerances to ensure even chemical penetration and predictable delignification; oversized chips and excessive fines impair cooking uniformity and can cause mechanical disturbances in continuous digesters (Hartler 1986, 1997). Although batch digesters are more tolerant to small fractions, maintaining a high proportion of acceptable chips remains essential to stable mill operation. Chip properties are governed both by intrinsic characteristics of the raw material—such as moisture content, structural homogeneity, and temperature—and by operating conditions of the chipping system, including chipper design, cutting angle, and knife condition (Hartler 1986; Hernández *et al.* 2014; Naylor and Hackney 2013). In addition to these factors, broader variability among lignocellulosic feedstocks, including differences between wood-based and non-wood materials, also affects pulping behavior and kraft pulp quality, as demonstrated in comparative studies of unbleached pulps from diverse sources (Danielewicz *et al* 2021.).

Knife sharpness is one of the most influential parameters controlling chip formation. Properly sharpened knives reduce cutting forces, lower chip deformation, and yield more uniform geometry (Smith *et al.* 1999; Naylor and Hackney 2013). Decreasing the cutting-edge angle improves thickness uniformity by reducing pressure at the knife–wood interface, yet it can compromise edge durability and accelerate wear (Hartler 1986;

Uhmeier 1995). As wear progresses, the cutting mechanism transitions from clean shearing to crushing/grinding, increasing specific energy and degrading chip structure (Facello *et al.* 2013; Spinelli *et al.* 2013). Field studies have consistently shown that dull knives drive productivity losses and chip-quality decay; frequent wet sharpening mitigates these effects and lowers total chipping cost (Spinelli *et al.* 2014; Mihelič *et al.* 2024). The response of different species and wood conditions further modulates chip size distribution via anatomy, density, moisture, and temperature (Hernández *et al.* 2014; Zhu *et al.* 2019).

Recent investigations have characterized knife wear using complementary approaches. Krilek *et al.* (2023) combined gravimetry with 3D edge scanning, reporting a maximum edge recession of 240 µm and average mass loss of 0.58 g; microstructural and spectroscopic analyses revealed cracking/abrasive wear and Al–Cr–N particles in wood fragments from AlCrN-coated knives. Similar wear mechanisms (cracking, abrasion, micro-cutting/ploughing) have been documented for chipper-canter knives (Heidari *et al.* 2013). At an operational scale, progressive wear increases chipping time per cycle. Dry sharpening offers partial recovery but remains inferior to wet sharpening or full knife changeover (Mihelič *et al.* 2024; Spinelli *et al.* 2014).

Particle size distribution (PSD) is most often measured by sieve analysis. In energy and small-scale contexts, ISO 17225-4 limits fines (≤ 3.15 mm) and defines particle classes; dull knives raise fines and produce more fractured shapes (Kuptz and Hartmann 2022; Nati 2010). In controlled and semi-industrial trials, dull blades reduce throughput, raise fuel consumption, and shift PSD toward higher fines and fewer accepts (Nati 2010; Spinelli *et al.* 2013). In disc-chipper applications, sieve-based PSD has been used to link knife geometry and process parameters to the share of small fractions and overall granulometric homogeneity (Krilek *et al.* 2024a, 2024b).

Operational variability further complicates interpretation. Drum and disc chippers differ in knife configuration, cut length, and screening (Mihelič *et al.* 2024; Spinelli *et al.* 2013). Disc chippers operate over diverse rotational speeds, cutting angles, and knife–anvil clearances; industrial studies demonstrate that clearance angle and cutting speed critically influence chip length and fines/pins content (Reczulski 2016, 2018, 2020). Knife materials range from tool steels to coated systems (AlCrN) that enhance wear resistance (Heidari *et al.* 2013; Krilek *et al.* 2023). Beyond mechanical aspects, vibration-based monitoring can be considered as a potential approach for inferring knife wear in real time.

