Industrial Sawing of *Pinus sylvestris* L.: Power Consumption

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The wood industry continues to strive to reduce production costs and increase productivity to remain competitive. Knowledge of the effect of wood cutting parameters on power consumption could increase energy efficiency, reducing operating costs and increasing profitability. Measuring power consumption also provides information about other variables, such as tool edge wear, occurrence of catastrophic failures, and other parameters that affect the quality of the sawn boards and the momentary efficiency of the breakdown process. In this work, power consumption during sawing of *Pinus sylvestris* L. using a double arbor circular saw was investigated. Both climb-sawing and counter-sawing were considered. The experiments were carried out under normal production circumstances in two Swedish sawmills. The relationship between cutting parameters and theoretical power consumption was investigated. The experimental power consumption increased by 11 to 35% during an 8-h shift, mainly due to an increase in the tooth radius. Additionally, this study showed that climb-sawing consumed more power than counter-sawing.

Keywords: Climb-sawing; Counter-sawing; Cutting force; Power consumption

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INTRODUCTION

Large numbers of logs are machined in sawmills every day, and the prediction of power consumption is becoming an increasingly important economic factor throughout all processing stages. Understanding the effect of wood cutting parameters on power consumption could increase energy efficiency, reduce operating costs, and enhance profitability.

Predicting power consumption and cutting forces is very complex, with many interacting phenomena. It requires a fundamental understanding of the interaction between wood properties, the cutting tool, and machining parameters. The primary issue that confounds machining research is the extreme anisotropy and heterogeneity of wood. The cutting force direction and its magnitude also change due to the cutting tool rotation. Cutting is interrupted as each tooth enters and leaves the workpiece.

In Sweden, modern sawmills normally use double arbor circular sawblades for the resaw (deal saw). A resaw on a modern high-production saw line has an installed power in the range of 1 MW. Compared to a single arbor circular sawblade, a double arbor blade offers the advantage of increasing the sawing accuracy and reducing the kerf losses to minimize sawdust waste. Double arbor saws are also able to run at high feed speeds with small variations of accuracy. Depending on the relative motion between the log and the circular sawblade, two feeding modes can be observed: counter-sawing and climb-sawing. The selection of feeding mode has important effects on the mechanics of the process, such as the type of chip, surface quality, mode of chip transportation, cutting forces, power consumption, and tool wear.

Important works for predicting power consumption were written by Aguilera and Martin (2001) and Kováč and Mikleš (2010). Aguilera and Martin (2001) predicted the power consumption of climb-sawing and counter-sawing by measuring the main cutting force and determined power consumption from the known cutting speed. Kováč and Mikleš (2010) determined the power consumption of the wood cutting process using circular saws and studied the influence of different cutting tool geometries. Although much attention has been given to developing models using a single cutting tool, little is known about power consumption using double arbor circular sawblades.

The aim of this study was to analyze how different geometrical parameters affect the power consumption in a double arbor circular sawblade during sawing of *Pinus sylvestris* L. Another aim was also to compare how well theoretical calculation can mimic measurements in full industrial production.

THEORETICAL BACKGROUND

Mechanics of the Sawing Process

The power consumption when cutting with a circular sawblade is cyclic and depends on the position angle of the tooth, ϕ (Fig. 1).

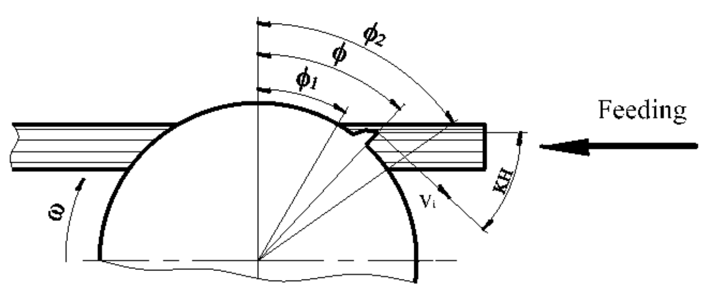

Fig. 1. Cutting zone for counter-sawing (ϕ_1 = entry angle, ϕ_2 = exit angle, *KH* = angle between the cutting speed vector and the wood grain)

