1 INTRODUCTION

In the face of fierce competition and increasing requirements concerning products available on the market, improvement of manufacturing processes has become one of the main challenges for modern manufacturing companies. The pace of changing customer requirements, products and technologies is accelerating and at the same time shortening the time for learning, mastering and optimizing the manufacturing process [1, 2, 3]. Hence the automation of process data collection is so important. Analysis of the data can provide valuable support in the decision-making concerning the manufacturing process [4]. Analysis results can be utilised in many ways in process management. For example, data analysis can be utilized in the detection of process disruptions, search for their root causes and making the process resilient to their impact. Analysis results can be applied in the selection of optimal process settings for predefined criteria [5, 6].

Some examples of process optimization support Lean Six Sigma methods include the Statistical Process Control (SPC) and the Design of Experiments (DoE) [7, 8]. Through monitoring and analysis of changes of product (process) critical features, the SPC facilitates the minimization of process variability. The DoE, on the other hand, permits to identify variables (also called factors) which have a material impact on process results, and determine how strong the impact is. In addition, the DoE can be applied to examine mutual dependencies among factors. The DoE is most often used to determine levels at which certain factors should be set in order to optimize the process. Both approaches are based on a process model which, on the basis of process input data (e.g. properties of raw materials) and data describing the course of the process, facilitates the estimation of process output data, taking into consideration a random variable. A well designed model should facilitate control of the manufacturing process and making it resilient to internal and external disruptions, as well as leave room and provide mechanisms for optimization of the process.

Many successful applications of SPC and DoE tools prove that they should be used in the manufacturing industry [9, 10, 11]. However, efficient use of the tools is often hindered by a lack of clear guidelines concerning particular industrial applications. Concepts are not put into practice due to little knowledge about the modelled process or multiple factors affecting the process. Such is the case in the wood industry, characterized by high complexity of processes and elevated variability of the input material, generating high costs of manufacturing [12].

The costs incurred by wood processing companies are increased by material waste caused by large machining allowances, which result from low stability, i.e. high variability of manufacturing processes. Such is the case in the manufacturing of the surface layer of three-layer floorboards. According to Orłowski, the costs of raw material in the manufacturing of the oak surface layer of floorboards have the greatest – more than 80% – share in the total costs of manufacturing, with the costs of tools amounting to 6% for the frame saw and 5% for the band saw [13]. Therefore, in order to optimize the lamella manufacturing process, it is crucial to identify the sources of process variability and minimize it, rather than give large machining allowances which cause excessive waste of raw material.

The study conducted by the authors was aimed to optimize the process of grinding lamellas – the final operation in the manufacturing of the oak surface layer of floorboards. A full factorial experiment was designed and conducted.

2 SUBJECT MATTER OF THE STUDY

The subject matter of the study is the manufacturing of 3-layer floorboards (Fig. 1). The top layer, also called the surface layer, is made of European or exotic wood of specified toughness (e.g. oak or beech). The middle layer is made of coniferous wood and typically placed transversely to the top and bottom layers. Such an arrangement relieves tension and natural working of wood and thus prevents swelling, creaking and gap formation in the floor. The bottom layer is also made of soft coniferous wood. In the last stage of manufacturing, the three layers, bonded together, are coated with varnish which gives the board a nice finish and protects it from any mechanical damage. Typically, the boards are laid as a floating floor [14].
The surface layer – the lamella – is an especially important component of the floorboard. It gives the floorboard an aesthetic finish and at the same time makes the floor robust and durable.

One of the critical features of the lamella is its thickness. According to the Polish regulations, bonded layers of wood can be called a floorboard if the top layer is at least 2.5mm thick. A block whose top layer is thinner than that is classified as a panel – a lower class product.

Thickness of the lamella is shaped in three operations: timber cutting, drying, and surface grinding (Fig. 2).

One of the basic technologies of the surface layer processing is mechanical processing. It generates substantial waste of the raw material. Typically, the waste is caused by high operational allowances, which must be given due to a non-homogenous character of the raw material. Natural defects of wood may include uneven surface, deformation in the process of drying, etc. Large machining allowances are given to prevent the manufacturing of semi-finished products whose dimensions do not meet the requirements. However, they generate additional costs.

Machining allowances should be economically justified and ensure the required geometrical precision of the product and quality of its surface. At the same time, minimum possible waste of the raw material should be ensured.

The core element in the structure of manufacturing costs of lamellas is the cost of the raw material. It amounts to almost 80% of the total manufacturing cost [14]. Therefore, identification of the sources of raw material waste and opportunities for the reduction of the same is of utmost importance. One of the means to this end is conducting factorial experiments for specific operations. This paper presents assumptions for and results of a factorial experiment for the last operation in the lamella manufacturing process, i.e. grinding of its surface, which has a decisive influence on the quality of the lamella.