It is hypothesized that progressive knife wear in a disc chipper leads to systematic deterioration of particle size distribution of pine wood chips along the chip handling line, resulting in an increased share of fines and a reduced proportion of acceptable chips at downstream process stages.

Despite extensive research on chip formation, knife wear, and chipper performance, little is known about how PSD evolves along the complete handling line, from chipper discharge through conveying/screening to final pile. This gap is critical because chip quality at the digester inlet reflects the combined performance of chippers, conveyors, screens, and pile management; degradation can occur downstream even if chipping is optimized (Hartler 1986; Rahman *et al.* 2020; Reczulski 2018, 2020).

This study evaluated the effect of knife wear in a disc chipper on the PSD of pine wood chips at multiple points along an industrial processing line. Conducted in pulp mill, it linked knife condition to PSD evolution across the production chain, providing practice-relevant guidance for chip quality control and maintenance strategies under real operating conditions (Krilek *et al.* 2024a,b; Mihelič *et al.* 2024; Reczulski 2016, 2018, 2020).

MATERIAL AND METHODS

Experimental Design

The study included three chipper operating conditions (Stages I–III) and three sampling locations along the production line (after the cyclone (A), screening (B), and pneumatic conveying (C)). The main variables were knife condition (new or worn) and knife–anvil clearance, while the analyzed outcome was particle size distribution expressed as mass fractions. For each operating condition and sampling location, one composite sample was collected and divided into ten analytical subsamples, which were analyzed separately to assess result repeatability.

Industrial Wood Chip Production Line

The industrial wood-chip production line used in this study is shown in Fig. 1. Logs leaving the debarker are transported by a conveyor to the disc chipper, where they are converted into wood chips. The chips are pneumatically conveyed to the cyclone and next discharged onto the screening machine. After size classification, the accepted fraction is transported by a pneumatical conveyor to the wood-chip storage yard.

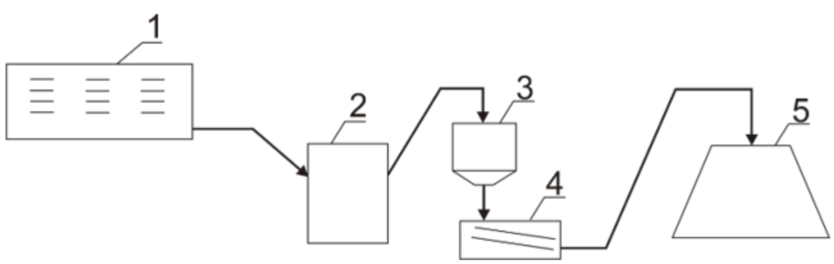

Fig. 1. The diagram of the production of chips of pine pulpwood: 1 – debarker, 2 – helical disc chipper, 3 - cyclone, 4 - screening machine, 5 – wood chip storage yard

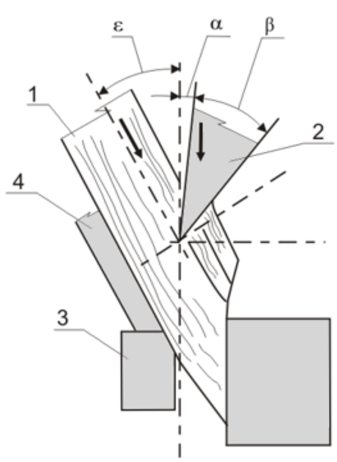

Fig. 2. The cutting parameters of the disc chipper, 1 - log, 2 - knife, 3 -anvil, 4 - spout
α- clearance angle (pull-in angle), ε - spout angle, β - edge angle

The chipping process was carried out using a Carthage–Norman helical disc chipper (Fig. 2). The disc had a diameter of 2440 mm and carried 15 knives. The rotational speed was 370 rpm, the motor power was 630 kW, and the spout angle ε was 38°. The chipper is equipped with a profiled disc featuring a variable clearance angle along the length of the knife, ranging from 3°25′ to 1°40′. The wood feeding system consisted of an inclined top infeed spout, while the chip discharge was directed upward. The nominal capacity of the chipper was 400 m^3/h of chips. Knife replacement took place every 8 h, and one complete knife set was used for the entire study.