The momentary power P_i is given by,

$$P_i = \frac{dE}{dt} \quad (1)$$

where E is the energy and t is the time. For a circular sawblade rotating at angular frequency ω, the tooth engaged in the cutting zone repeats cutting after a time interval of $2\pi/\omega$, which is denoted T, the period required to make one complete cycle. Thus, the total energy per revolution is the result of the following integral:

$$E_{total} = \int_0^T P_i \cdot dt = \int_0^{2\pi} \frac{P_i}{\omega} \cdot d\phi \quad (2)$$

If the total number of teeth engaged is *z* and the increment is $\Delta\phi = 1^o$, the total energy per revolution can be approximated:

$$E_{total} \approx z \cdot \sum_{i=1}^{360} \frac{P_i}{\omega} \cdot \Delta\phi \qquad (3)$$

Substituting this result in Eq. 1, the following can be obtained,

$$P_{total} \approx \frac{z \cdot n}{360} \cdot \sum_{i=1}^{360} P_i \qquad (4)$$

where *n* is the number of circular sawblades in the arbor. The momentary power (P_i) is computed according to the general laws (force x velocity) with an additional term describing the energy needed for the chip acceleration as described by Koch (1964) and Orlowski *et al.* (2013),

$$P_i = F_{pi} \cdot v_i + \frac{H \cdot k \cdot S \cdot d \cdot v_i^{\,2}}{2} \qquad (5)$$

where F_{Pi} is the main cutting force (N), *H* is the depth of the cut (mm), *S* is the feed speed (m/min), v_i is the cutting speed (m/s), *k* is the saw kerf width (mm), and *d* is the wood density (kg/m^3).

In wood machining, there are three different approaches used to model the main cutting force. Kivimaa (1950) and Scholz *et al*. (2009) calculated the main cutting force based on specific cutting resistance. Orlowski *et al*. (2013) developed a cutting force model based on modern fracture mechanics. Axelsson *et al*. (1993) and Cristóvão *et al*. (2011) established a predictive model using multivariate methods such as multiple linear regression and partial least squares regression. In order to calculate P_i and proceed with the modeling operations, F_{pi} is needed and it can be computed according to Equation 6 proposed by Axelsson *et al*. (1993),

$$F_{pi} = -7.37 + \delta_m \cdot (0.38 \cdot d8 - 224.5 \cdot \alpha) + 15.61 \cdot KH - 2.6 \cdot KH^3 + 1.31 \cdot r + 0.2 \cdot v_i + U \cdot (0.3 \cdot KH - 0.01 \cdot T) \qquad (6)$$

where *α* is the rake angle (radian), δ_m is the average chip thickness (mm), *r* is the edge radius (µm), *d8* is the average density at 8% of moisture content (kg/m^3), *T* is the temperature (°C), *KH* is the grain angle (radian), and *U* is the moisture content (%).

Figure 1 illustrates the angle between the wood grain and the cutting speed vector. The equation 6 was used to predict the main cutting forces when cutting Scots pine with kerf width 4.25 mm. To extend the range of application, the Equation 6 was multiplied by the ratio of tested saw kerf width *k* to 4.25 as shown in Equation 7.

$$F_{pi} = (-7.37 + \delta_m \cdot (0.38 \cdot d8 - 224.5 \cdot \alpha) + 15.61 \cdot KH - 2.6 \cdot KH^3 + 1.31 \cdot r + 0.2 \cdot v_i + U \cdot (0.3 \cdot KH - 0.01 \cdot T)) \cdot \frac{K}{4.25} \qquad (7)$$

