Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Note

# Investigating the influence of work piece geometry on the specific energy use in size reduction with a multi-blade shaft mill

Atanu Kumar Das*, David A. Agar, Sylvia H. Larsson, Magnus Rudolfsson

*Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology, SE-901 83 Umeå, Sweden*

ARTICLE INFO

*Article history:*
Received 21 December 2020
Received in revised form
22 June 2021
Accepted 4 July 2021

*Keywords:*
Comminution
Wood powder technology
MBSM
Fine grinding
Experimental design
Milling

This study investigated the specific milling energy of rectangular pine (*Pinus sylvestris* L.) boards using a new size reduction technology, which can produce fine wood powders in a single-step operation. Multilinear regression (MLR) analysis was used to model the milling energy of a multi-blade shaft mill through a designed series of experiments having three input parameters: the moisture content of the board, milling blade speed and board feeding speed. The observed specific milling energy ranged from 60 to 172 kWh $t^{-1}$ [DM] and the MLR model showed it was proportional to the blade speed and the moisture content. The results suggest that multi-blade shaft milling is a two-dimension extension of singular circular blade milling with regard to work piece shape and sawblade teeth engagement effects. The findings were compared with the specific milling energy of pine logs obtained in a previous study.



## 1. Introduction

With the resurgence of various wood-based applications in society and wood powder feedstock for bio-based industries, new size reduction technologies have the potential to improve utilisation by supplying better-suited wood powders for refining processes and products (Karinkanta et al., 2018). Eliminating multistep pre-processing and thermal treatments saves time and unlocks more benefits from the green chemical profile of wood.

A new size reduction technology, known as the multi-blade shaft mill (MBSM), has recently been assessed for the production of wood powders in a single-step milling operation from whole tree stems (Das et al., 2021). As the MBSM uses a packed shaft of circular cutting blades, which can be viewed as a parallel combination of rotary-blade sawing processes, the observation that moisture content is negatively correlated to milling energy appeared reasonable in an earlier study. Models showed that milling energy was inversely proportional to the moisture content of the wood and the log feeding speed, whilst being directly proportional to the blade speed.

* *Corresponding author.*
E-mail address: atanu.kumar.das@slu.se (A.K. Das).
https://doi.org/10.1016/j.biosystemseng.2021.07.002

**Nomenclature**

| | |
|---|---|
| MBSM | Multi-blade shaft mill |
| BS | Blade speed |
| DM | Dry mass |
| FS | Feeding speed |
| MC | Moisture content |
| w.b. | Wet basis |
| $e_M$ | Specific milling energy (kW h $t^{-1}$) |
| $m_M$ | Mass of milled board (kg) |
| $P_f$ | Board feeding power (kW) |
| $P_m$ | Board milling power (kW) |
| $Q^2$ | Goodness of prediction |
| $R^2$ | Goodness of fit |
| $t_M$ | Board milling time (s) |
| $Y_E$ | Modelled specific milling energy (kW h $t^{-1}$) |

High moisture content in wood generally lowers the energy required for sawing (Moradpour et al., 2013; Morita et al., 1999) since every increment of moisture content up to fibre saturation point decreases the modulus of elasticity, fracture toughness and hardness of wood (Nordstrom & Bergstrom, 2001). Power consumption in single-blade circular sawing is analysed using two contributions; the applied power needing to generate the cutting force and the power used in chip formation (i.e. sawdust) and removal from the work piece (Cristovao et al., 2013). Both these contributions are functions of MC and a number of other factors (Orlowski et al., 2013) whose influence can be difficult to evaluate because the experimenter only observes the total power of the sawing process. Moisture content plays a dual role in power consumption as water in wood can lower the cutting force (Axelsson et al., 1993) while simultaneously increasing work piece density (mass) and the power needed for chip formation. Due to the complexity of modelling the sawing process and the anisotropic effects of wood (Sjöström, 1993), power consumption is best determined through direct experiment.

Power consumption with circular sawblades depends on the position angle between the sawblade teeth and the work piece (Cristovao et al., 2013) as well as the number of teeth engaged, i.e., in contact with the kerf (Orlowski et al., 2013). The question arises, is power consumption in MBSM milling analogous to sawing wood with a singular circular saw blade? The answer has practical implications for improving mill design and the potential benefits of the technology.