The knife edge angle β was measured at three positions along the knife using a universal protractor (±10′). The measurement positions were located near the disc center (in), at mid-length of the knife corresponding to the mean cutting radius (cent), and near the outer edge of the disc (out).

Five measurements were taken at each position and averaged. Knife dimensions (610 × 127 × 12.7 mm) were measured with a caliper (±0.1 mm). The knife–anvil clearance was measured using a feeler gauge, giving an initial range of 1.0 to 1.8 mm (mean 1.4 mm), which was later reduced to 0.4 to 0.6 mm for optimized operation.

Downstream of the chipper, chips were pneumatically conveyed to a cyclone separator with the same throughput capacity as the chipper. The external diameter of the cyclone was D = 3386 mm. At the bottom of the cyclone, a screw feeder was installed, operating at three selectable speeds depending on the degree of cyclone filling.

The industrial chip screen used for chip classification had the same throughput capacity as the previous units. It was an octagonal KMW vibrating screen suspended on four hangers. The upper deck was equipped with square apertures of 55 mm (open area 62%), while the lower deck consisted of round openings with a diameter of 5 mm (open area 49%). The screen was driven by a gear-motor with a 7.5 kW electric motor operating at 178 rpm.

The pneumatic transport system conveying chips from the chipper area to the storage yard had the same nominal capacity as the chipper. The pipeline length was 287 m, with a vertical lift of 23 m. The total change of flow direction along the pipeline corresponded to a cumulative deflection angle of 422°.

Sampling

Scots pine (*Pinus sylvestris*) logs of 70 to 80 mm diameter were processed. Chip samples were collected from three points along the production line: after the cyclone, after the screening machine, and after pneumatical transport to the storage pile. Due to chipper design, sampling immediately after the cutting system was not possible. Composite samples (3 to 5 kg) were collected in polyethylene bags. Three stages of tests were carried out under different technical conditions of the chipper.

The samples collected after the screening machine and after the pneumatical conveyor transporting the chips to the storage yard contained only the acceptable fraction, *i.e.*, chips that met the dimensional criteria of the screen. In contrast, the samples collected after the cyclone included the full spectrum of particle sizes, as no classification had yet occurred at that stage.

The chip-size distribution was analyzed under three chipper operating conditions corresponding to successive stages of the study and to changing technical parameters of the machine. Sampling was performed as point sampling (instantaneous sampling) and carried out as quickly as possible after the chipper reached the target operating state. This was done in order to accurately capture the effect of knife dulling and knife–anvil clearance on chip quality.

In the first stage, the tests were conducted under the existing operating conditions of the production line. Samples were collected immediately after an 8-hour chipper operating cycle, when the knives were markedly dull and the knife–anvil clearance was approximately 1.4 mm. In the studied mill, chipper knives are routinely replaced after each 8-h operating shift, which represents standard industrial practice. Sampling was carried out as quickly as possible to reflect the actual wear state of the knives during normal operation. In the second stages, a freshly sharpened knife set was installed, and the knife–anvil clearance was reduced to approximately 0.5 mm. Samples were taken directly after the chipper reached stable operating conditions with the new knives, allowing the determination of the reference chip-size distribution under optimal cutting parameters.

In the third stages, samples were collected after another 8-hour operating cycle using the same previously sharpened knife set, with the knife–anvil clearance maintained at 0.5 mm. The third stage was designed to separate the effect of knife sharpness from that of knife–anvil clearance. Keeping the clearance constant while allowing knife wear made it possible to evaluate the impact of knife dulling on particle size distribution independently.

Sampling was again performed immediately after the planned operating time had elapsed, enabling assessment of the effect of knife dulling at a small, optimized clearance.