EXPERIMENTAL

Materials and Methods

The experimental tests were carried out under normal circumstances in two Swedish sawmills, named A and B. The tests were performed in the second saw for re-sawing (resaw). The resaw machine cuts two main boards (2ex) in sawmill B and three main boards (3ex) in sawmill A. The machined material in both sawmills was Scots pine (*Pinus sylvestris* L.). The cant heights were 154 mm and 206.5 mm for sawmills A and B, respectively. It has been reported by Sehlstedt-Persson (2008) that the green moisture content for Scots pine vary considerably between sapwood and heartwood; it is approximately 150% for sapwood and 40% in heartwood. Wood density, like moisture content, is extremely varied; it was measured from 550 kg/m^3 for sapwood to 980 kg/m^3 for heartwood by Esping (1992). Equation 7 made it possible to predict the main cutting force for a workpiece with average moisture content and density measured at 8% moisture content. Therefore, it was assumed in this study that the average green moisture content was 80% and the average green density was 840 kg/m^3. The wood density at 8% moisture content was calculated using volumetric shrinkage of 12.4% which resulted in $d8$=548 kg/m^3. All experimental tests were carried out during summer at a temperature around 20 °C. One set of tests was conducted in each sawmill, as summarized in Table 1. A double arbor saw with a horizontal arbor was used in the second saw (resaw) test for both sawmills. In sawmill A, the first sawblade to cut was the counter-saw (lower sawblades), while in sawmill B, the first sawblade to cut was the climb-saw (upper sawblades). The resaw machines were equipped with four motors: two for climb-sawing and two for counter-sawing. A schematic representation of the two sawmills is shown in Fig. 2.

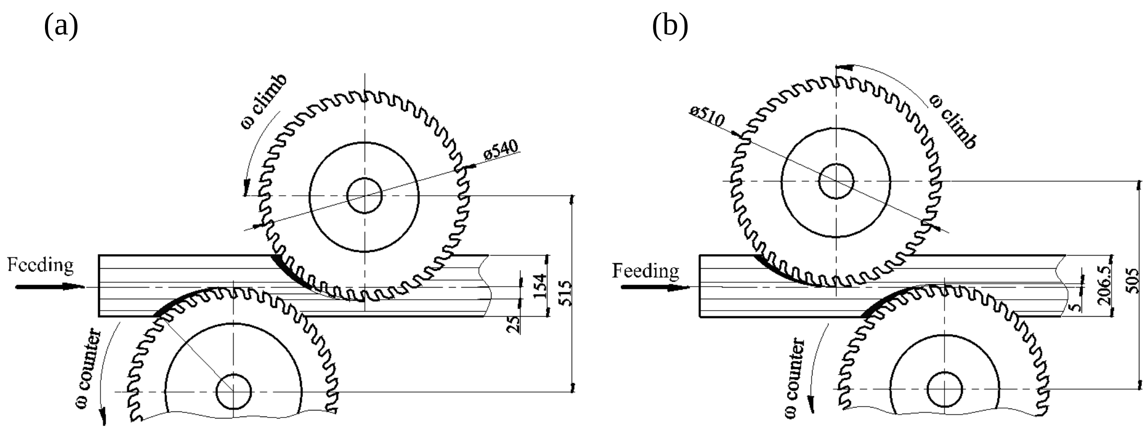

Fig. 2. Cutting geometry in climb-sawing and counter-sawing: (a) sawmill A, (b) sawmill B

The inserts of the circular sawblades for both sawmills were made of tungsten carbide, denoted 242. The cutting edges were sharpened with similar condition and carefully examined before the experiment to ensure the cutting edge was free of defects. A standard microscope was used to examine the edge radii of the cutting tools before and after the test. Edge radius tests were performed only in sawmill A. However, in sawmill B, the tool edge was sharp at the beginning of the test. Based on experience, the edge radius was assumed to be 5 μm at the beginning and 50 μm at the end of the test.

Table 1. Sawing Conditions in the Two Sawmills

Cutting Parameters	Sawmill A	Sawmill B
Sawblade diameter, mm	540	510
Sawblade thickness, mm	2.6	2.9
Saw kerf width, mm	3.8	4.2
Rake angle, degree	30	30
Gullet area, mm^2	519	432
Initial edge radius, µm	5	-
Number of teeth	36	36
Feed speed, m/min	119.2	64.0
Overlap between blades, mm	25	5
Bite/tooth, mm	1.07	0.71
Blade rotation, rpm	3100	2500
Number of sawn logs	7669	6277

The experimental tests were performed during one shift, which lasted approximately 8 h, as shown in Fig. 3. The power consumption of a circular sawblade was measured using a Fluke 1375 Power Logger with the capability to measure average active power and maximum active power. The power consumption was measured separately for upper sawblades motor (climb-sawing) and lower sawblades motor (counter-sawing). Power consumption was recorded every 5 s for both sawmills. After recording, the logger was disconnected and the data were downloaded to a computer and reviewed.

