A theoretical model for the prediction of energy consumption during the chipper canter process

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KEYWORDS: Canter chipper, Energy consumption, Specific cutting energy

SUMMARY: In modern sawmills, chipper canters are used to transform the approximately circular cross section of logs into a rectangular shape before the log is sawn into planks and boards. The chipper canter is in essence a conical disc equipped with knives on its periphery and a circular saw blade at its base. Thorough the action of the chipper canter, the outer parts of a log is removed and transformed into sawdust and chips. In some situations it might be important to be able to predict the energy consumption during canting, for example when one wants to know whether a particular canting strategy can be used considering that there is a limit to the electrical power supply. The aim of this paper was therefore to develop a theoretical model that can perform such a prediction. The canting process can be divided into two parts; the chipping performed by knifes and the sawing performed by the saw blade on the chipper head. The sawing part is performed in order to get a smooth enough surface of the reduced portion of the log. In this paper, emphasis is put on the chipping part of the process and the contribution from sawing is treated only in principal. The results from the theoretical model were compared to results from a field trial and it was concluded that the model gave a fair prediction of the power needed.

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Since energy consumption in general becomes a more and more important issue, there is a general need to be able to optimize this consumption. In the sawmill industry, there are a number of sources of energy consumption, apart from sawing and canting, e.g. debarking, log in-feed system, log positioning, conveying, edging, drying etc. However, it was chosen to put focus on the canting process i.e. when the circular cross section of a log is reduced to a rectangular or semi rectangular shape before sawing. The reason for this was that one company, being a major supplier to the sawmill industry, claimed that there would be a general interest in this.

The canting is performed using a chipper canter, which in essence is a conical disc with knifes on its periphery according to *Fig 1* (shown with the permission of Andritz Iggesund Tools).

From *Fig 1* it can be observed that the chipper canter is equipped also with a saw blade in order to obtain a reasonably smooth surface of the reduced region of the log.

Fig 1. A chipper canter.

To be able to reduce the energy consumption during e.g. canting, it is necessary to understand how energy is consumed in both the chipping and sawing processes. However, in this paper, emphasis is put on the chipping part and the sawing part will be treated only in principal by showing (without derivation) some results related to the power input.

Even though decreasing the energy consumption for every sub-process (e.g. in the canting operation) is an important issue in the sawmill industry; little research has been conducted in this field. Some results from the literature, touching upon items relevant for canting, are given below.

Uhmeier and Persson (1997) performed a numerical two-dimensional finite element analysis aiming at the predicting of chip thickness and chip damage during wood chipping.

Caughley and King (2003) performed a numerical study of wood during orthogonal cutting using a hybrid cellular/macroscopic finite element method. More specifically, the effect of the knife sharpness was studied.

Utilizing the finite element method together with a particular constitutive model, Holmberg and Peterson (2000) studied the impact of the annual ring structure on the deformation and fracture in wood. The results indicated that when the loading was transverse to the fibres (shear loading), it was possible to predict not only the fracture load but also the actual fracture pattern.

There are some results from energy studies that have been performed during different machining processes on solid wood and fibre boards. In e.g. (Aguilera, Martin 2001) an experimental study of cutting forces and power requirements during machining of beech and spruce is carried out and Aguilera (2011) investigates the energy consumption during sawing of medium density fibreboards.

Model for predicting the power input

In order to develop a theoretical model describing the energy dissipation during canting, one has to figure out which dissipation mechanisms are active. For instance, some of the energy input is transferred to kinetic energy in the chips and in the sawdust, some is transferred to heat through friction, some is spent in creating new surfaces and some is spent in irreversible deformation of the material. In the developed model, only the two last mechanisms are considered. Furthermore, in a real canting process, the ratio between the feed rate and peripheral speed of the canter is in the order of a few per cent and all possible simplifications that can be made from this fact are inherent in the model.