Sieve Analysis

Wood samples were collected in accordance with TAPPI T257, while the fractional size distribution was determined using a vibrating screen equipped with sieves of Ø32, Ø16, Ø6, and Ø3 mm. In each test series, approximately 3 to 5 kg of chips were collected at once into a single bag immediately after the chipper reached its target operating state. The material was then homogenized through thorough, gentle mixing and subsequently divided by quartering until ten analytical portions were obtained. From each portion, a subsample of 3.000 kg ± 0.010 kg was weighed for an individual sieve analysis; every tenth sample was additionally analyzed in duplicate.

Each portion was screened for 10 minutes at a constant vibration amplitude and frequency. After screening, each sieve and the bottom pan were weighed with an accuracy of ±1 g, and the results were expressed as a percentage of the initial sample mass (0.1% resolution). Visible foreign contaminants were removed and documented. Mass recovery was monitored and required to fall within the range of 99.0 to 100.5%, in accordance with the criteria of the relevant standards.

The mass share of each size fraction P_i was calculated using Eq. 1,

$$P_i = \frac{m_i}{m_0} \times 100\% \quad (1)$$

where m_i is the mass retained on sieve i and m_0 is the initial sample mass (3000 g).

Moisture content was determined gravimetrically. Fresh sample mass m was recorded before drying, and dry mass $m_s$after drying at 103 to 105°C to constant mass (change <0.002 g). Moisture content was calculated as,

$$W = \frac{m - m_s}{m} \cdot 100\% \quad (2)$$

where m is the sample mass before drying (g) and m_s is the sample mass after drying (oven-dry mass) (g).

For each operating condition and sampling location, one composite sample was divided into ten analytical subsamples. Mean values and standard deviations were calculated based on these subsamples. Statistical significance of differences in particle size distribution between operating conditions and process stages was evaluated using analysis of variance (ANOVA) with a significance level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

The sharpness angles of the knives are known to play a crucial role in the wood-cutting process. A reduction in the β angle decreases the cutting resistance generated during chipping and, consequently, reduces the energy consumption required for the process (Hartler 1996). The results of the knife sharpness angle (*β*) measurements are presented in Fig. 3. The measurements revealed noticeable differences in the sharpness angle values along the knife edge. This variability indicates non-uniform edge geometry, which may result from uneven sharpening or localized wear along the cutting edge.

