Prediction Model of Wooden Logs Cutting Patterns and Its Efficiency in Practice

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Abstract: This article deals with the testing of a methodology for creating log cutting patterns. Under this methodology, programs were developed to optimize the log yield. Testing was conducted by comparing the values of the proportions of the individual products resulting from an implementation of the proposed cutting pattern of a specific log with the calculated values of these proportions of products using the tested methodology. For this test, nine pieces of logs (three pieces of oak, three pieces of beech and three pieces of spruce) were chosen, and then the proposed cutting pattern was applied on each log and the proportions of the resulting products were determined gravimetrically. The result of the statistical comparison is as follows: The prediction model that has been tested meets the basic requirement of insensitivity to the tree species. This means that the model tested does not create differences in the results based on the type of wood. In the case of timber, the model statistically significantly underestimates its proportion by 3.7%. The model underestimates the proportion of residues by 0.14%, but is not statistically significant. This model statistically significantly underestimates the proportion of sawdust by 2.25%. By evaluating the results obtained, we can conclude that the prediction model is a good basis for optimizing log yields. In its further development, it has to be supplemented with a log curvature parameter and for the most accurate yield optimization, in terms of the product quality, it must be connected with new scanning technologies as well. These will supplement the prediction model with information about internal and external wood defects and these defects will be taken into account then.

Keywords: log; cutting patterns; prediction model; timber volume; diameter; sawdust volume

1. Introduction

The need to reduce operating costs by optimizing production processes in order to maximize the yield of the input raw material has not been avoided in the wood processing industry. According to several authors, we stand at the threshold of the fourth industrial revolution, transforming the established processes [1]. The broadness and depth of these changes herald the transformation of entire production and control systems [2,3]. When processing logs, the use of innovative technologies is essential for the wood processing industry. In order to make the wood processing industry more competitive in the future, an increase in the technological level of industry leaders is a priority, but on the other hand, this industry is very conservative, and therefore innovations must be introduced gradually and be presented through demonstration examples and objects [4]. It is clear from the literature collected that many authors have been involved in the creation of cutting patterns of logs. In 1984, Philp H. Steele dealt with factors influencing the use of logs for timber. He identified the main factors influencing the resulting lumber yield from the logs [5]. Lundahl et al. extensively...
investigated the increase in the timber yield from logs due to the effect of log rotation [6]. They stated that the implementation of the cutting pattern in which the log has a proper position results in a 4.5% increase in the timber yield. Extensive work on optimizing log cutting was conducted by [7]. The results described the different types of cutting patterns and methods of their implementation, defined the factors that affect the choice of the cutting pattern and described the basic mathematical model for the program that created the cutting patterns of the logs. Among the other works focusing on cutting pattern optimization and programming include the development of a 3D log sawing optimization system for small sawmills in central Appalachia [8], a mathematical solution for optimizing the sawing pattern of a log specified by its dimensions and its defect in the heartwood [9], and detailed methodologies for optimizing the cutting plans of logs, which are developed in [10].

The proposed prediction model would be used to develop a program for proposing cutting patterns of logs. Such programs provide the necessary information on the timber volume, sawdust and waste generated. They are essential to optimize the use of inputs for primary products as well as the use of waste in cascade appreciation. The production of agglomerated materials (OSB boards) from chips and MDF, DTD boards from sawdust produced from the realization of the cutting pattern or other applications [11,12] is an example. The developed program would then serve as a basis for setting up scanning technologies. Today, various types of scanners are available for the wood processing industry. The simplest ones are log metal detectors. At a higher level, they are combined with an optical or laser scanner to MAP the surface of the logs. An example is a study presenting how to use 3D scanning technology to track wood without marking. The originality of the approach is that the log is treated as a unique piece with unique characteristics [13]. An accurate determination of the log volume is necessary to optimize the log processing. The authors compare the standard log volume estimation methods with the estimation of the log volume by laser technology in [14]. In some cases, they noticed significant differences between the two methods. Other authors have developed their own log scanning system using laser-triangulated sensors. This system is useful in optimizing log cutting too [15]. Two-dimensional stationary X-ray scanners are available for information on internal log defects [16]. The 3D CT log scanners, which create an accurate 3D model of the scanned log [17,18], represent the latest technology. Wood defects detection algorithms [19] are applied to this model. By combining the software for cutting patterns of logs with an accurate 3D log model with identified defects, it is possible to achieve higher yields of the input raw material [20,21]. The assumption of the importance of innovation is based on the analyses of the development of log prices in the future [22] and ensures the sustainability of the sector [23].