The sawing part of the power input

A model relevant for the sawing part of the canting process is presented below, without giving any details. It is assumed that during sawing, the major contribution to the energy dissipation is through the creation of new surface and through the irreversible compression of the wood below a saw tooth. If the assumption that the ratio between the longitudinal and peripheral speed of the canter is small i.e. that $v_0/(\omega R) << 1$ (where v_0 is the feeding rate i.e. longitudinal speed, ω the angular frequency and R is the radius of the saw blade) is utilised, the energy E dissipated during one rotation of the saw blade can be approximated as:

$$E = N_T \int_{\phi_0}^{\phi_1} Rb(\frac{v_0}{\omega}\beta\gamma_V(\phi) + \gamma_S(\phi))d\phi \qquad [1]$$

where N_T is the number of saw teeth, b is the width of a saw tooth, $\beta=2\pi/N_T$, γ_V is the energy needed to compress one unit of volume of wood, γ_S is the energy needed to create one unit of new surface and ϕ_0, ϕ_1 are defined in *Fig 2*.

In *Fig 2*, h is the height of the cross section that is sawn (which might vary along a log), d is the distance from the centre of the saw blade to the bottom of the log cross section and the horizontal lines denote the fibre direction. An average power P_s can now be defined as:

$$P_S = E\omega/(2\pi) \qquad [2]$$

where E is given by *Eq 1*. *Eq 2* is nothing but E divided with the time for one rotation with the angular frequency ω i.e. $2\pi/\omega$. Even though the contribution from sawing is given, it is not a part of the model due to the lack of information regarding the energies γ_V and γ_S.

The chipping part of the power input

One part of the energy input to the canter, which is not used in the sawing part of the process, will be spent on forming new surfaces both through cutting and through the crack growth along the fibre direction when a chip is formed. The other part will be spent on internal work i.e. through increasing the elastic strain energy in the chip, but will also be dissipated through irreversible deformations. If the only cause for dissipation had been through the formation of new surfaces, then it becomes of course natural with a concept of surface energy. However, since irreversible deformations are presents in parts of the chip volume, it might be that this contribution to the dissipation depends on the chip length. This hints at that

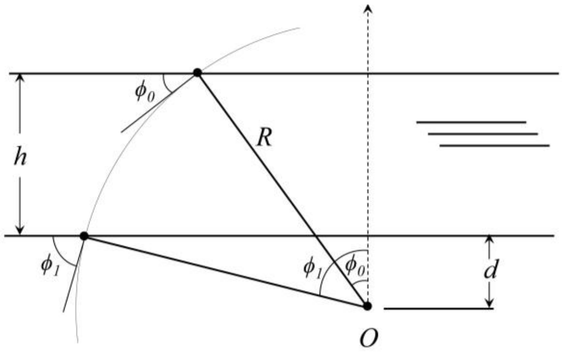

Fig 2. Geometrical parameters relevant for sawing

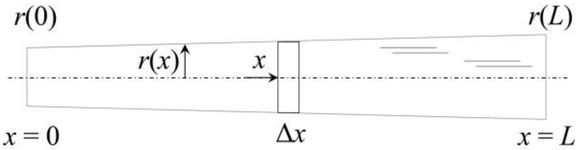

Fig 3. The geometry of the log

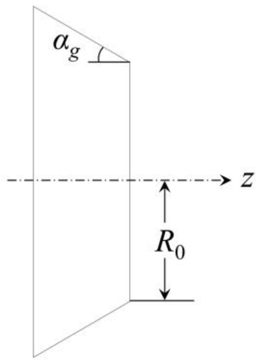

Fig 4. Geometry of the chipper canter.

the concept of a surface energy might be connected to a specific chip length.

To proceed, it will again be assumed that the feeding rate is much less than the peripheral velocity of the knife. For example, using the numerical data presented in the section **Field trial**, it can be concluded that the ratio of the feeding rate to the peripheral velocity is less than 1/20. Another simplifying assumption will be discussed with reference to *Fig 3*.

In a real situation, the taper of a log i.e. $(r(L) - r(0))/L$, is typically of the order 2-4 cm/m. Again, using the numerical data relevant for the field trial, it is found that the log will move some 10 cm (Δx in *Fig 3*) during one rotation of the canter. The chipper canter will then, during one rotation, see a change in the radius of the log cross section of the order of millimetres. Thus is it reasonable to, for every value of x, consider a cylindrical geometry with the radius $r(x) = r(0) + (r(L) - r(0))x/L$.

The geometry of the chipper canter is defined in *Fig 4*, where, α_g defines the taper of the canter and R_0 is its radius at $z = z_0$. Hence, for an arbitrary value of z, the radius $R(z)$ is given by:

$$R(z) = R_0 + (z - z_0)\tan(\alpha_g) \qquad [3]$$

For the first part of the canting process, the geometrical parameters are defined in *Fig 5* and *Fig 6*.