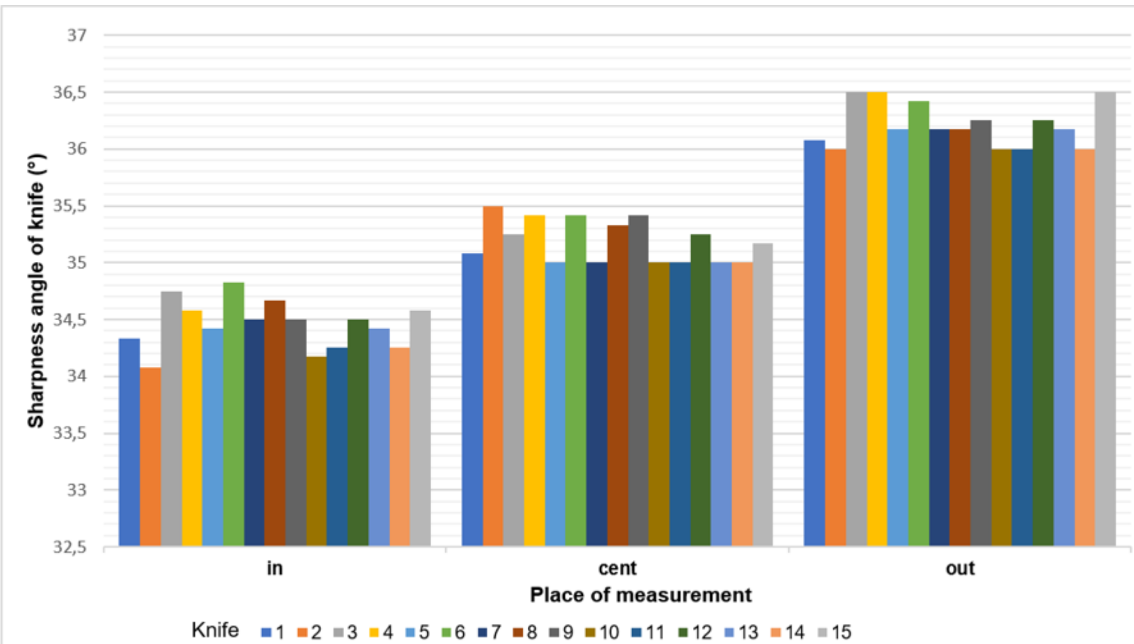

Fig. 3. Average values of knife sharpness angle (*β*) measured for worn knives corresponding to stage I of the study (after 8 h of operation), where "in" is the measurement position near the disc center, "cent" is the measurement position at the mid-length of the knife, and "out" is the measurement position near the disc edge

Measurements were also taken to determine the projection length of the cutting edges of each knife relative to the front surface of the disc. This value was measured using a gauge mounted on the arm of a tripod, which was fixed at a constant reference point on the chipper housing. For each knife, five measurements were performed. The difference in the projection length of any knife relative to the first knife did not exceed 0.1 mm.

The measurements of the chip size distribution and wood moisture content along the production line are presented in Table 1. The results show that the accept fractions (16 and 6 mm) constitute the dominant share of the chip mass, while the proportion of fines

(<3 mm) varies between operating stages and sampling locations. Table 2 summarizes the Coefficient of Variation (CV, %) for all chip fractions, indicating higher variability for the oversize and fine fractions compared to the accept fractions.

Table 1. Results of Measurements of Chip Size Distribution

Dimensions of the Holes in the Sieves (mm)	Particle Size Distribution of Wood Chips (average value), % Stage of the Study									Notes
	I			II			III			
	A	B	C	A	B	C	A	B	C	
32	2,8 (0.6)	1.7 (0.3)	1.4 (0.7)	1.7 (1.0)	1.3 (0.1)	1.3 (0.6)	2.4 (0.4)	1.6 (0.3)	1.3 (0.1)	Oversize fraction
16	45.9 (0.6)	42.5 (2.5)	38.9 (2.1)	48.5 (1.8)	46.4 (0.8)	44.0 (0.4)	46.1 (1.6)	44.1 (1.3)	40.5 (0.6)	Accept fraction (desired)
6	46.0 (0.1)	52.9 (1.0)	57.0 (2.5)	46.5 (2.3)	50.2 (1.0)	51.9 (2.6)	46.6 (1.4)	51.7 (1.1)	55.4 (0.8)	Accept fraction (fraction too small)
<3	5.3 (1.0)	2.9 (1.3)	2.7 (1.2)	3.3 (1.2)	2.1 (0.6)	2.8 (1.2)	4.9 (1.0)	2.6 (0.8)	2.8 (1.1)	Absolutely harmful fraction (pins and fines)
Moisture content of wood, %	46.5	46.5	46.5	44.8	44.8	44.8	44.6	44.6	44.6	

( ) Standard deviation

The following section provides a description of the sampling locations along the production line and the technical condition of the chipper.

Sampling locations (series):

A – after the cyclone,
B – after the screening machine,
C – after the transport of chips to the storage pile.

Chipper operating conditions during the study stages:

Stage I – knives worn after 8 hours of operation; knife–anvil gap of 1.4 mm.
Stage II – new knives; knife–anvil gap of 0.5 mm.
Stage III – knives worn after 8 hours of operation; knife–anvil gap of 0.5 mm.