3 ASSUMPTIONS FOR THE EXPERIMENT

The factorial experiments conducted for the grinding operation covered three types of studies aimed to obtain lamellas whose surface meet the requirements concerning its quality and dimensions. Three types of experiment were designed, with the following objectives (Fig. 3):

- determination of optimal machining parameters – Experiment 1,
- determination of the parallel arrangement of lamellas – Experiment 2,
- determination of the minimum machining allowance – Experiment 3.

The input material for the study were lamellas, put through the drying process in MÜHLBÖCK TYPE 606/1306 chambers. Three various drying procedures were conducted in the semi-automatic mode, taking into consideration the fact that the process of drying a wet lamella after the cutting operation has a material impact on the quality of its surface in the next operation, i.e. grinding. Changes in the moisture level in the drying operation determine not only dimensions of the dry wood. Drying wood is prone to inner stresses, which change its shape and cause cracking. Such defects may prove difficult or even impossible to be eliminated in the grinding operation, and cause waste of the raw material. The parameters which differentiated the three drying procedures were: the chamber temperature t [°C], the psychometric difference dt [°C], air humidity UGL [%], duration of conditioning, and...
operation of reversing fans. Procedure 1 was quick (aggressive) and lasted only 67 hours. Procedure 2 lasted 73 hours, procedure 3 – 121 hours (slow). The expected 12% wood moisture level was obtained in all the three procedures. An evaluation of the surface of dry lamellas led to a conclusion that procedure 1 (quick) did not have any material negative impact on the quality of lamellas, compared to procedures 2 or 3 (slower). Slowing up of the drying process did not produce a significantly higher percentage of lamellas meeting the predefined requirements. Therefore, the three drying procedures are comparable.

3.1 Experiment 1 – results and analysis

Experiment 1 was designed to determine the grinding operation parameters which would produce the expected surface quality for the bonding operation. A sample of 160 lamellas dried in procedure 1 was selected, as the number of lamellas which did not meet the requirements was not materially different from that obtained in drying procedures 2 or 3. The experiment was conducted on a Buffering machine, the rated dimension was assumed at 3.4 mm. Four lamellas were arranged in parallel (Fig. 4). The lamellas were ground on both sides.

![Grinding machine – four lamellas in parallel.](image)

The study was conducted according to the following scheme:
- The experiment was conducted according to the scheme in Table 1 on lamellas ground on one side to the rated dimension of 3.8 mm. The experiment covered the grinding and evaluation of the other side of the lamella.
- Twenty lamellas were examined for each of the settings of the three analysed factors – class of lamellas [15], combination of advance and speed of the grinding belt, and number of passes.
- Once the best combination of factor levels was identified (one which produced the highest percentage of lamellas compliant with the requirements), 42 lamellas were examined for verification.

Study results and conclusions:
- The highest percentage (75%) of lamellas compliant with the requirements was obtained for the combination of class without knots, advance of 7 m/min and speed of the grinding belt of 17 m/s, in one pass.
- The lowest percentage (15%) of lamellas compliant with the requirements was obtained for the combination of class with knots, advance of 7 m/min and speed of the grinding belt of 17 m/s, in one pass.
- For the class with knots, the best combination of factors which permitted to obtain the highest percentage (30%) of lamellas compliant with the requirements was: advance of 7 m/min, grinding belt speed 17 m/s, two passes.

![Cube plot for the factorial experiment](image)

The values of fractions of lamellas compliant with the requirements for specific combinations of factor levels are shown in a cube plot (Fig. 5).

### Table 1. Experiment scheme.

<table>
<thead>
<tr>
<th>List of factors levels</th>
<th>Class of lamellas</th>
<th>Advance (m/min)+grinding belt speed (m/s)</th>
<th>Number of passes</th>
<th>Number of parallel arrangements</th>
<th>Number of lamellas evaluated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>without knots</td>
<td>5/14</td>
<td>1</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>without knots</td>
<td>5/14</td>
<td>2</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>without knots</td>
<td>7/17</td>
<td>1</td>
<td>5</td>
<td>50</td>
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<tr>
<td>4</td>
<td>without knots</td>
<td>7/17</td>
<td>2</td>
<td>5</td>
<td>50</td>
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<tr>
<td>5</td>
<td>with knots</td>
<td>5/14</td>
<td>1</td>
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<tr>
<td>6</td>
<td>with knots</td>
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<td>2</td>
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<tr>
<td>7</td>
<td>with knots</td>
<td>7/17</td>
<td>1</td>
<td>5</td>
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<tr>
<td>8</td>
<td>with knots</td>
<td>7/17</td>
<td>2</td>
<td>5</td>
<td>50</td>
</tr>
</tbody>
</table>