In *Fig 5*, e is the distance from the centre of the canter to the foundation on which the log rests and $R(z)$ is defined in *Eq 3*. $\theta_{in}(z)$ and $\theta_{out}(z)$ are the angles defining

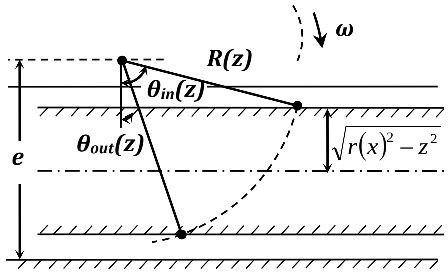

Fig 5. The movement of a certain point on the knife-edge.

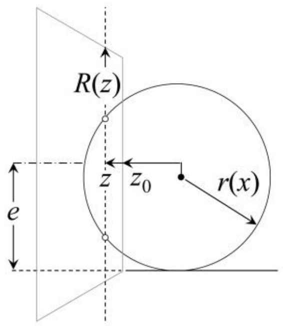

Fig 6. A view of the log cross section.

the entrance and exit of a point on the knife edge at a distance z from the log centre line and ω is the angular frequency of the canter. The distance $\sqrt{r(x)^2 - z^2}$ is defined with reference to *Fig 6*.

Assuming that the log cross – section can be approximated with a circle with a radius $r(x)$, $\theta_{in}(z)$ and $\theta_{out}(z)$ are with *Eq 3* given by:

$$\theta_{in} = cos^{-1}\left(\frac{e - r(x) - \sqrt{r(x)^2 - z^2}}{R_0 + (z - z_0)\tan(\alpha_g)}\right)$$
$$\theta_{out} = cos^{-1}\left(\frac{e - r(x) + \sqrt{r(x)^2 - z^2}}{R_0 + (z - z_0)\tan(\alpha_g)}\right) \quad [4]$$

Now, utilizing the assumption that the feeding rate is much less than the peripheral velocity, the area dA swept by a portion of the knife edge with length $dz/\cos(\alpha_g)$ and during the time $dt = d\theta/\omega$ is given by:

$$dA = R(z)d\theta dz/\cos(\alpha_g) \quad [5]$$

The total work W_{knife} performed by one knife during one rotation of the canter is now given by:

$$W_{knife} = \int_{z_0}^{r(x)} \int_{\theta_{in(z)}}^{\theta_{out(z)}} \gamma(\theta) d\theta dz/\cos(\alpha_g) \quad [6]$$

where z_0 is the distance from the log centre line to the base of the canter (see also *Fig 6* for reference) and $\gamma(\theta)$ is the energy associated with the cutting of one unit of surface. In Lusth et al. (2012) are presented results from an experimental study of $\gamma(\theta)$. In this study, experiments were performed in a pilot wood chipper where the energy consumption per unit of cut surface was determined for a range of cutting angles θ and for a side angle of 45° which should resemble the taper of the chipper canter used in the field trial. Now, if there are N_k knifes on the periphery of the canter, an average power P_c can be defined, in analogy with *Eq 2*, as:

$$P_c = N_k \omega W_{knife}/(2\pi) \quad [7]$$

In the most general situation, the canter is equipped with different number of knifes in different layers (with heights h_1, h_2 etc) such that when $z_0 < z < z_0 + h_1$, $N_k = N_{k1}$, and when $z_0 + h_1 < z < z_0 + h_1 + h_2$, then $N_k = N_{k2}$ etc. Assuming that e.g. three layers are active at a certain instant then the work W performed during one rotation of the canter is given by:

$$\begin{aligned} W &= N_{K1} \int_{z_0}^{z_0+h_1} \int_{\theta_{in(z)}}^{\theta_{out(z)}} \gamma(\theta) d\theta dz/\cos(\alpha_g) \\ &+ N_{K2} \int_{z_0+h_1}^{z_0+h_1+h_2} \int_{\theta_{in(z)}}^{\theta_{out(z)}} \gamma(\theta) d\theta dz/\cos(\alpha_g) \\ &+ N_{K3} \int_{z_0+h_1+h_2}^{r(x)} \int_{\theta_{in(z)}}^{\theta_{out(z)}} \gamma(\theta) d\theta dz/\cos(\alpha_g) \end{aligned} \quad [8]$$

and the average power is:

$$P_C = \omega W/(2\pi \quad [9]$$

In the above situation, the second layer starts to contribute when x is such that $r(x) = z_0 + h_1$ and the third layer becomes active when x satisfy $r(x) = z_0 + h_1 + h_2$. In case $N_{k1} = N_{k2} = N_{k3}$ (which is most common) the three layers can of course be treated as one layer.

