Thickness Accuracy of Sash Gang Sawing

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Thin lamellae, corresponding to the layer components of structural glued members, *i.e.* 2-ply or 3-ply glued parquet, can be manufactured in re-sawing operations of kiln-dried wood blocks. These must be prepared with high dimensional accuracy and adequate surface quality following specific technical requirements for lamellae thickness variations, especially in the upper layers of the glued composite parquet. The accuracy of oak lamellae thickness was examined here for a re-sawing process performed on the sash gang saw. A series of cutting tests were carried out in sawmill production conditions. The overall objective for these observations was to determine an effect of both the cumulative time of sawing (progress of the tool wear) and the lamella position (distribution of lateral forces) on the dimensional accuracy of production. Lamellae size control was conducted following the Brown methodology. Detailed within-board, between-board, and total sawing standard deviations for the examined lamellae positions in the gang were determined. The obtained results revealed that outermost lamellae are more subjected to dimensional inaccuracy than lamellae from the centre of the sawn block or frieze.

Keywords: Sawing accuracy; Sash gang saw; Thickness; Lamellae; Upper layer; Quality

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INTRODUCTION

The breakdown of logs into timber in sawmills as well as re-sawing of cants and friezes into lamellae are the most common wood machining operations performed in primary and secondary wood industries. The emerging necessity for sustainable usage of raw natural resources, limitation of log supply, rising cost of production, and increasing international market competition are only some of the incentives stimulating wood companies to seek continuous improvement of their production practices (Breinig *et al*. 2015; Johansson 2008; Nasir and Cool 2018). It was known to sawmill professionals, and evidenced by Brown (2000a), that sawmills utilizing a “tight machinery” paradigm can set the target thickness of manufactured boards a few millimeters closer to the expected target size, compared to sawmills with “looser machinery”. Thus, tightening dimensional tolerances leads not only to saving wood resources but also higher economical profits for a sawmill (Vuorilehto 2001).

The target size of a wooden board is a combination of several allowances that are necessary to add up to the nominal dimension to assure the final size of product required by a customer (Fig. 1). These are directly related to downstream production operations and may include oversizing, shrinking, warping, planning, or sawing allowances. The detailed values of allowances depend on the processed wood species, implemented process, quality of tooling, and general technical development of the factory, among others. As a rule, any not justified additional thickness in excess of a target size is considered as a loss, which should be avoided. The oversizing of lumber during the primary sawing process leads to considerable financial losses and impairs an organization's competitiveness. Young *et al.* (2007) reported that the oversizing of rough sawn lumber can lead to losses of $50000 to $250000 per year depending on the sawmill capacity.

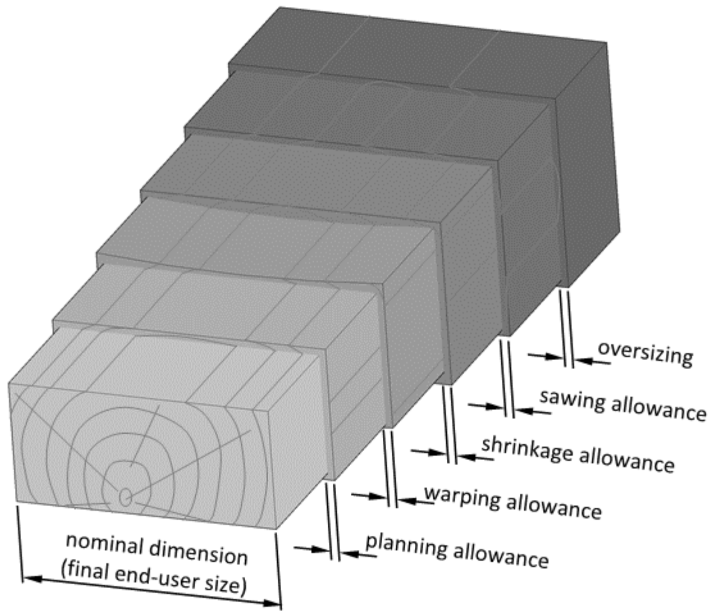

Fig. 1. Allowances from rough green target size to the final size of the board (after Vuorilehto, 2001).