3.2 Experiment 2 – results and analysis

The experiment was designed to evaluate selected combinations of parallel arrangement of four lamellas for the grinding operation, to see whether or not the arrangement has an impact on the obtained quality.
A number of 48 lamellas, selected after drying in procedure 1, was examined, grouped into:

- 18 lamellas which, as a result of the operation of cutting timber into 6 lamellas, were the “end” lamellas – thicker than others,
- 30 lamellas which, as a result of the operation of cutting timber into 6 lamellas, were the “middle” lamellas.

The study was conducted on a Butfering grinding machine as follows: advance 7m/min, grinding belt speed 17 m/s, rated dimension 3.4mm, one pass, 4 lamellas in parallel. Four combinations of parallel arrangement of the lamellas were examined (Fig. 6). Three parallel arrangements were examined for each combination.

![Figure 6. Combination of parallel arrangement of lamellas (C – thin lamella, G – thick lamella).](image)

An analysis of the experiment results led to the following conclusions:

- No pattern was observed in the arrangement of faultily ground lamellas for combinations CCCC, GCCG or CGGC.
- In 2 of 3 examined parallel arrangements for combination CCGG, the faultily ground lamella is marked in red in Fig. 7.

![Figure 7. CCGG combination of parallel lamella arrangement; faultily ground lamella marked in red.](image)

### 3.3 Experiment 3 – results and analysis

The experiment was aimed to determine the optimum thickness of the layer which must be secured for the grinding operation in order to obtain a surface quality acceptable by the customer for the operation of bonding the floorboard. The input material were lamellas after the experiment for the drying operation, of the mean thickness of 4.0mm. The experiment was conducted on a Butfering grinding machine as follows: advance 7m/min, grinding belt speed 17 m/s, 4 lamellas in parallel.

The experiment was conducted according to a fixed scheme (Fig. 8):

- grinding of one side/surface of the lamella to a thickness of 3.8 mm at one pass,
- grinding of the other side/surface of the lamella; a layer of 0.1mm was removed at each pass,
- evaluation of the surface quality after each pass against the criterion of compliance with the requirements for a finished product.

![Figure 8. Experiment scheme.](image)

The following factors were taken into consideration in the experiment (Fig. 9):

- class of the input timber: with knots (A, B, C) and without knots (D, F);
- drying procedure: the three drying procedures analysed were named as follows: procedure 1 – aggressive, procedure 2 – normal, procedure 3 – slow;
- position of lamellas in the basket for drying; ground side/surface of the lamella relative to its position in the basket.

![Figure 9. Factors taken into consideration in the experiment.](image)
Figure 10. Number of lamellas: (a) of unacceptable surface quality, for various drying procedures, (b) of unacceptable surface quality, for classes of timber without knots, (c) of unacceptable surface quality, for classes of timber with knots. The experiment led to the following conclusions:
moreover, it was also stated that:

- The normal drying procedure permits to obtain the smallest number of lamellas of unacceptable surface quality for a given thickness of the ground layer.
- More lamellas of unacceptable surface quality were obtained from timber with knots than from timber without knots, for a given thickness of the ground layer (Fig. 10b and 10c).
- Position of lamellas in the basket for the drying operation has an impact on the number of lamellas of unacceptable surface quality.

4 SUMMARY

Chart analysis of grinding process variation showed that the process has a huge potential – it has little variation with respect to the specification limits, but requires a shift towards the nominal value (shift to down). It is also important that grinding "copes" with the lack of stability previous operations.

The next step was to indicate the optimal settings for the process for the assumed assumption: minimum material waste and acceptable quality level of lamellas surface. The implementation of this task was based on conducting a number of active experiments. As a result, the machining parameters that met the postulates were determined and, moreover, it was also stated that:

- the thickness of the grinding lamella layer depends on the conditions of the drying operation,
- normal drying method allows to achieve the smallest amount of lamellas with unacceptable surface quality for a given layer thickness,
- the timber classes without knots for a given layer thickness have a smaller proportion of lamellas with an unacceptable surface quality compared to classes with knots,
- the placement of the lamella in the drying basket has an effect on the lamellas with an unacceptable surface quality.

The carried out experiments for grinding process were part of the research work, which in consequence allowed to develop a model of selection of machining allowances in the lamella manufacturing process.

5 ACKNOWLEDGEMENTS

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6 REFERENCES