For comparison purposes, only the average maximum active power was reported in this study. During sawing with a double arbor, the upper sawblades are usually not in perfect alignment with the lower sawblades on the other arbor. As result, a slight saw mismatch occurs in the sawn boards. The sawn boards were analyzed and the saw mismatch was measured in this study.

To understand the effects of the cutting parameters on power consumption, theoretical power consumption was modeled using Equations 4, 5, and 7 and then compared with the experimentally measured power. The calculation was made for a complete cycle in 1-degree increments of the cutting edge position. The chip thickness, main force, and power consumption were a function of the cutting edge position.

The program Microsoft Visual Basic C++ was used to build the models. The models also incorporated the effects of the saw kerf width, overlap, and saw mismatch between circular sawblades.

The cutting force model developed by Axelsson *et al.* (1993) was extended to apply other saw kerf width and used to estimate the power required to cause a failure (Equation 7). Saw mismatch was incorporated by adding the cutting zone, which is shadowed by the first sawblade (Fig. 4). The saw kerf width used to calculate power consumption in the overlap zone was the value of mismatch. A change in the overlap between sawblades affected the angle of tooth entry and exit, the path length of tooth engagement, the number of teeth engaged, *etc.* (Fig. 4).

To understand the effects of overlap between sawblades on theoretical power consumption, only the second sawblade to cut (climb-sawing for sawmill A and counter-sawing for sawmill B) was varied in the distance between workpiece and axis of sawblades rotation (Fig. 4).

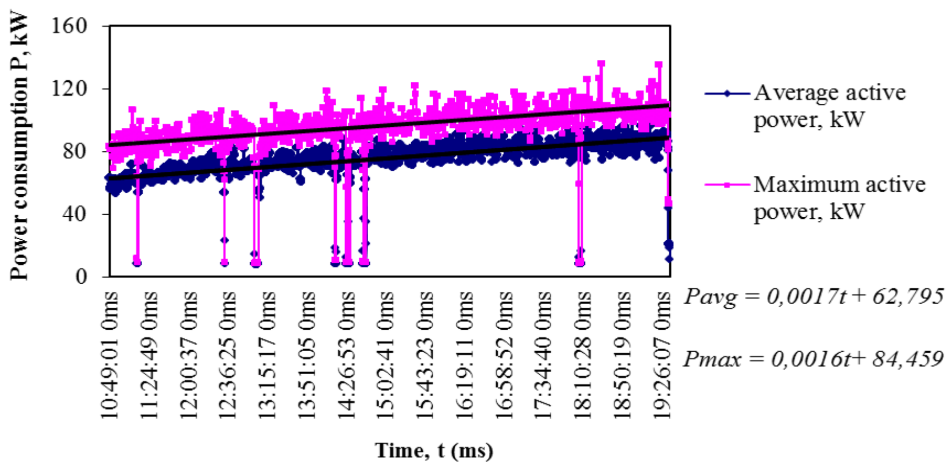

Fig. 3. An example of the measurement of maximum and average power consumption

For comparison purposes between experimental and theoretical power consumption, the idling power was subtracted from the experimental power consumption for each sawmill.

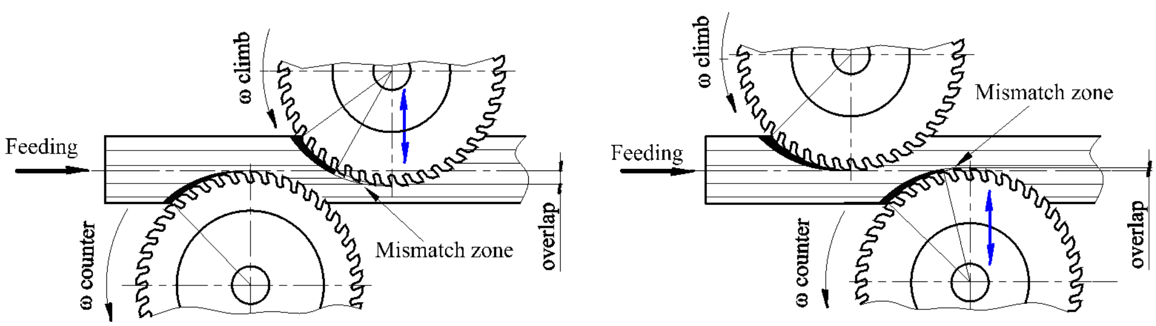

Fig. 4. Mismatch zone and overlap between sawblades: (a) sawmill A, (b) sawmill B