Such a financial (or quality) loss L was defined by Taguchi as a mathematical function $L(g)$ (Eq. 1) where g is a variable describing the workpiece dimension (Young and Winistorfer 1999; Hamrol and Mantura 2002; Orlowski 2009). Size errors correspond therefore to the difference between the measured and tolerated dimensions, expressed as g and g_{EN} respectively. K represents a loss constant defining a financial effect of the dimensional imperfection.

$$L(g) = K(g - g_{EN})^2 \tag{1}$$

The Taguchi loss function shows that even small deviations from a target dimension induce financial loss (Hamrol and Mantura 2002). In fact, product is considered as not usable when measured dimensions exceed the consumer's tolerance specification. In some cases, the out-dimensioned product can be re-conditioned in the following operation or used as a raw material for manufacturing of alternative products. However, this creates additional costs and production planning challenges.

The methodology for determination of optimal machining allowances and its application in the technological process of manufacturing oak components for the upper layer of glued floorboards is described in the work of Kujawinska *et al.* (2018). The soft modeling approach for estimation of raw material waste during production of 3-ply flooring board middle layers was proposed by Kujawinska *et al.* (2017a). Likewise, optimization of raw material allowances in the production of thin lamellae made from selected European and exotic species by implementation of "wet technology" production on band sawing machines was researched by Kujawinska *et al.* (2017b). Schultz and Haas (2001) analyzed an economic efficiency of engineered flooring production. It was reported that sash gang sawing is the most productive technology when processing lamellae of 4 mm thickness and width <180 mm (Schultz and Haas 2001). Nevertheless, band sawing was confirmed as the most productive when assuming other sawing configurations (Orlowski and Walichnowski 2013).

The assurance of accurate board thickness is a major challenge for statistical control of the wood sawing process. For that reason, a proper methodology for thickness measurement is indispensable. Unfortunately, board thickness is not frequently measured on-line or in a continuous manner. In production reality, the measurement is usually performed manually, with a caliper, on a few randomly selected boards at different times arbitrarily chosen along the production sequence. The resulting data are rarely utilized for consistent statistical analysis of the process performance, but they are usually used as *ad hoc* assurance of the machine's current settings. As an alternative, board thickness could be controlled with diverse optical devices that are capable of continuous measurement (Vuorilehto 2001; Sandak *et al.* 2006). Thickness profiles obtained with high precision laser displacement sensors may be affected by wood anatomical features that reduce the reliability of measurement. However, this limitation can be handled with proper use of signal filtering methods (Sandak *et al.* 2006). Similarly, the sawmill's harsh environment highly influences the reliability of measurement. Advanced signal processing, dedicated numerical algorithms and multi-sensor arrangements can be used to compensate for relative motions between the wood and sensors (Vadeboncoeur *et al.* 2008). Simplification of the routine thickness measurement procedure, utilizing dedicated accessories, is an alternative to costly optical instrumentation. A manual thickness scanner designed specifically for the routine assessment of thin lamellae thickness was developed by authors (Wasielewski and Orlowski 2009).

Even if automatic thickness measurement systems allow continuous acquisition of data, the manual procedure considerably limits the data collection frequency. The board thickness assessment is performed usually after changing the machine set-up or cutting tools, and after that randomly for verification of the process consistency. The collected data in most companies are not really used for the statistical analysis or process control. This results in a poor understanding of the process and consequently increases losses. A very simple improvement would be therefore to connect the measurement device (usually caliper) to the dedicated database and to perform automatized statistical analysis.

Uniform thickness, regular shape, smooth surface, and low roughness is the expected quality of a timber piece from the thin lamellae sawing process. Nevertheless, diverse imperfections of the form and shape may occur due to wood-, tool- or machine-related issues. Errors in form for longitudinal direction may be related to the taper, hook, or snaking. The wedge, step, and off-set are most frequent on the sawn surfaces processed on two arbour circular sawing machines (Vuorilehto 2001). The accuracy of sawing is highly related to the tool and cutting edge quality. This includes tool sharpness that highly affects generated surface roughness. Similarly, imperfection of the tool geometry (lack of symmetry, deviation from the centre line, wrong cutting angles, or other faults caused by regrinding) could result in a flutter error or *washboard pattern* (Orlowski and Wasielewski 2006). The latter phenomenon may also occur when cutting wood on the bandsaw (Lehmann and Hutton 1997; Okai *et al*. 1997; Okai 2009).

Even if accurate and frequent measurement of board thickness is essential to assure refined production quality, appropriate use and interpretation of the obtained data are still problematic. Therefore, the goal of this research was to demonstrate a complete approach for statistical assessment of production accuracy. A special focus was placed on the re-sawing operation of the most valuable wooden boards that are used, for example, as the visible layers of engineered flooring composites. An overall objective was to evidence an effect of the lamella position in the gang on obtained accuracy, expressed as a standard deviation of thickness distribution.