It should also be pointed out that the canters always appears in pair such that the average powers defined in *Eq 2*, *Eq 7* and *Eq 9* should be multiplied with two.

The canting procedure

The canting is performed in two steps as shown in *Fig 7* (shown with the permission of Andritz Iggesund Tools). In the first step, two parallel sides are cut off after which the log is turned and the remaining two sides are reduced. After the first reduction and during the second, the cross-section geometry of the log is according to the lower figure. Depending on how the canting is performed, there are a number of different situations that are possible. With reference to *Fig 8 a)*, if the path B is chosen, the canting will start in $x = x_i$, given by $r(x_i) = z_0$. Path A will result if $z_0 < r(0)$. In both case A and B and in the general case with different levels, the power is estimated by use of *Eq 8* and *Eq 9*. It can be noted that for path B and in $x = x_i$, $\theta_{in} = \theta_{out}$ such that $P_C = 0$ in that point.

In the second part of the process (if path A was followed i.e. if $z_0 < r(0)$) the log cross section will initially have the geometry shown in *Fig 8 b)*. Note the appearance of the dimension z_0. Now, in principal, can all cases be treated in a similar way and to prevent the text from being to extensive only one case will be treated i.e. $z_0 = z'_0 = r(0)/\sqrt{2}$ so that a square cross – section results. z'_0 is the distance from the centre of the log to the base of the canter, in the second canting. This differs from the geometry shown in *Fig 7* where a curved part of the log is remaining after the second part of the canting. $s(0)$ is defined in *Fig 8 b)* and if $s(x)$ is taken to mean the vertical distance from the mid plane to the curved part of the cross – section at some point x, then:

$$s(x) = \sqrt{r(x)^2 - z_0^2} \quad [10]$$

For z-values in the interval $z_0 < z < s(x)$, the angles θ_{in} and θ_{out} appearing in e.g. *Eq 8* are given by (here called θ'_{in} and θ'_{out} for clarity):

$$\theta'_{in} = cos^{-1}\left(\frac{e - 2z_0}{R_0 + (z - z_0)\tan(\alpha_g)}\right)$$
$$\theta'_{out} = cos^{-1}\left(\frac{e}{R_0 + (z - z_0)\tan(\alpha_g)}\right) \qquad [11]$$

In the interval $s(x) < z < r(x)$, θ_{in} and θ_{out} are given by *Eq 4* with a slight modification i.e. that the second term in the denominator ($-r(x)$) is substituted with $-z_0$. So, to summarize, during one rotation, one knife will perform the work:

$$W_{knife} = N_{K1}\int_{z'_0}^{s(x)}\int_{\theta'_{in}}^{\theta'_{out}}\gamma(\theta)d\theta dz/\cos(\alpha_g) + \int_{s(x)}^{r(x)}\int_{\theta_{in}}^{\theta_{out}}\gamma(\theta)d\theta dz/\cos(\alpha_g) \qquad [12]$$

For N_k knifes in one layer or if a number of layers are involved the power is defined according to *Eq 7* and *Eq 9* respectively.

Numerical study

As mentioned in the previous section only the case $z_0 = z'_0 = r(0)/\sqrt{2}$ will be considered and in addition it will be assumed that only one level of knifes is involved. The following numerical data (relevant for the field trial performed in this study) were assumed: R_0 = 0.325 m, α_g = 45°, N_k = 4, L = 4.7 m (length of the log), $r(0)$ = 0.1 m, $r(L)$ = 0.125 m, z_0 = 0.0707 m, e = 0.257 m, ω = 62.6 rad/s, v_0 = 60 m/min (feeding rate)

It should be mentioned here that for some chipper canters the number of knifes can be quite large. This is since in order to have a production rate as high as possible, the feeding rate should be high while on the other hand, the rotational speed has a limit on it, determined by the maximum allowable inertia forces, so that in order to get chips which do not exceed a certain length, it might be necessary to increase the number of knifes.