Table 2. Coefficient of Variation (CV, %) for All Chip Fractions, Study Stages, and Sampling Locations

Fraction	Stage	A (CV, %)	B (CV, %)	C (CV, %)
32 mm	I	21.43	17.65	50.00
	II	58.82	7.69	46.15
	III	16.67	18.75	7.69
16 mm	I	1.31	5.88	5.40
	II	3.71	1.72	0.91
	III	3.47	2.95	1.48
6 mm	I	0.22	1.89	4.39
	II	4.95	1.99	5.01
	III	3.00	2.13	1.44
<3 mm	I	18.87	44.83	44.44
	II	36.36	28.57	42.86
	III	20.41	30.77	39.29

Statistical analysis using analysis of variance confirmed that both the chipper operating stage and the sampling location along the production line had a statistically significant effect on particle size distribution ($p < 0.05$). Significant differences were observed particularly for the fine fraction (<3 mm) and for the accept fractions ($p < 0.05$). These differences were consistent with the trends presented in Tables 1 and 2.

The deformation of wood chips during cutting depends not only on the design and operating parameters of the chipper but also on the physical properties of the wood, including compressive strength along the fibres. According to Vörös *et al.* (2019) and Fu *et al.* (2023), increasing wood moisture reduces both compressive and bending strength, thereby increasing susceptibility to chip cracking. In the present study, moisture content differed only slightly along the production line (1.9%), indicating that such a small variation could not significantly influence the particle-size distribution observed at the individual sampling points.

Measurements of the knife sharpness angle β were carried out at three positions along the knife length (inner, centre, outer). Considerable variation was found, reaching up to 75′ in the inner section and up to 50′ in the centre and outer sections. These differences imply non-uniform cutting conditions across the knife width, which inevitably affect chip formation and contribute to variability in chip-size distribution.

When interpreting the results, it is essential to compare data only from identical sampling locations. Chips were therefore collected at three points along the production line: after the cyclone (I-A, II-A, III-A), after the screening machine (I-B, II-B, III-B), and after transport to the chip pile (I-C, II-C, III-C). This approach isolates the effects of knife wear and knife–anvil clearance from the mechanical influence of the screening machine and from degradation occurring during pneumatic transport.

At the first sampling point (after the cyclone), the oversized fraction (>32 mm) reached 2.8% for worn knives and a wide gap (I-A), 1.3% for sharp knives and a narrow gap (II-A), and 2.4% after 8 h of wear at the narrow gap (III-A). A similar trend was observed for the fine fractions (<3 mm), which amounted to 5.3% (I-A), 3.3% (II-A), and 4.9% (III-A). These results indicate that sharp knives combined with a properly adjusted knife–anvil gap produced fewer oversized particles and fewer fines. After 8 hours of operation, both fractions increased again, confirming that knife blunting promoted chip cracking and the formation of small fragments. The acceptable chip classes (16 and 6 mm sieves) at this stage showed only minor variation, which suggests that cutting conditions primarily affect the two extreme fractions.

At the second sampling point (after the screening machine), the acceptable fraction passing the 16 mm sieve slightly decreased from 52.9% (I-B) to 50.2% (II-B) and 51.7% (III-B). This pattern reflects the expected behaviour of the screening process, which redistributes particle-size classes without improving the intrinsic quality of chips. At this stage, the fine fraction decreased substantially because fines are efficiently removed by the screening machine, while the share of chips in the 16 to 6 mm range increased due to the mechanical separation of the smallest particles.

At the final sampling point (after transport to the chip pile), the increase in the 16 to 6 mm fraction relative to the chipper outlet amounted to 11.1% for worn knives and a wide gap (I-A→I-C), 5.4% for sharp knives and a narrow gap (II-A→II-C), and 8.8% for worn knives at a narrow gap (III-A→III-C). This demonstrates that pneumatic transport contributes significantly to chip degradation, especially when chips are already weakened by unfavourable cutting conditions. Sharp knives and a narrow gap reduce this negative effect, as evidenced by the smallest increase observed in stage II. A similar effect of chip handling on chip degradation has been reported previously for industrial chippers (Spinelli and Magagnotti 2012). The fine fraction also increased along the production line, confirming that damaged chips are prone to further cracking during mechanical handling and pneumatic transport.