THEORETICAL BACKGROUND

Birch (*Betula* L.), beech (*Fagus sp.*), hornbeam (*Carpinus betulus* L.), great maple (*Acer pseudoplatanus* L.), oak (*Quercus* L.), and ash (*Fraxinus* L.), as well as some exotic woods, are species most frequently used in Poland for production of the surface layers in composite flooring panels. Tolerance for lamella thickness is very limited, and, according to Polish and European standards (PN-EN 13226 (2004)), the allowed variation must be less than ±0.2 mm. The suggested methodology for accurate assessment of board thickness variations was proposed by Brown (2000a,b). In that case, it was recommended to measure thickness with a caliper in a discrete manner, considering at least 8 points that are located along both edges of each examined board. The quantifier of thickness inaccuracy is the total standard deviation S_T.

Within-board standard deviation S_w and between boards standard deviation S_B are two components contributing to the total standard deviation S_T of board thickness produced by a gang saw in a single batch. The gang saw is considered here as a multi-tool machine capable to re-saw several lamellae at once during a single pass of the material. Within-board standard variation S_w is, therefore, a quantifier of the thickness variance along the length of a single board, computed separately for each lamellae within a gang. Between boards standard deviation S_B is a measure of how the average thickness of all re-sawed boards varies within a batch, considering only those lamellae that were produced at the same position within the saw gang. The following formulae (Brown 2000a) were used for statistical process evaluation of lamellae re-sawing:

- Standard deviation S_j of the lamella thickness in lamella j (Eq. 2):

$$S_j = \sqrt{\frac{\sum_{i=1}^{n_j} x_i^2 - \frac{\left(\sum_{i=1}^{n_j} x_i\right)^2}{n_j}}{n_j - 1}} \tag{2}$$

where: x_i – lamella thickness in a single measurement point (mm), n_j – total number of measurements on the upper and lower measurement lines as defined in Fig. 4.

- Mean square (variance) MS_j (Eq. 3):

$$MS_j = (S_j)^2 \tag{3}$$

- Within-lamella standard deviation S_W, assumed as an average of the individual lamella standard deviations on the lower or upper measurement line for the number of lamellae in a gang k (Eq. 4):

$$S_W = \sqrt{\frac{\sum_{j=1}^{k} MS_j}{k}} \tag{4}$$

where k is the number of boards.

- Between board standard variation S_B between successive boards sawn in the same place of the gang (Eq. 5),

$$S_B = \sqrt{\frac{\sum_{j=1}^{k} \bar{x}_j^2 - \frac{\left(\sum_{j=1}^{k} \bar{x}_j\right)^2}{k}}{k-1}} \tag{5}$$

where $\bar{x}_j$ is the average thickness of the board j (mm),

- Total standard deviations S_T that describes total changes of the lamella thickness on the upper and lower measurement lines for all lamellae within a batch that were sawn in the same place of the gang (Eq. 6),

$$S_T = \sqrt{\frac{\sum_{i=1}^{N} x_i^2 - \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N}}{N-1}} \tag{6}$$

where N is a total number of measurement points either on the upper or lower line.

Eklund (2000) applied similar methodology for determination of the total standard deviation of boards' thickness after the band sawing process. The difference, aside from the cutting process configuration (single saw), was in the methodology where investigated boards were thicker (22 mm) and longer (4m), while thickness was measured at 10 points.

MATERIALS AND METHODS

Experimental cutting tests were carried out at the Łączy - Kołczygłowy Sp. z o.o. plant in Barnowo (Pomerania Region, PL). This company specializes in production of engineered floorings composed of multi-layer glue-laminated wooden boards. The re-sawing process of the most valuable upper layers of the floor composite was under investigation. The machine used for this operation was a frame saw Mamuth (Neva, CZ) equipped with a channel system for simultaneous feeding of boards (Fig. 2). The number and configuration of saw blades installed in the gang was identical in each channel and consisted of two scraper and two thin cutting saw blades. The scraper saw was thick and used for processing the outermost lamella of every board. The thin cutting blades were empirically pre-selected to assure a high level of cutting accuracy while minimizing the saw kerf. All saws used during the experimental campaign were new and sharpened by the saw producer. The consistent tooth geometry, tooth symmetry as well as precise radial and tangential clearance angles were inspected for all blades used in the experiment (Fig. 3). The overall set of scraper and thin saws were S_{t_sc} = 2.9 mm and S_t = 1.4 mm, respectively. The thickness of the scraper saw blade was s_{sc} = 2.4 mm, compared to the thin cutting saws at s = 0.9 mm. The scraper saws had rectangular windows cut-out in the blade (Fig. 3b) to allow reaching the proper strain in thin cutting saws, because they are strained in the manner that was described by Orlowski et al. (2001). Each tooth was stellite tipped with the rake angle γ_f = 8° and clearance angle α_f = 11°. The number of strokes of the frame was set to a constant 400 spm (stroke per minute) with the feed speed of 0.25 m·min^{-1}.