RESULTS AND DISCUSSION

The experimental and predicted results of power consumption, as a function of edge radius, assuming that wear is linear, are presented in Fig. 5. The idling power was 8.5 kW in sawmill A and 7.2 kW in sawmill B. For both sawmills, an increase in edge radius resulted in higher power consumption.

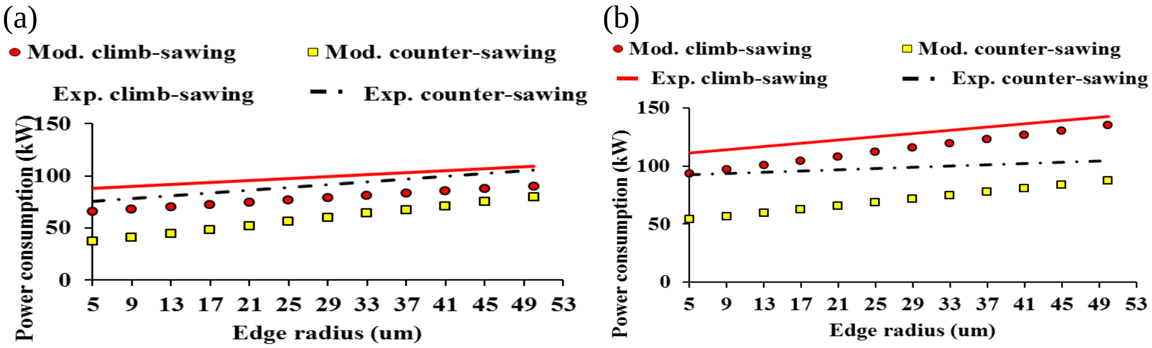

Fig. 5. The change in power consumption depending on edge radius: (a) sawmill A, (b) sawmill B (mismatch=0)

The predicted model showed lower power consumption than the experimental. The differences between the predicted and experimental results might be due to the presence of wiper slots, back sawing, motor efficiency, and other losses between the interaction of the cutting tool and workpiece, which were not considered in this study. Climb-sawing consumed more power than counter-sawing in the range tested. The difference between climb-sawing and counter-sawing was more pronounced in sawmill B. Surprisingly, the theoretical and experimental power consumption data converged with an increase of cutting tool edge radius. The power consumption was higher in sawmill B than in sawmill A due to a high saw kerf width, cant height, high mismatch, and low overlap between sawblades.

In general, the experimental test showed an increase of power around 35% in sawmill A during counter-sawing and of 30% in sawmill B during climb-sawing. The lowest increase in the experimental data was 11%, observed in sawmill B during counter-sawing. Additionally, the power consumption in sawmill A during the experimental test had an increase of 24% when climb-sawing. It should be emphasized that the edge radius was not measured in sawmill B. In general, the climb-sawing model for both sawmills was able to estimate the power consumption better than counter-sawing.

To accelerate a chip, sawmill B required 6.2 kW for climb-sawing and 4.8 kW for counter-sawing. Alternately, sawmill A required 11 kW for climb-sawing and 6.6 kW for counter-sawing. The relatively high values required to accelerate a chip in sawmill A were due to the high sawblade rotation combined with a high feed speed (Equation 6).

Wood is an anisotropic and heterogeneity material and when machined using circular sawblade, each tool edge engaged is cutting at different wood grains that result in different cutting forces direction and magnitude. Figure 6 illustrates the predicted power consumption as a function of grain angle for a single sawblade. The theoretical power consumption was computed using Equations 4, 5 and 7. During counter-sawing, the theoretical power consumption gradually increased from the beginning of the cut to a maximum when the cutting tool left the workpiece. However, in climb-sawing, the theoretical power consumption reached a maximum at the beginning of the cut and gradually decreased until reaching the exit angle. The variation of chip thickness for each sawmill is shown in Fig. 2 and 4.