The knife–anvil gap also influenced chip-size distribution. When comparing stages with worn knives (I-A and III-A) but different clearances, both the oversized and the fine fraction decreased slightly at the narrow gap. Although the magnitude of these differences was relatively small, they were statistically significant, indicating that a smaller knife–anvil gap improves cutting performance even when knives are worn.

These results demonstrate a statistically significant influence of knife sharpness on chip quality. Sharp knives produce fewer fines and oversized chips, whereas worn knives increase the proportion of both fractions. This finding is consistent with results reported by Gendek and Nawrocka (2014), who showed that sharp knives reduce chip cracking and the formation of pin chips. Additionally, chipper construction and condition—including variation in knife protrusion and excessive rounding of the anvil edge (up to 6 to 8 mm in this study, compared with the recommended 2 to 3 mm)—play a crucial role in chip quality. Excessive rounding impairs cutting efficiency and accelerates chip fragmentation.

Transport conditions and cyclone design further affect chip integrity. High chip velocity and impacts within the pneumatic system promote cracking, particularly in chips weakened by dull knives. This mechanism explains the substantial increase in the 16 to 6 mm fraction observed along the production line, especially in stage I.

Overall, the study demonstrated that knife condition and knife–anvil clearance are key factors influencing chip quality. To maintain uniform chip size distribution, knives should be replaced more frequently, even though this reduces machine availability. The improvement in chip quality justifies such maintenance, particularly when high-quality pulp production is the priority.

High coefficients of variation (CV) observed in the extreme chip fractions constitute an important technological indicator, as they reflect irregularities in the chipping process and insufficient stability of the material stream delivered to subsequent fibre-processing operations. The greatest variability occurred in the oversize fraction (32 mm) and the harmful fines (<3 mm), where CV values frequently exceeded 40%, indicating unstable occurrence and strong sensitivity to changes in knife condition and wood-feeding behaviour.

In contrast, the acceptable chip fractions (16 and 6 mm), which dominate in properly produced chips, exhibited low CV values (typically <5%), demonstrating high measurement repeatability and overall stability of the cutting process. This pronounced contrast between acceptable and extreme fractions clearly illustrates how the mechanical condition of the chipper and the quality of wood feeding influence the uniformity of the final product. Elevated CV in the extreme fractions therefore serves as a valuable diagnostic signal, highlighting the need to adjust knife–anvil clearance, stabilise feed parameters, or replace worn knives.

It should be noted that particle size distribution was assessed under the given operating conditions without repetition. Although several subsamples were analyzed to ensure repeatable measurements, the production conditions themselves were not repeated. Therefore, systematic effects, such as changes in raw material properties occurring at the same time as changes in operating conditions, cannot be fully excluded. This is a typical limitation of industrial-scale studies. However, the observed trends are consistent along the processing line, suggesting that the results mainly reflect process-related effects.

CONCLUSIONS

1. Knife sharpness was identified as a key factor influencing chip quality, with sharp knives producing lower proportions of both oversized and fine fractions.
2. A narrow knife–anvil gap contributed to improved cutting stability; however, its effect on chip quality was less pronounced than that of knife sharpness.
3. Pneumatic transport and the screening machine modified the chip fraction distribution but did not improve intrinsic chip quality; chips produced under unfavourable cutting conditions showed increased susceptibility to degradation along the processing line.
4. Variations in knife geometry and increased anvil rounding led to non-uniform cutting conditions and increased chip fragmentation.
5. Variations in wood moisture content of approximately 2% did not result in statistically significant changes in chip size distribution.
6. Maintaining sharp knives and an appropriate knife–anvil gap is important for producing uniform chips and reducing degradation during downstream handling operations; the results indicate that knife replacement after an 8-hour chipping period is justified under the studied operating conditions.
7. Increasing knife maintenance frequency can be justified when consistent high-quality pulp production is required.

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