This study aimed to deepen the understanding of multi-blade shaft milling technology from earlier work (with cylindrical logs) by applying it to rectangular shaped boards. The main objective was to see how work piece shape affects the energy requirements of size reduction.

## 2. Materials and methods

Experimental work was performed at the Biomass Technology Centre at the Swedish University of Agricultural Sciences in Umeå, Sweden.

### 2.1. *Multi-blade shaft mill*

A multi-blade shaft mill (Klingmill AB, Torshälla, Sweden) that has been described in an earlier study (Das et al., 2021) was used here. The machinery mills the work piece using two shafts of packed circular sawblades driven by two separate electric motors (55 kW, 1480 rpm) (Fig. 1). The first shaft is the primary milling shaft and consists of 110 parallel-mounted 352 mm diameter and 3 mm thickness blades having eight teeth per blade. The clearance angle, rake angle and kerf of the blade teeth are 18°, 5° and 4.2 mm, respectively. Every second blade on the shaft is rotated by 360/16° so that around the circumference of the packed blades there are 16 rows of teeth. The second shaft has 137 parallel-mounted blades having 24 teeth per blade and rake angle and kerf of each tooth are 15° and 3 mm, respectively. The feeding level was tangent to the lower side of the blades. Wood powder was collected in a plastic bag through a filtered vacuum system. The mill can accept log diameters and board widths up to approximately 280 and 300 mm, respectively.

### 2.2. *Experimental design*

MSBM milling was performed according to a full factorial (two-level) experimental screening design with one centre point varying three factors in their corresponding ranges: board moisture content (13–33%, wet basis), board feeding speed (1.3–2.3 m $min^{-1}$) and blade speed (52–72 m $s^{-1}$). The analysed response was the specific milling energy (kW h $t^{-1}$ [DM]). Experiments from each of the experimental design points were replicated three times, bring the total number of MBSM experiments for the response to 27. The experimental range of the feeding speed and blade speed was defined previously (Das et al., 2021).

### 2.3. *Material preparation*

Ten boards were collected from a saw mill (Sävar såg, Norra Timber, Umeå, Sweden) and cut to obtain 27 boards having equal length. Board samples had dimensions of approximately 1100 × 150 × 50 mm. The boards came from trees having a minimum average age of 60 (SD = 18) years, as determined by counting growth rings. Three moisture content ranges, approximately at and below the fibre saturation point, were used: 13 to 16, 20 to 24 and 21–33% wet basis (w.b.). To achieve the three ranges, the boards were dried at 25 °C in a drying cabinet (Elvärmedetaljer, Skurup, Sweden) to minimise wood properties changes. The boards were kept separate from each other and wrapped in plastic to prevent changes in moisture content prior to experiments. An overview of the experimental procedure is presented in Fig. 2.

### 2.4. *Milling procedure*

All boards were weighed, and within each moisture content range, ordered randomly with relation to the experimental design. During milling, the electric power (kW) was monitored and data gathered (1 Hz) with an acquisition system (INTAB PC-logger 3100). The MBSM was cleaned thoroughly between each experiment.