Oak (*Quercus* L.) boards of 24 mm thickness were re-sawed to produce three lamellae of 200 × 2000 mm^2 (width × length, respectively), as shown in Fig. 2. The nominal thickness was t_l = 6 mm with a tolerance for lamellae thickness deviation defined as < ±0.2

mm. The average moisture content of wood was *MC* = 8.5% as a "dry" technology of the lamellae production applied on the frame saw.

Two successive lamellae from channel A, B, and C (Fig. 3a) were collected every hour for the thickness measurements. The whole experiment lasted for 13 hours and resulted in 14 measurement sets. The lamellae thickness was manually measured with a digital caliper (type Gedore No. 711, 0–150 mm, UK, accuracy ±0.03 mm) three times on both edges, providing six thickness values for each lamella. The location of measurement points on the lamellae is presented in Fig. 4.

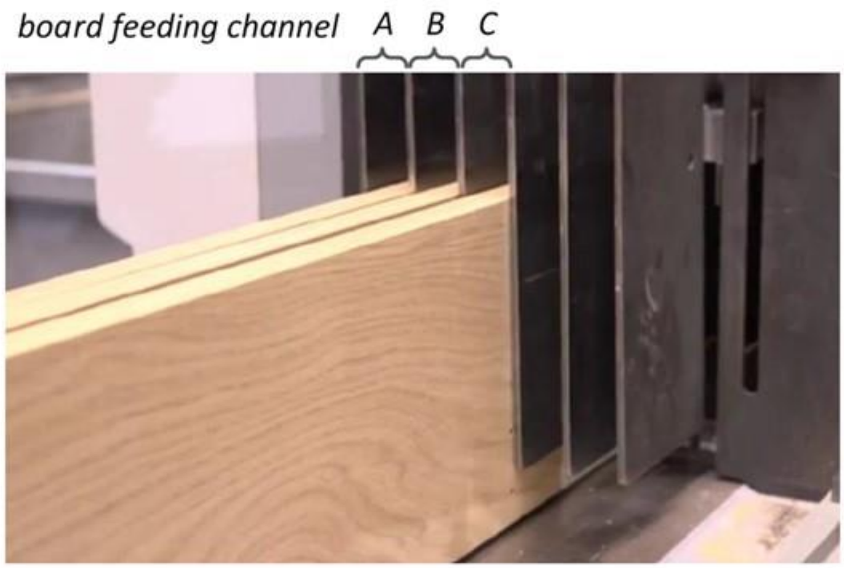

Fig. 2. Channel system for board feeding

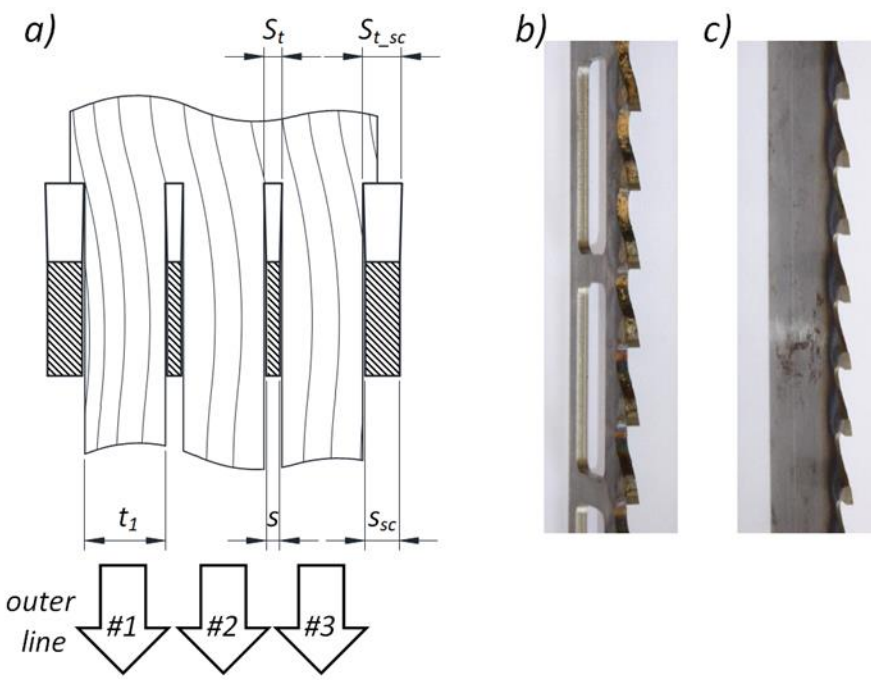

Fig. 3. Gang of saw blades (a), with the scraper (b), and the thin cutting saw (c)

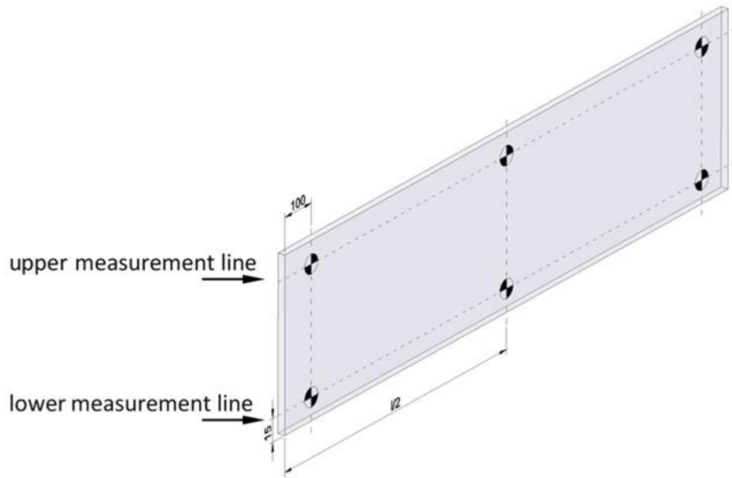

Fig. 4. Locations of measurement points on the sawn lamella

RESULTS

Overall, 168 thickness measurements per channel were performed during the experimental campaign. Within-lamella standard deviation S_W, between lamella standard deviation S_B and total standard deviations S_T were computed for each channel (A, B, and C) in the gang separately. The summary of results obtained is presented in Fig. 5. The most accurate thickness was noticed for all lamellae produced in the inner line (#2). In this case, each quantified deviation was smaller than corresponding results of outer lines #1 and #3. Thus, the total standard deviations S_T obtained for lamellae in line #2 were assumed as best possible