Before testing the prediction model to optimize cutting plans, the following hypotheses were specified:

- The prediction model methodology tested approximates the actual measurement of the product share values resulting from the implementation of the cutting plan;
- The accuracy of the prediction model does not depend on the tree species;
- The prediction model systematically underestimates or overestimates the measured parameter values by less than 5%.

2. Materials and Methods

In order to compare the calculated values of the proportion of products produced by sawing the logs with the actual values obtained by implementing a cutting pattern for a specific log, a test set of 9 logs (Figure 1) (3 pieces of spruce, 3 pieces of beech, 3 pieces of oak) was chosen. The logs had to meet the following parameters: a length of 4 to 4.2 m, a diameter of the thicker end of 35 cm to 45 cm and a saw log quality of class III-B.
For spruce, this class is characterized as logs of a healthy raw timber of standard quality with several qualitative features, at an overall average quality. Sound knots up to 6 cm in diameter are allowed. Ring shakes up to 1/8 of the end diameter, heart shakes up to 1/4 of the end diameter and frost cracks are not allowed. Sweep is allowed up to 2 cm/m. Taper is allowed up to 2 cm/m. Stain is allowed as the core staining up to 1/3 of the end area. Rot is not allowed. The bark may be damaged mechanically. Defects caused by insects are allowed to a maximum depth of 3 mm. The log dimensions are at least 2 m.

In the case of beech, this class is characterized as logs of a healthy raw timber of standard quality with qualitative features, at an overall average quality. Sound knots are allowed in 2 pieces per running meter up to a knot diameter of 10 cm. Decayed knots are not allowed. Ring shakes are not allowed, heart shakes are allowed up to 1/2 of the end diameter and a frost crack is allowed without signs of rot. Simple sweep is allowed up to 4 cm/m for logs shorter than 6 m. Stain is allowed up to 1/3 of the end diameter, and rot is not allowed. Defects caused by insects can be on the surface to a depth of 3 mm.

In the case of oak, this class is characterized as logs of a healthy raw timber of standard quality with qualitative features, at an overall average quality. Sound knots are allowed in 2 pieces per running meter up to a diameter of 10 cm. Decayed knots are allowed in 1 piece up to 6 cm diameter. Ring shakes are allowed up to 1/4 of the end diameter, heart shakes are allowed up to 1/3 of the end diameter and a frost crack is allowed without signs of rot. Simple sweep is allowed up to 4 cm/m for logs shorter than 6 m. Heartwood color stain is not allowed, the sap stain is allowed to its thickness and rot is not allowed. Defects caused by insects can be on the surface to a depth of 3 mm, in the case of deep insect attacks, up to 10 bores per running meter are allowed.

Subsequently, the dimensional characteristics of the selected log were measured in accordance with ISO 13059: 2011(en) Round timber—Requirements for the measurement of the dimensions and methods for the determination of the volume. Table 1 shows the measured parameters of the logs tested.

| Tree Species | Markings | Diameter of Thicker End (mm) | Diameter of the Centre (mm) | Diameter of the Thinner End (mm) | Total Length (mm) |
|--------------|----------|-----------------------------|-----------------------------|-------------------------------|-----------------|
| Spruce       | 1.1      | 440                         | 410                         | 410                           | 4080            |
| Spruce       | 1.2      | 365                         | 360                         | 350                           | 4090            |
| Spruce       | 1.3      | 380                         | 340                         | 350                           | 4110            |
| Beech        | 2.1      | 375                         | 350                         | 350                           | 4110            |
| Beech        | 2.2      | 440                         | 430                         | 420                           | 4120            |
| Beech        | 2.3      | 395                         | 390                         | 380                           | 4080            |
| Oak          | 3.1      | 430                         | 415                         | 410                           | 4110            |
| Oak          | 3.2      | 380                         | 370                         | 360                           | 4055            |
| Oak          | 3.3      | 415                         | 400                         | 400                           | 4060            |
The selected log was cut with a MEBOR 1000 HTZ horizontal band saw. The log was laid with its thinner end to the saw band on the working track, where it was hydraulically attached with fixation tips. At the head of the thinner end, the proposed cutting pattern was transferred. The MEBOR 1000 HTZ horizontal band saw is a semi-automatic type, with hydraulic log rotation, automatic greasing and saw blade tensioning and integrated sawdust suction into the hopper as well. Sawn timber thicknesses are entered into the sawing program.