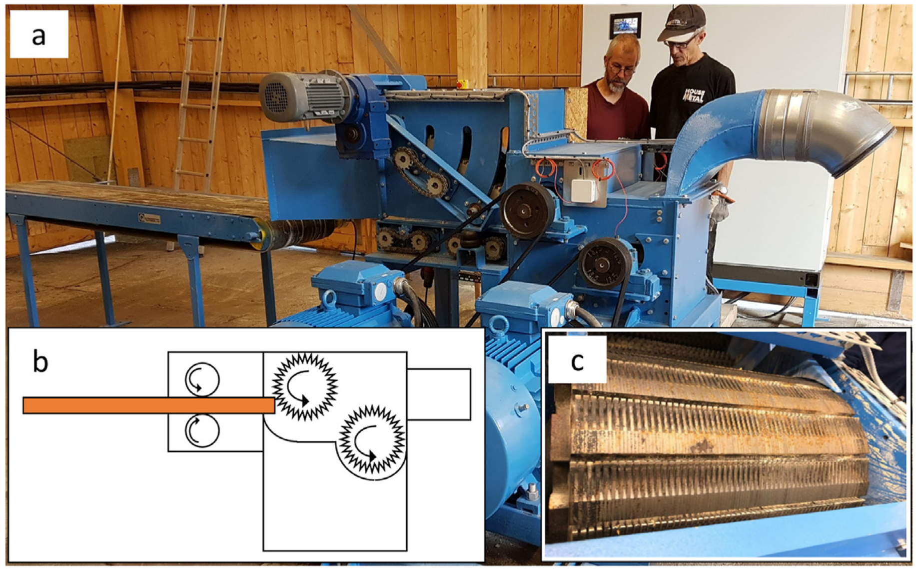


**Fig. 1 – (a) The prototype multi-blade shaft mill (MBSM) without its housing enclosure. The roller table, feeder and the two shafts connected to the motors are visible. The sample collector is not fitted to the outlet in the photograph. (b) The principle of operation of the MBSM and (c) the multi-blade shaft (Das et al., 2021).**

### 2.5. *Milling energy analysis*

The specific milling energy $e_M$ (kWh $t^{-1}$ [DM]) of MBSM milling was calculated using the following equation:

$$e_M = m_M^{-1} \sum_{t_M} (P_f + P_m)\ t_M$$

in which $m_M$ (kg [DM]) is the dry mass of the milled board, $t_M$ (s) = board milling time, $P_f$ (kW) = board feeding power and $P_m$ (kW) = board milling power.

Multilinear regression (MLR) analysis was utilised to build predictive models for the measured responses from input parameters. The modelling was performed with MODDE Pro-12 software (Umetrics Sartorius, Umeå, Sweden).

## 3. Results and discussion

The MLR modelled effects and observed versus predicted plots are shown in Fig. 3. The feeding speed (FS) has significant ($p < 0.05$) negative effects on milling energy, whereas, the board moisture content (MC) and blade speed (BS) have significant positive effects. Specific milling energy decreased by 48 kWh $t^{-1}$ [DM] over the full range of FS variation. Full range increases of MC and BS produced higher specific energy by 48 and 18 kWh $t^{-1}$ [DM], respectively. No significant interaction terms were observed between effects. The model's $R^2$ and $Q^2$ values are 0.79 and 0.72 which represent good model validity and predictability (Eriksson et al., 2008).

The influence of the three design factors on the milling energy response is presented as contour plots (Fig. 4), a representation of the obtained specific milling energy equation: $Y_E$ (kWh $t^{-1}$ [DM]) = − 48.13FS + 2.38MC + 0.91BS + 93.58 in which FS, MC and BS have units of m $min^{-1}$, % and m $s^{-1}$, respectively. $Y_E$ decreases with increasing FS and increases with MC and BS. The lowest specific milling energy (60 kW h $t^{-1}$ [DM]) occurs for a FS of 2.3 m $min^{-1}$, a MC less than 17% and a BS less than 64 m $s^{-1}$.

Rectangular pine board milling had an observed specific milling energy range of 60–172 kWh $t^{-1}$ [DM] (Table 1), almost half of that observed using cylindrical pine logs (99–232 kWh $t^{-1}$ [DM]) (Das et al., 2021). The only significant differences between the boards and logs were the shape, average age of wood (60 versus 29 years) and range of moisture content (13–33% versus 11–51%).

The rectangular (cross-sectional) shape of the boards (50 × 150 mm) differed from that of the cylindrical logs (100–140 mm diameter). With singular circular saw blades, the thickness of the work piece, determines the angle of teeth engagement and consequently the path length travelled by the teeth through the kerf (Orlowski et al., 2013). As power consumption depends on the path length, because greater frictional forces act over a longer path (Chuchala et al., 2014), the involvement of more teeth for a thicker work piece (Fig. 5)