performance indicators for the machine-tool-workpiece configuration analysed. It was found that the value of S_T for oak lamellae re-sawn in line #1 was nearly 40% higher than the total standard deviation S_T obtained in line #2. Similarly, the value of S_T measured for line #3 was more than 25% higher than reference line #2.

Further analyses of the thickness changes reveal a noticeable variation of the initial saw gang's setting. The nominal thickness of the lamella was defined as 6.0 mm (indicated as black arrows). However, even if cutting with sharp tools at the initial phase of the working shift, the mean lamellae thickness varied from 5.8 to 6.2 mm. The time-released trend (black line in Fig. 5) indicates dependency of the production quality (thickness accuracy) on the re-sawing period and related cutting tool sharpness. This is especially apparent for lamellae produced in lines #1 and #3, where a nearly monotonic increase of the thickness is evident. Unfortunately, it was not possible to confirm capability of this production system to fulfil refined requirements of the tolerable deviation (± 0.2 mm) from the nominal thickness (6.0 mm). A similar conclusion can be derived by analysis of the lamella standard deviation S_W, between board standard deviation S_B and total standard deviation S_T changes as summarized in Fig. 6. The tolerable thickness deviation (marked as black arrow) was exceeded in a majority of time periods, especially for lamellae produced in lines #1 and #3. The variation of indicators presented in Fig. 6 indicates the relative steadiness of the thickness deviations after the first half of the working shift, corresponding to 8 hours of cutting after replacement of saws. However, if considering the continuous change of mean thickness, the process cannot be assumed as stable.