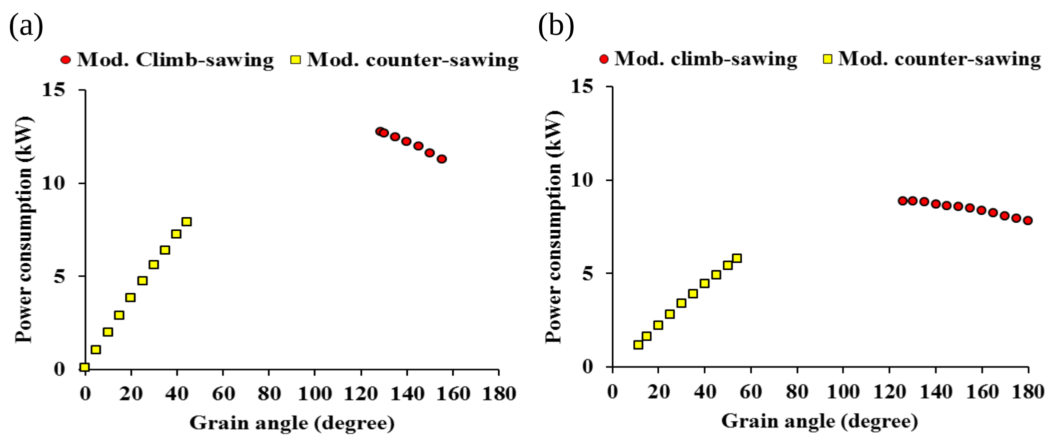

Fig. 6. Theoretical power consumption depending on grain angle for a single sawblade: (a) sawmill A; (b) sawmill B (saw mismatch=0)

It is important to note that counter-sawing starts to cut at a grain angle of 0° (90-0° mode), while climb-sawing starts to cut at around 125° (approximately 90-90° mode). Kivimaa (1950), Goli (2009), and Axelsson (1993) found that the main cutting forces are slightly smaller at grain angles between 0 and 90° than they are between 90 and 180°. Therefore, changes in chip thickness, grain angle, and cutting length explain the differences in power required to remove a chip *via* climb-sawing and counter-sawing.

Figure 7 illustrates how variation in overlap affects the theoretical power consumption in each sawmill. In the experimental test, sawmills A and B had 25 mm and 5 mm overlaps, respectively. As the overlap between sawblades increased, the theoretical power reduced for both sawmills due to the change in the angle of tooth entry and exit, grain angle, length of path of tooth engagement, and the number of teeth engaged, *i.e.*, the greater the overlap between sawblades was, the shorter the path of tooth engagement and the fewer the number of teeth engaged in the cut.

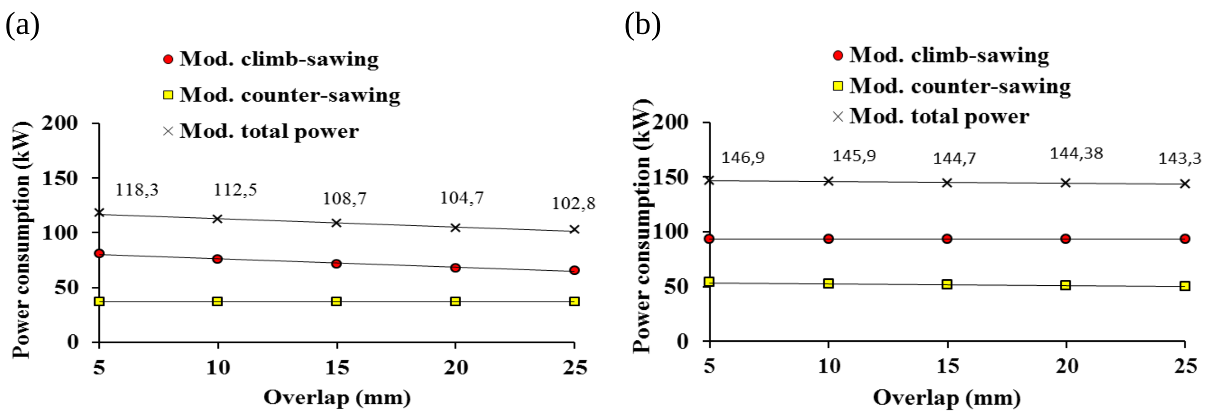

Fig. 7. Theoretical power consumption depending on overlap between sawblades: (a) sawmill A, (b) sawmill B (saw mismatch=0)

A potential reduction in power consumption can be seen in sawmill A, where the sawblades had 25 mm of overlap.