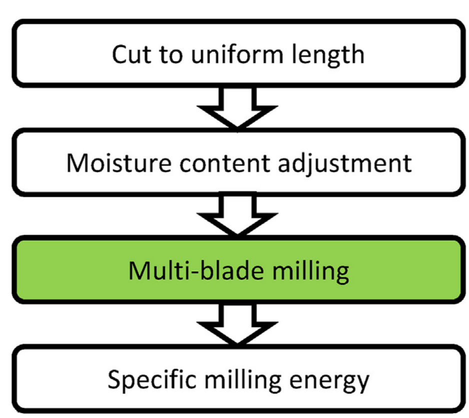


**Fig. 2 – An overview of the experimental procedure used in the study.**

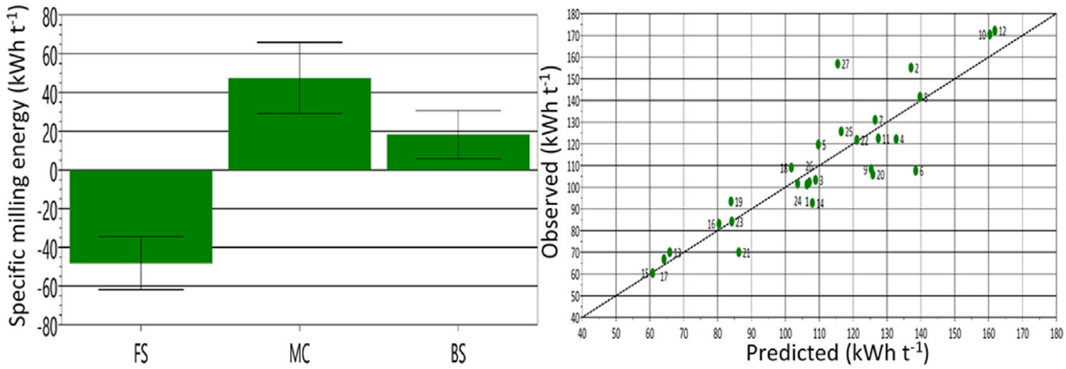


**Fig. 3 – Effects of scaled and centred factors in the response models for the specific milling energy, when each individual factor is varied from its lowest to its highest value, keeping all other factors at their average values in the design. The error bars indicate 95% level of confidence. Symbols refer to FS = feeding speed, MC = moisture content and BS = blade speed.**

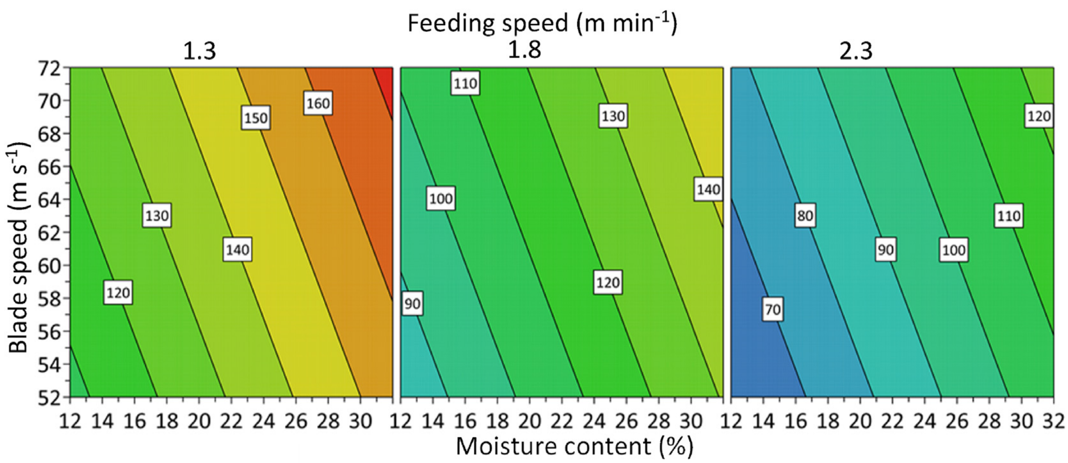


**Fig. 4 – Contour plots showing the influence of the three experimental design factors (feeding speed, moisture content and blade speed) on the specific milling energy.**

increases the specific milling energy. These relationships have been confirmed during sawing of *Pinus sylvestris* L. by a singular working blade (Cristovao et al., 2013). In board milling, there were comparatively fewer teeth engaged in the vertical plane and a shorter path length due to the thinner work piece.