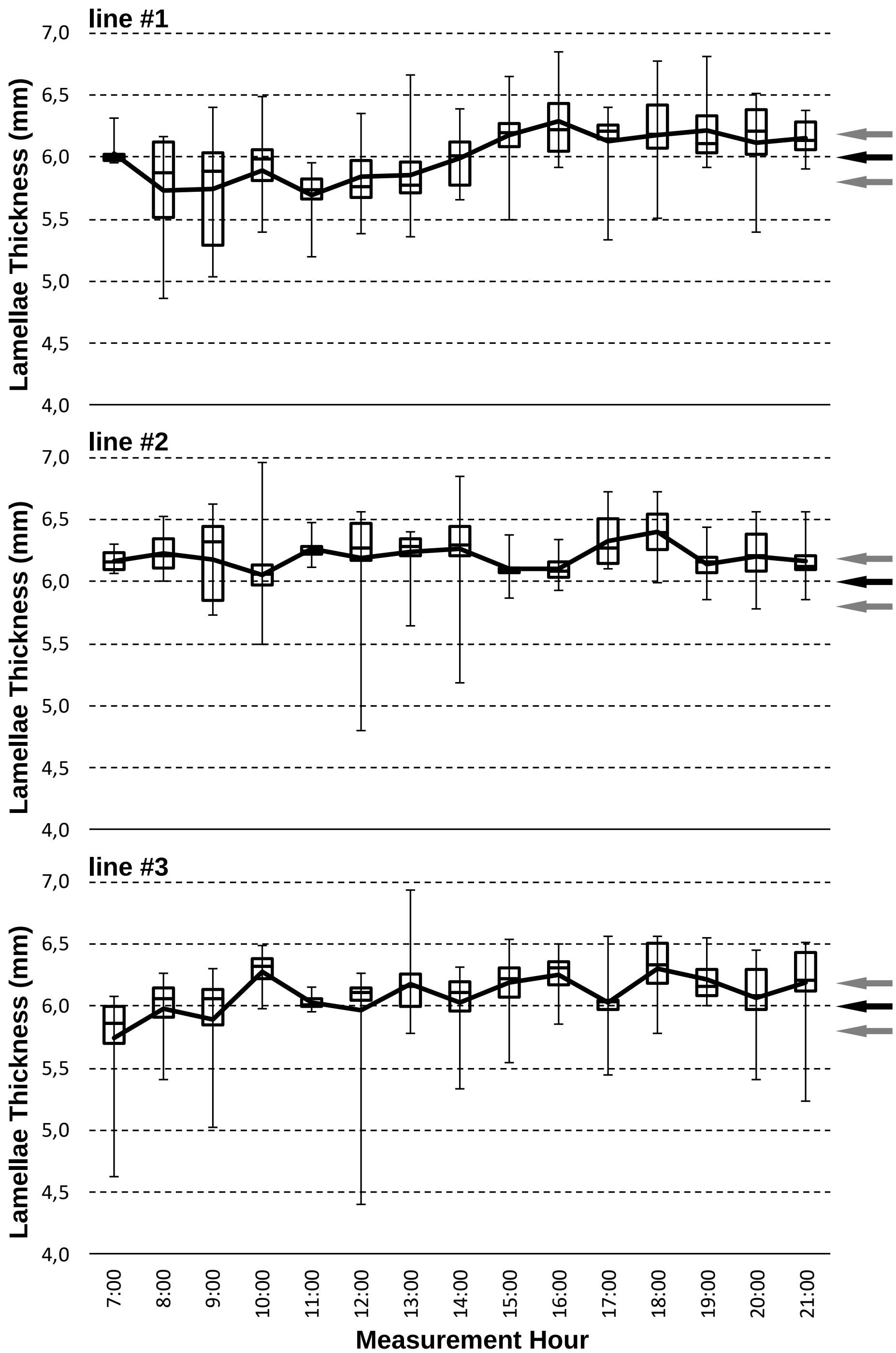

Fig. 5. Changes of lamella thickness in different lines during re-sawing operation with a single set of saws along two working shifts. Note: Box plot corresponds to median and Q1/Q3 quartiles, black line reveals the trend of the mean thickness, whiskers indicate min-max range of measurements. Black arrow: Set thickness of lamella. Grey arrows: Range of tolerated thickness variation.