Based on the results in Lusth *et al* (2012) regarding the energy consumption during chipping, the following was assumed for $\gamma(\theta)$: $\gamma(\theta) = c_0 + c_1\theta + c_2\theta^2$ where c_0 = 195 kJ/m^2, c_1 = - 205 kJ/m^2 and c_2 = 139 kJ/m^2 when θ is given in radians. The relation for $\gamma(\theta)$ is valid in the interval $30° \leq \theta \leq 90°$. Briefly put, $\gamma(\theta)$ was determined by chipping of 100 by 50 mm^2 spruce planks at different cutting angles θ, such that a 10% decrease in the rotational speed of a freely rotating (with the electrical supply switched off) chipper disc (with a known moment of rotary inertia) was accomplished. The number of cuts N performed was calculated from the chipped length of a plank and the nominal chip length 25 mm (the same chip length was used in the field trial). Knowing the area A of each cut and the loss in kinetic energy ΔE of the chipper disc $\gamma(\theta)$ was given by: $\gamma(\theta) = \Delta E/(NA)$.

In *Fig 9* the total energy per unit volume of reduced wood (specific canting energy E_s) is shown versus e in the interval: $0 \leq e \leq 0.26$ m. The upper limit of e is chosen such that θ should always be approximately in the interval $30° \leq \theta \leq 90°$.

The energy is obtained by numerical integration (using (Matlab (2010)) of the power as a function of $x = v_0 t$ over the time interval $0 \leq t \leq L/v_0$.

It can be observed that the theoretical model predicts a strong influence of the distance e on the energy consumption. This is because that when e is increased, the angles θ_{in} and θ_{ut} becomes smaller such that $\gamma(\theta)$ (which is an increasing function of θ) becomes smaller.

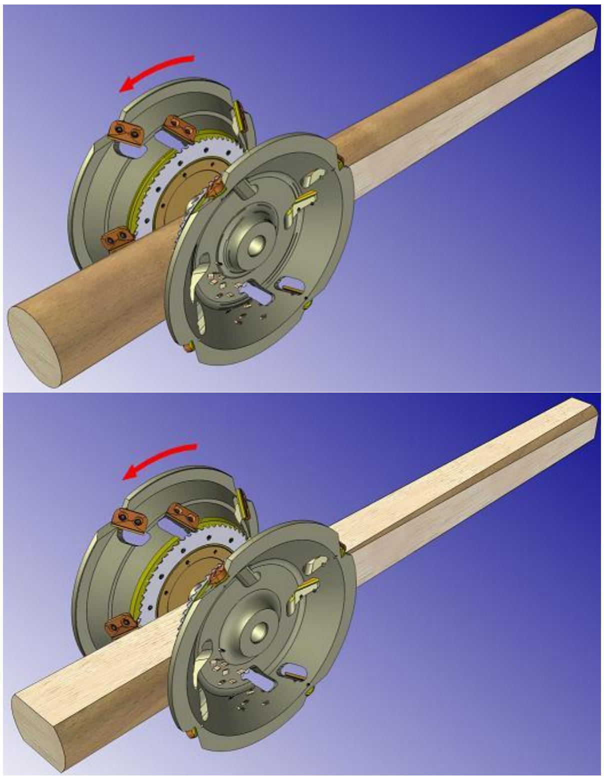

Fig 7. The two steps in the canting process.

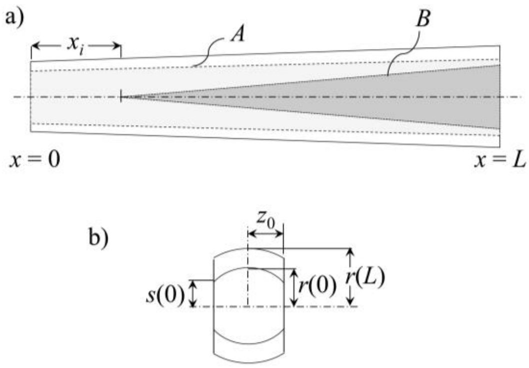

Fig 8. The two steps in the canting process.