Because the MBSM has parallel blades along the shaft, there is also teeth engagement in the horizontal plane, which depends on the work piece width (Fig. 5). The boards, which were wider than the logs, engaged more teeth from parallel blades in the horizontal plane. The number of teeth and engaged angle of teeth have influence on the specific milling energy during size reduction of wood (Orlowski et al., 2013). The cutting time also influences the energy consumption; the longer the cutting time the higher the energy consumption (Morita et al., 1999). Thus, more teeth involvement along the shorter path may reduce the specific milling energy. In this case, the wider and thinner work piece may be easier to mill compared to the thicker work piece.

Therefore, the combination of thickness and width differences of the boards is suggested to be responsible factor for the differences in observed milling energy with the MBSM. This suggests that the MBSM milling action is a two-dimension extension of singular circular blade milling.

However, the modelled effect of MC on milling energy was opposite to log milling (+48 versus −18 kWh $t^{-1}$[DM]) (Das et al., 2021). Why does moisture play an opposite role in the models? The work piece shape appears to affect the influence of MC on the observed and modelled energy use but the precise reason is unclear. The presence of heartwood in the material may have contributed to the observed differences in the specific milling energy as the proportion of heartwood (where extractive content is high) increases with tree age. In order to optimise the configuration of the mill, it is important to clarify the effect of work piece shape and MC on the specific milling energy. Future work will investigate the influence of extractive content and tree species on specific milling energy

**Table 1 – Full factorial design (2 Levels) for MBSM board experiments and specific milling energy.**

| Experiment name | Run order | Feeding speed (m min$^{-1}$) | Moisture content (%) | Blade speed (m s$^{-1}$) | Specific milling energy (kW h t$^{-1}$ [DM]) |
|---|---|---|---|---|---|
| N1 | 18 | 1.4 | 13.7 | 52 | 101.2 |
| N2 | 9 | 1.4 | 26.6 | 52 | 155.3 |
| N3 | 8 | 1.4 | 14.8 | 52 | 103.4 |
| N4 | 1 | 1.4 | 24.8 | 52 | 122.2 |
| N5 | 20 | 1.4 | 15.1 | 52 | 119.6 |
| N6 | 6 | 1.3 | 25.2 | 52 | 107.7 |
| N7 | 22 | 1.4 | 14.5 | 72 | 130.9 |
| N8 | 23 | 1.5 | 22.1 | 72 | 141.6 |
| N9 | 4 | 1.4 | 14.0 | 72 | 108.2 |
| N10 | 2 | 1.4 | 28.7 | 72 | 170.5 |
| N11 | 17 | 1.4 | 14.9 | 72 | 122.6 |
| N12 | 27 | 1.3 | 27.3 | 72 | 172.2 |
| N13 | 11 | 2.3 | 14.9 | 52 | 69.90 |
| N14 | 16 | 2.3 | 32.6 | 52 | 92.80 |
| N15 | 7 | 2.3 | 12.8 | 52 | 60.40 |
| N16 | 15 | 2.3 | 21.0 | 52 | 83.10 |
| N17 | 21 | 2.3 | 14.2 | 52 | 66.80 |
| N18 | 10 | 2.3 | 30.0 | 52 | 109.0 |
| N19 | 25 | 2.3 | 14.8 | 72 | 93.30 |
| N20 | 5 | 2.3 | 32.4 | 72 | 106.0 |
| N21 | 24 | 2.3 | 15.8 | 72 | 69.90 |
| N22 | 14 | 2.3 | 30.4 | 72 | 122.0 |
| N23 | 19 | 2.3 | 14.9 | 72 | 84.10 |
| N24 | 26 | 2.3 | 23.1 | 72 | 101.7 |
| N25 | 3 | 1.8 | 22.2 | 62 | 125.8 |
| N26 | 13 | 1.9 | 20.3 | 62 | 102.2 |
| N27 | 12 | 1.9 | 23.8 | 62 | 157.1 |

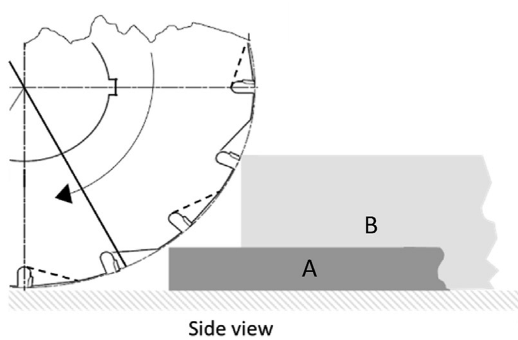


**Fig. 5 – Side and front views of the main shaft of the multi-blade shaft mill. The thickness and width of the boards (A) and logs (B) influence the engagement angle and the number of teeth engaged, both in the vertical (left) and horizontal (right) planes.**

and particle size distribution so that MBSM technology can be fully characterised.