In the first step, a cut was done in the upper part of the log so as to form a continuous horizontal surface.

Subsequently, in the second step, the log was rotated 180° so that the cut surface in the first step was in contact with the saw working track, and the cutting operation was the same as in the first step.

In a third step, the log was rotated 90° to cut off the third side. The perpendicularity of the individual cuts was ensured by the stops which were activated at the log rotating.

In the fourth step, the log was turned so that the last side could be cut to form a tetrahedron. The tetrahedron had to be trimmed to maintain the demanded width of the timber by further cutting.

In the fifth step, the resulting tetrahedron was cut to the demanded timber. Using the horizontal band saw, it was possible to adjust the new sawn timber to a sharp edge, in case of the resulting rounding of the edges caused by the imperfect shape of the sawn log. The log cutting steps are shown in Figure 2.

After carrying out the proposed cutting pattern for a specific log, the weights of these products (timber, residues and sawdust) were determined. The resulting weight values were converted to percentages. The resulting values of the proportions of individual products from the cutting pattern implementation are compared with the values calculated according to the prediction model above.

On the basis of the literature search, the mathematical model was chosen for the formation of the program that enables the creation of cutting patterns. Specifically, it is the mathematical model created by Meier and Rukki, 2001, Saekavade koostamine ja arvutamine [10]. The main task of this model is to calculate the basic log diameter for the corresponding cutting pattern. The basic calculation is based on the ideal log model, which is a geometric cone. To determine the optimum log diameter for the proposed cutting pattern, the following input parameters are required:

- Cut thickness (s) (Figure 3): depends on the thickness of the cutting tool. As the thickness of the cut increases, the volume of sawdust produced increases and the volume of timber produced decreases. In the program, it will be possible to set the cut thickness in the interval from 0 to 10 mm;
Appl. Sci. 2020, 10, 3003

Figure 3. Cut thickness.

- Log conicity ($c$) (Figure 4): depends on tree growth conditions. It is determined as the difference between the log end diameter, $d$, and the log diameter at a distance of one meter, $D$, and is expressed in centimeters per meter of length;

![Figure 4](image1)

**Figure 4. Log conicity.**

- Log length ($L$) (Figure 4): determines the distance between the centers of the front and end surfaces of the log. In the program, it will be possible to set the log length in the interval between 0 and 10 m;
- Cutting pattern mode (Figure 5): the program must allow the use of a simple cutting pattern and a compound cutting pattern;

![Figure 5](image2)

**Figure 5. Cutting pattern mode.**

- A layout of the cutting pattern in relation to the center of the log: in the program, it must be possible to select a cutting pattern in which the cutting plane passes through the center of the log (Figure 6a) or the center of the log is a part of the central timber (Figure 6b). The choice of method depends on the need to remove the lower quality wood;
Figure 6. Layout of the cutting pattern in relation to the center of the log with the simple cutting pattern. (a) The cutting plane passes through the center of the log, (b) the center of the log is a part of the central timber.

- The same setting can be adjusted for the compound cutting pattern: in the program, it must be possible to select a cutting pattern in which the cutting plane passes through the center of the log (Figure 7a) or the center of the log is a part of the central timber (Figure 7b). The choice of method depends on the need to remove the lower quality wood;

Figure 7. Layout of the cutting pattern in relation to the center of the log with the compound cutting pattern. (a) The cutting plane passes through the center of the log, (b) the center of the log is a part of the central timber.