Field trial

During the course of this work access was given (through the cooperation with Andritz Iggesund Tools Company) to results from power measurements from a field trial at the Tjärnvik sawmill in Gnarp, Sweden. It should again be pointed out that the numerical data used in section **Numerical study** are taken from this trial. The power measurements were performed for the first part of the canting process only and for eight logs. To determine the power input, a Chuvin Armux (CA 8332) instrument with a sampling rate of 1 Hz was connected to the electrical engines. The calculated power (from the theoretical model) as a function of x is shown in *Fig 10*.

In *Fig 10*, x is the position of the centre of the canter along the log. It can be noted that the power is increasing with x (since the radius is increasing) and that the largest value of the power is 185 kW. The measured power during the first reduction of eight logs is shown in *Fig 11*. The maximum power is in the interval 150 to 220 kW that fits the calculated value (185 kW) reasonably well. It should be noted that the power associated with the sawing part of the reduction is included in the measured values but not in the calculated ones such that the calculated value should be higher. However, it should be pointed out that the specimens used for the experimental determination of $\gamma(\theta)$ contained quite a large portion of heartwood while in the field trial the parts that were removed consisted entirely of sap wood with a lower density and presumably also lower values of the surface energy.

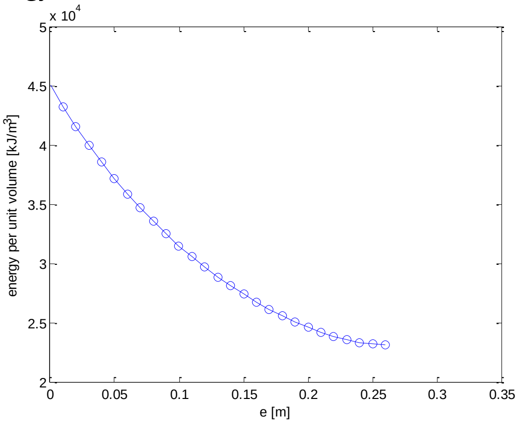

Fig 9. The specific energy E_s as a function of *e*

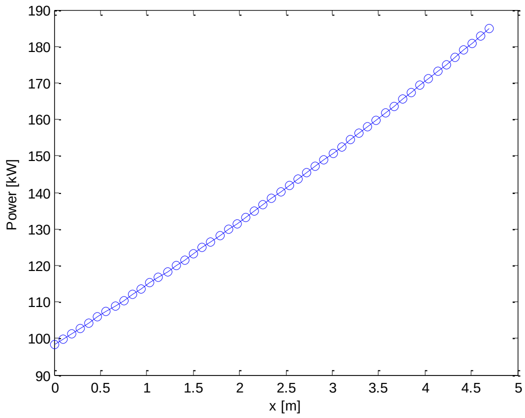

Fig 10. The calculated power as a function of *x*.

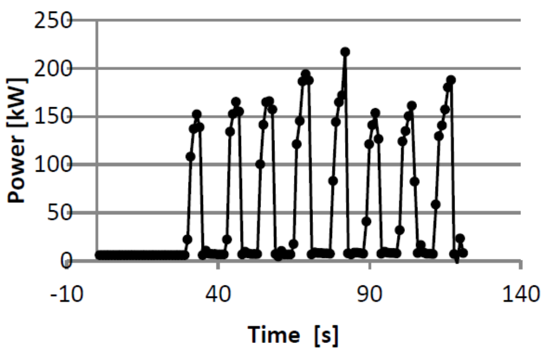

Fig 11. The power during the first reduction of eight logs.

Conclusion

In the development of a theoretical model, intended for the prediction of the power needed for performing the chipping part of the canting process, two simplifying assumptions are made. First it assumed that the peripheral velocity is large compared to the feeding rate. This is most often the case. The second assumption is that the taper of the log is small, such that during one rotation of the canter chipper, the knives will experience a geometry which is almost constant. Both these assumptions are actually based on what is experienced during the field trial. It should however be pointed out that in situations where these assumptions are not realistic, there is in principal no difficulty to include large feeding rates and large tapers.

When applying the theoretical model together with the experimental data to a field trial it was concluded that the model gave realistic results as compared to the measured power values. Since the number of logs included in the field trial is limited (only eight logs) it is not possible to make any advanced statistical evaluation but it is realistic to assume that one can expect at least the scatter observed in $\gamma(\theta)$ i.e. a standard deviation of about 10%. To make the model complete, it should be augmented with the contribution from sawing. A theoretical model for that exists but as for now, no experimental data concerning the energy dissipation during the sawing part are at hand.

Acknowledgements

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