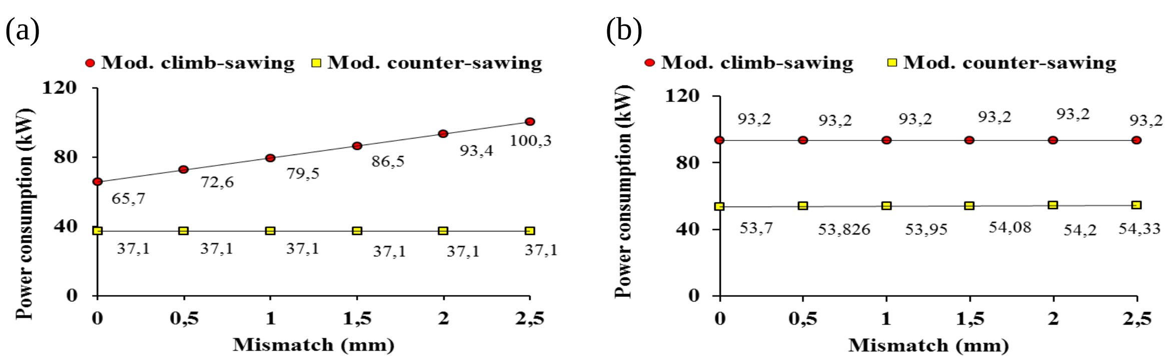

Fig. 8. Theoretical power consumption depending on the mismatch between sawblades: (a) sawmill A (overlap = 25 mm), (b) sawmill B (overlap = 5 mm)

During sawing, the blades are subjected to severe loads and vibrations that lead to poor surface quality and reduced cutting accuracy. Figure 8 illustrates the effect of saw mismatch on theoretical power consumption in sawmill A and B. The experimental tests revealed the highest values of saw mismatch to be 2.5 mm in sawmill B and 1.75 mm in sawmill A. These saw mismatch values are quite high; the average values were much smaller. The theoretical results showed that an increase in saw mismatch resulted in high power consumption. Interestingly, the changes in power consumption in sawmill B due to saw mismatch were negligible. This is because the overlap was only 5 mm.

As expected, the power required to accelerate a chip when the saw mismatch was 2.5 mm increased by 0.8 kW in sawmill B; with a saw mismatch of 1.75 mm in sawmill A, the power required was 2.8 kW. This value in sawmill A was due to the long cutting length in the overlap zone between sawblades.

From Figs. 7 and 8, it is reasonable to conclude that sawmills that use thinner sawblades that are prone to instability should consider using less overlap between sawblades. However, the choice of operating conditions in a sawmill is not based exclusively on power consumption; it is a compromise between productivity, lumber recovery, and sawing accuracy. In the future, more controlled experimental tests are planned. Resaw machines with thicker saw kerf widths for climb-sawing and thinner ones for counter-sawing, or *vice versa*, will be considered.

CONCLUSIONS

1. The cutting force model by Axelsson *et al*. (1993) was able to estimate power consumption better during climb-sawing than in counter-sawing.
2. The lowest difference between experimental and theoretical power consumption was 7.4 kW observed at the end of the test during climb-sawing (sawmill B) while the greatest difference was 38 kW observed at beginning of the test during counter-sawing (sawmill A).
3. The power consumption was higher in sawmill B than in sawmill A, due to a high saw kerf width, cant height, and low overlap between sawblades.
4. Power consumption increased by 11 to 35% in the experimental test.
5. Climb-sawing required more power than counter-sawing.
6. The lowest theoretical power consumption was found using greater overlap.

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