- Diameter of the thinner end of the log \( (d) \) (Figure 4): the program should allow adjustments between 14 and 40 cm. The program calculates this parameter when the cutting pattern is set. However, this parameter can also be entered manually;
- Timber loss due to log conicity: this value should be adjustable between 0\% and 40\% of the length of the upper half of the timber. This value is chosen on the basis of the qualitative sorting of the timber;
- Standard timber length: with the entered input parameters, the program calculates the exact lengths of the individual timber pieces. It allows one to select the standard timber lengths (rounded to an integer in tenths of a meter);
- Nominal dimensions of timber (Figure 8): the cutting pattern is compiled using two tables. One table is intended for vertical timber and the other for horizontal timber. The program scheme is symmetrical; the timber list begins with the log center and the numbering increases to the edge of the log. It will be possible to design the cutting pattern for 40 pieces of timber at maximum;
Figure 8. Nominal dimensions of timber.

Calculation of parameters:

• Diameter of the log end (D) (the diameter of the butt end) calculated by

\[ D = L \cdot c + d \]  \hspace{1cm} (1)

where:
- \( L \): the log length in (m);
- \( c \): the log conicity in (cm/m); and
- \( d \): the thickness of the thinner end of the log (m);

• Number of timber pieces used in the program calculation (\( q \)): the timber in the pattern exists as a pair due to the symmetry of the cutting pattern. Depending on the method of the log center working, the first piece of timber may have a value of 1, provided that the log center is a part of the central timber. This value is automatically changed by the condition in MS Excel, which first checks the distance of the timber outer surface from the center of the log. If it is equal to the timber thickness, it writes the value 2, and if it is half the distance, it writes the value 1.

If \( q_1 = 1 \), then the relation for calculating the distance of the timber outer surface from the log center is

\[ a_1 = (m_1 + m_2)/2 \]  \hspace{1cm} (2)

where:
- \( m_1 \): the nominal timber thickness in mm (the first of the pair); and
- \( m_2 \): the nominal timber thickness in mm (the second of the pair).

If \( q_1 = 2 \), then the relation for calculating the distance of the timber outer surface from the log center is

\[ a_1 = m_1 + k_1 + s/2 \]  \hspace{1cm} (3)

where:
- \( k_1 \): the coefficient of timber reduction from drying in mm; and
- \( s \): the cut thickness in mm;

• The timber length depends on several factors. In the first step, the program checks whether the standard timber width fits into the appropriate diameter at the appropriate position. The situation is checked by the condition \( b_k < b \). If the condition is true, the timber length is the same as the log length. If false, the timber will be shorter than the log length or will be zero (Figure 9);
Figure 9. Check of the condition \( b_k < b_l \). (a) Timber is the same as the log length. (b) Timber is shorter than the log length.

- The value of \( b_k \) is calculated according to the relation
  \[
  b_k = b + k
  \tag{4}
  \]
  where:
  - \( b \): the nominal timber width in mm; and
  - \( k \): the coefficient of timber reduction from drying in mm;

- The value of \( b_l \) is calculated according to the relation
  if \( a \leq d/2 \), then
  \[
  b_l = \sqrt{d^2 + 4a^2}
  \tag{5}
  \]
  and if \( a \geq d/2 \), then
  \[
  b_l = 0
  \tag{6}
  \]
  where:
  - \( d \): the diameter of the log at the narrower end in mm; and
  - \( a \): the distance of the timber outer surface from the log center in mm.

In the second step, it is necessary to calculate the length of the shorter timber from the log (Figure 10).

- The diameter \( d_1 \) is calculated using the following equation:
  \[
  d_1 = \sqrt{b_k^2 + 4a^2}
  \tag{7}
  \]

- The diameter \( d_1 \) is used to find the timber length \( l \) in mm
  \[
  l = \frac{L \cdot (D - d_1)}{(D - d)}
  \tag{8}
  \]
  where:
  - \( L \): the log length in mm; and
  - \( D \): the diameter at the thicker end of the log in mm.
Figure 10. Principle of shorter timber calculation.

If chamfering is enabled, the timber length is extended by the percentage allowed. If it is specified that the timber should have a standard length, then the timber is shortened to the nearest value of the standard timber length;

- The timber volume ($V_L$) is calculated as follows

$$V_L = l \cdot m \cdot b \cdot q$$

where:
- $l$: the timber length in m;
- $m$: the timber thickness in m;
- $b$: the timber width in m; and
- $q$: the number of timber pieces of the given dimensions;

- The volume of the log ($V_p$) is calculated from the following equation:

$$V_p = \frac{1}{3} \cdot \pi \cdot L \cdot \left( \frac{D}{2} \right)^2 + \frac{D}{2} \cdot \frac{d}{2} + \left( \frac{d}{2} \right)^2$$