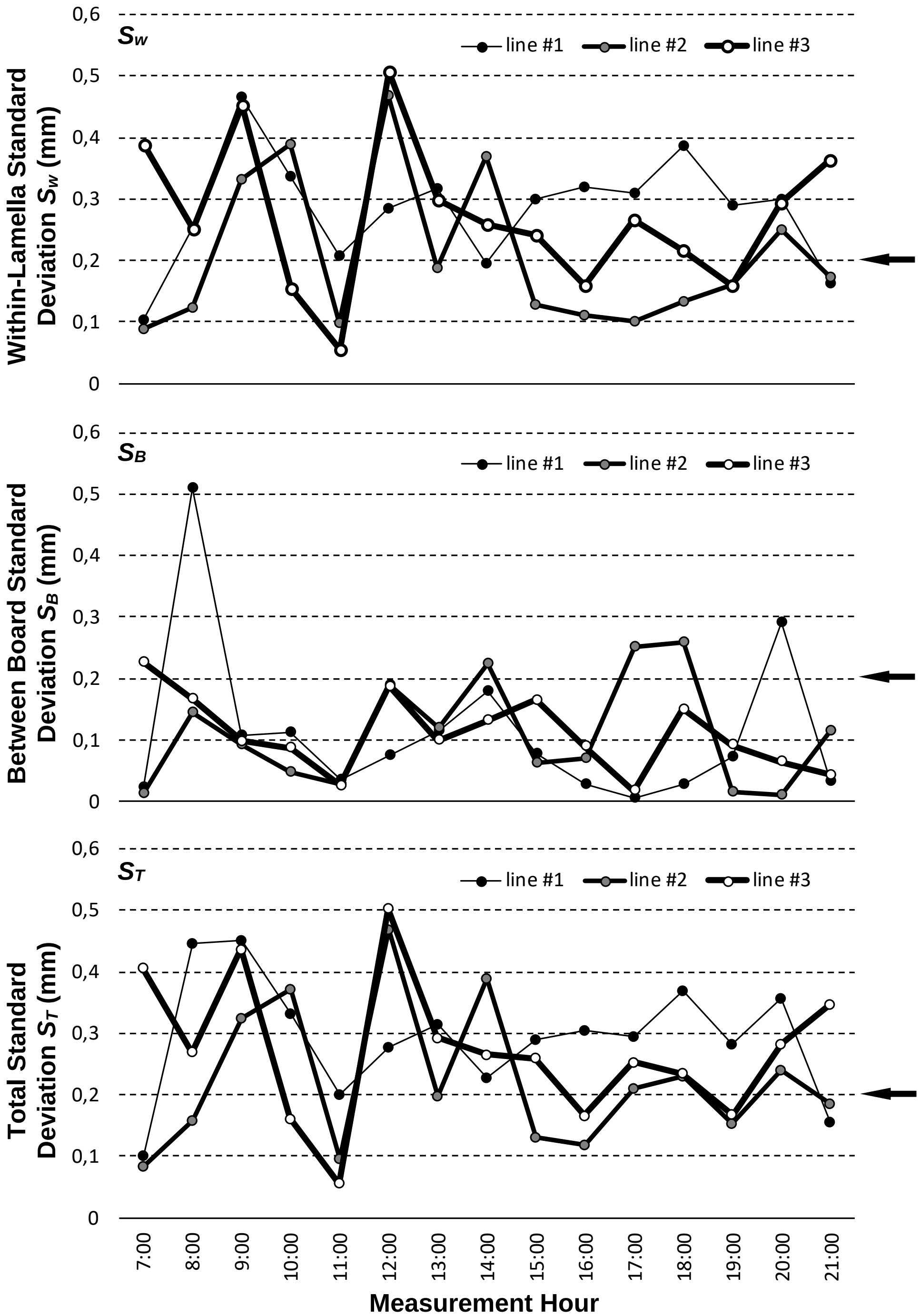

Fig. 6. Changes of within-lamella standard deviation (S_W), between board standard deviation (S_B) and total standard deviation (S_T) of the lamella thickness recorded separately for each line along two working shifts

The daily summary of investigated re-sawing process deviations is presented in Fig. 7. It confirms the set of observations derived from hourly assessments. The superior thickness accuracy was in lamellae re-sawed in line #2. In that case, S_W, S_B as well as S_T deviations were smallest, only little exceeding the permitted level of 0.2 mm.