## 4. Conclusions

Pine boards at moisture contents up to the fibre saturation point, were milled using a novel multi-blade shaft mill (MBSM). According to the generated MLR model, the milling energy was proportional to the moisture content of the wood. The effects of blade speed (BS), feeding speed (FS), engagement of number of teeth and shape of the work piece indicate that MBSM milling energy is analogous to the sawing of wood and opposite to impact-based milling. The effect of work piece geometry may explain the observed differences in specific milling energy from previous work in two ways: 1) differences in height and width determine the number of blade teeth engaged in milling and 2) height differences alter the angle of engagement with blade teeth.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

Funding from the Swedish Energy Agency, Sweden, Swedish Bio4Energy Strategic Research Environment, Sweden, and the Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Sweden is acknowledged. The authors thank Gunnar Kalén, Markus Segerström, Borislav Vujadinovic and KlingMill AB for their assistance and technical support.

## REFERENCES

Axelsson, B. O. M., Lundberg, Å. S., & Grönlund, J. A. (1993). Studies of the main cutting force at and near a cutting edge. *Holz als Roh- und Werkstoff: European Journal of Wood and Wood Industries, 51*(1), 43–48. https://doi.org/10.1007/BF02615376

Chuchala, D., Orlowski, K. A., Sandak, A., Sandak, J., Pauliny, D., & Baranski, J. (2014). The effect of wood provenance and density on cutting forces while sawing Scots pine (*Pinus sylvestris* L.). *Bioresources, 9*(3), 5349–5361.

Cristovao, L., Ekevad, M., & Gronlund, A. (2013). Industrial sawing of Pinus sylvestris L.: Power consumption. *Bioresources, 8*(4), 6044–6053.

Das, A. K., Agar, D. A., Larsson, S. H., Holdo, T., Fernando, D., & Rudolfsson, M. (2021). Multi-blade milling from log to powder in one step – experimental design and results. *Powder Technology, 378*, 593–601.

Eriksson, L., Johansson, E., Kettaneh-Wold, N., Wikström, C., & Wold, S. (2008). *Design of experiments: Principles and applications*. Stockholm: Umeå Learnways AB.

Karinkanta, P., Ammala, A., Illikainen, M., & Niinimaki, J. (2018). Fine grinding of wood - overview from wood breakage to applications. *Biomass and Bioenergy, 113*, 31–44. https://doi.org/10.1016/j.biombioe.2018.03.007

Moradpour, P., Doosthoseini, K., Scholz, F., & Tarmian, A. (2013). Cutting forces in bandsaw processing of oak and beech wood as affected by wood moisture content and cutting directions. *European Journal of Wood and Wood Products, 71*(6), 747–754. https://doi.org/10.1007/s00107-013-0734-z

Morita, T., Banshoya, K., Tsutsumoto, T., & Murase, Y. (1999). Corrosive-wear characteristics of diamond-coated cemented carbide tools. *Journal of Wood Science, 45*(6), 463–469. https://doi.org/10.1007/bf00538954

Nordstrom, J., & Bergstrom, J. (2001). Wear testing of saw teeth in timber cutting. *Wear, 250*, 19–27. https://doi.org/10.1016/s0043-1648(01)00625-1

Orlowski, K. A., Ochrymiuk, T., Atkins, A., & Chuchala, D. (2013). Application of fracture mechanics for energetic effects predictions while wood sawing. *Wood Science and Technology, 47*(5), 949–963. https://doi.org/10.1007/s00226-013-0551-x

Sjöström, E. (1993). Chapter 5 - Extractives. In E. Sjöström (Ed.), *Wood chemistry* (2nd ed., pp. 90–108). San Diego: Academic Press.