- The sum of all timber volumes ($V_s$) is calculated as follows:

$$V_s = \sum V_L$$

- The volume lost in the drying process ($V_{Kq}$) is calculated using the following equation:

For each piece of timber, the volume lost by drying is taken into account (Figure 11).

$$V_{Kq} = q \cdot l \cdot \left( k_{0b} \cdot m + k_{0m} \right) \cdot b$$

where:
- $q$: the number of identical pieces of timber;
- $l$: the timber length in m;
- $k_0$: the reduction in timber width in m;
- $k_{0m}$: the reduction in timber thickness in m;
- $b$: the timber width in m; and
- $m$: the timber thickness in m;
The total volume of timber lost in the drying process is calculated as follows:

\[ V_k = \sum V_{kq} \]  

(13)

- Sawdust volume

The sawdust volume is calculated on the basis of the body volume calculation shown in Figure 12. Its parameters change as the cutting pattern changes. When calculating, it is necessary to take into account whether the cutting plane passes through the log center or the log center is included in the central timber.

In the case of a cutting pattern in which the cutting plane passes through the log center for the first sawn timber, the following should be applied:

\[ V_{SPA} = (2m_k + 2b_k + 4s) \cdot s \cdot l \]  

(14)

where:

- \( m_k \): the timber thickness after drying in m;
- \( b_k \): the timber width after drying process in m;
- \( s \): the cut thickness in m; and
- \( l \): the timber length in m.

In the case of a cutting pattern in which the log center is included in the central timber for the first sawn timber, the following should be applied:

\[ V_{SPA} = (4m_k + 3b_k + 6s) \cdot s \cdot l \]  

(15)

The following relation should be used for further timber:

\[ V_{SPA} = (2m_k + b_k + 2s) \cdot s \cdot l \cdot q \]  

(16)

The total sawdust volume is then calculated as follows:

\[ V_{SP} = \sum V_{SPA} \]  

(17)
Figure 12. An example of a body whose volume represents the sawdust volume when sawing logs.

- Other volume of residues ($V_I$)

This represents the difference between the log volume and the sum of the timber volume, the volume lost in the drying process and the sawdust volume produced. It is calculated as follows:

$$V_I = V_P - (V_S + V_K + V_{SP})$$  \hspace{1cm} (18)

Optimal log diameter (a criterion of a maximum wood yield). The optimal diameter search is performed in the program using the MAX function [24], where the function finds the maximum numerical output and the VLOOKUP search function finds the corresponding log diameter.

The program developed according to this methodology is able to design a log cutting pattern, calculate the optimal log diameters, log volume, volume of produced timber, lengths of individual pieces of timber depending on log conicity and sawdust volume. All of these data are based on an ideal cone-shaped log model. The program displays these parameters in a 3D view.

3. Results

Figures 13–15 show the measured and calculated values of the product proportions (timber, residues and sawdust) for each log tested.

Figure 13. Graphical comparison of the measured and calculated proportion of timber produced from the cutting pattern implementation.
Figure 14. Graphical comparison of the measured and calculated proportion of residues produced from the cutting pattern implementation.

Figure 15. Graphical comparison of the measured and calculated proportion of sawdust produced from the cutting pattern implementation.

The measured values of product proportions were statistically compared with the values calculated using the prediction model. This comparison was carried out by a two-factor ANOVA method in the Statistica 7 program (TIBCO Software Inc., Palo Alto, California, USA). The calculated difference between the measured and calculated proportions of the individual products from the cutting pattern implementation were analyzed.

A statistical assessment shows that the prediction model tested is not sensitive to tree species (Figure 16). This model makes no distinction between tree species (spruce, oak and beech). Furthermore, the model systematically underestimates the amounts of product proportions within each tree species by 0.5%, but is not statistically significant. This is proved by the calculated confidence interval, which contains 0.
Figure 16. Average values of the differences in the measured and calculated values for each tree species.

Further statistical testing (Figure 17) showed that the model tested is sensitive to factor products. In the case of the timber product, the model significantly underestimates its proportion by 3.7% and the significance is confirmed by a confidence interval that does not contain 0. The proportion of residues is underestimated by 0.14%, but is not statistically significant. This is also proved by the calculated confidence interval, which contains 0. This model significantly underestimates the proportion of sawdust by 2.25%, and the significance is confirmed by the confidence interval, which does not contain 0.