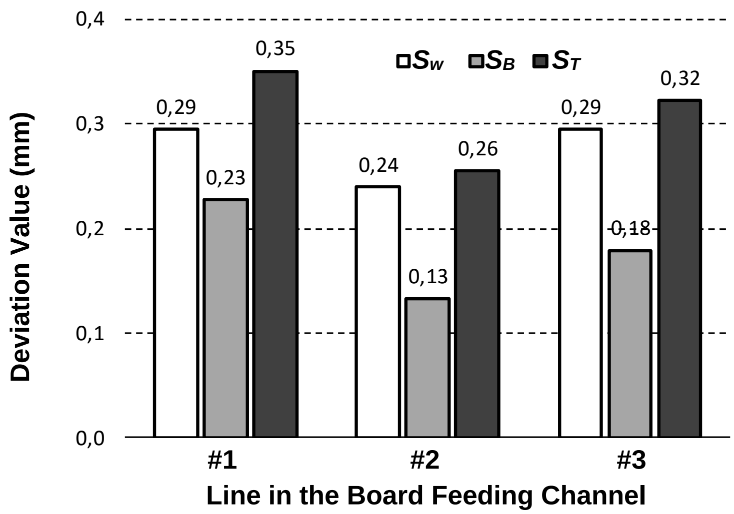

Fig. 7. Daily summary of within-lamella standard deviation (S_W), between lamella standard deviation (S_B) and total standard deviations (S_T) for outer lamellae (lines #1 and #3) and inner lamella (line #2) observed in all board feeding channels after 14 hours of sawing without saw replacement

DISCUSSION

The evidenced poorer thickness accuracy of all outermost lamellae is a result of the particular cutting conditions of the scraper saw. These saws are asymmetrically loaded with back (thrust) forces that are transverse to the blade. This force is unbalanced on the other side of the blade due to a lack of processed material. These loads cause side deflection of the blade, which results in the loss of sawing accuracy. The higher thickness of the scrapper saw blade is not contributing to the increase of its stiffness due to presence of rectangular windows. As a consequence, the same tensioning force applied in the scraper and thin sawblades does not assure equal resistance to back forces. It was also found that saw blades designed for thin kerf cutting are very flexible, especially under torsional loads caused by torque of the back force (Orlowski 2003). This results in not only an easy adaptation of the saw blade position in case of temporally excessive forces but also the straightforward returning of the blade to the nominal position when acting forces are balanced.

Even if not measured directly within this experimental campaign, the increase of tool wear along the working shift could contribute to overall sawing accuracy. Thrust forces are especially affected by the sharpness of the cutting edge, increasing rapidly for dull tools. It is related to a very low clearance angle of the side (minor) cutting edge (Orlowski 2003, 2007, Sinn and Lichtenneger 2017) combined with zero rake angle and high cutting angle, which in this particular case equals to 90°. Therefore, an increase of the lamellae thickness in lines #1 and #3 is related to the continuous rise of thrust forces at the working corners of scrapper saws along the progress of the tool wear.

The detailed analysis of experimental results leads to an overall assumption that the system investigated was not capable of producing the required quality products of refined dimensional tolerances (6.0 ±0.2 mm) in a single step. Therefore, it was recommended to the sawmill's management to reconsider the technological process flow and implement an additional step for thickness calibration. A suitable machine was already present in the factory that minimized production downtime and necessary investment. The revised process included one-side thickness calibration of all lamellae on the milling planer with a belt feed (Ledinek Rotoles 40 D-S, Hoce, Slovenia). This operation, even if it provides an additional cost for production, was identified as economically sustainable. It guarantees expected accuracy for the lamellae before gluing operation while benefiting from high yield of the re-sawing operation with very thin sawblades. It was found that the capacity of a single milling planner was sufficient to simultaneously serve two gang saws operating continuously at highest feeding speeds reaching 45 m·min^{-1}.

CONCLUSIONS

The manuscript presents a dedicated methodology for production quality control of gang sawing process. The carried-out analyses allowed identification and documentation of undesired wood machining effects resulting in lower accuracy of the re-sawing process of thin lamellae. The following conclusions can be derived:

1. All the process accuracy quantifiers implemented here (S_W, S_B and S_T) revealed that thickness deviations for outermost lamellae were continuously highest along the working shift. The main reason for such dimensional inaccuracy is the asymmetrical action of cutting forces induced on the minor cutting edges of the scraper saws.
2. Back (thrust) forces are unbalanced due to the lack of processed material and might cause torsional displacements of acting saws. This appears even if the scraper saw blade thickness (2.4 mm) is 270% higher than the inner thin cutting saw blade (0.9 mm).
3. A continuous increase of the thrust cutting forces causes steady increase of the lamellae thickness produced in lines #1 and #3.
4. Continued operation of the used tools and related excessive increased dullness may result in further sawing accuracy deterioration, including increase of the thickness deviation for inner lamellae.

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