Figure 17. Average values of the differences in the measured and calculated values for the products.
Note: Graphical overestimating or underestimating is displayed as the position of the calculated average difference. This value can be positive or negative, depending on whether the difference is calculated by subtracting the measured value from the calculated value or vice versa. This should be taken into account in the analysis and also draw the conclusions from Figures 13–15.

The sensitivity of the model to all three products is the same for all three tree species, as shown in Figure 18. The graph shows the average values of the differences in the measured and calculated values for each product and each tree species evaluated.

Figure 18. Average values of the differences in the measured and calculated values for the products of the individual tree species.

4. Discussion

The effect of overestimating the sawdust proportion is caused by the curvature of the sawn log. With the log curved, the sharp-edged timber is not cut off in its entire length, and thus no sawdust is produced in the cutting process. However, the prediction model counts on this sawdust. Another factor is the production of fine dust, which cannot be collected in the hopper and then weighed.

The effect of the underestimation of the timber proportion is also caused by the curvature of the sawn log. With the log curved, the sharp-edged timber is not cut off in its entire length, and some pieces of sawn timber are wider than it was specified in the cutting pattern.

The effect of the underestimation of the timber proportion may be due to heterogeneity of the wood density. The percentages of the individual products produced from the log cutting pattern applied are determined by the gravimetric method, and therefore this heterogeneous density factor within a log can result in this effect.

Responses were obtained to establish hypotheses from the statistical evaluation. It is important that the methodology does not create differences between the wood species tested. The calculated deviations from the measured values did not exceed 5% in the timber wood, sawdust and residues products. These results are valid for the given conditions. In further research, it is necessary to repeat the testing for logs of other quality classes and other length dimensions. In this case we assume that the curvature of the log and other parameters will be a more important factor. For the development of a program to optimize hardwood log cutting patterns using CT scanners, testing of the presented methodology is crucial. Only a few studies exist where similar methodologies have been tested and they are commonly used in practice at present.
Research in the first stage processing of logs is important because in recent years, intelligent scanning technologies were developed in the wood industry [4]. To successfully implement this technology, it is necessary to guarantee the software updates and at the same time to guarantee a linkage to the second stage of wood processing. In this stage, other factors are taken into account, such as the choice of cutting method, choice of cutting machine and lifetime of cutting tools [25]. The second stage of wood processing and the influences on its effectiveness are relatively well described in many studies such as in a study on the use of neural networks to predict dimensional defects [26] or a methodology for evaluating the effectiveness of cutting tool coatings in the processing of hard-to-machine materials [27]. Optimization and connectivity at all stages of wood processing ensures the maximum utilization of the wood logs.

5. Conclusions

• We can conclude from the results that the tested prediction model fulfils the basic requirement of insensitivity to the tree species. This means that the model tested does not produce differences in the result based on the type of wood. Otherwise, it would mean either favoring or disadvantaging some kinds of wood, which would be a negative effect;

• The use of this prediction model to calculate the quantity of products from the proposed cutting pattern is appropriate because the low values of the percentage differences of the individual products were confirmed by comparing the real values of the percentages of the resulting products with the calculated values;

• In the case of timber products, the model significantly underestimates this proportion by 3.7%. The model underestimates the proportion of residues by 0.14%, but is not statistically significant. The model significantly underestimates the proportion of sawdust by 2.25%. The proposed cutting pattern for a specific log provides very precise values of the yield, based on the measured parameters and the mentioned methodology. This fact makes it possible to design an optimal cutting pattern for the log;

• The results of the statistical comparison indicate that with the decreasing quality of the input log, especially the curvature parameter of the log, the prediction model will lose its accuracy. Similarly, the prediction model does not take into account any qualitative features of the log, so it does not provide us with any information on the quality of the produced timber in its prediction;

• By assessing the results obtained, we can conclude that the prediction model is a good basis for optimizing log yields. In further developments, it has to be supplemented with a log curvature parameter. Then, it must be connected with new scanning technologies, which will supplement the prediction model with information about internal and external wood defects and these defects will be taken into account to achieve the most accurate yield optimization in terms of product quality.

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