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Optimization of thermal modification of wood by genetic algorithm and classical mathematical analysis

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Abstract: The use of wood in outdoor conditions is of great importance for the service life of wood, and the process of thermal modification (TM) directly affects the effective value of wood products. This paper presents theoretical and experimental studies of the parameters influencing TM of wood on the changes of its physical and mechanical properties. Experimental studies were performed on thermally modified wood samples for different values of the influential parameters of thermal modification: T (°C), t (h) and ρ (g·cm^{-3}), while the tensile strength was obtained as the output parameter. The obtained experimental data were stochastically modelled and compared with the model obtained by genetic programming. The optimization of processing parameters was performed by classical mathematical analysis and compared with the results obtained by optimization with genetic algorithm. The results of the optimal design parameters obtained by different approaches to optimization were compared and based on that the analysis of the characteristics of the presented techniques was conducted.

Keywords: genetic programming; mathematical modelling; mechanical properties; model; tensile strength

Wood is one of the earliest construction materials. The structural use of wood and wood-based composites continues to increase steadily. New wood-based materials are continuously developed and are being successfully introduced into the engineering and construction marketplace, as claimed by Kržišnik et al. (2020). Wood modification can be defined as a process that improves wood properties by creating new materials. Therefore, modified wood is frequently advertised as a new species of wood (Esteves et al. 2014; Kržišnik et al. 2018; Popescu et al. 2020). Depending on the type of thermal modification, thermally modified wood has naturally improved properties and specific altered properties (reduction in specific mechanical properties, higher brittleness) that determine its use in the interior and exterior of wooden buildings, as cited in the research (Boonstra, Blomberg 2007; Hasanagić 2019). Wood is an important natural resource used in many applications, from construction through furniture to different domestic or industrial objects, tools, and artworks. Despite its properties, wood presents some limitations in the exterior environment use. The main disadvantages of wood, such as poor dimensional stability and biological degradation or deterioration, are mainly due to the nature of the main polymers of the cell wall of wood, especially due to the abundance of free hydroxyl groups (OH), as reported in previous studies (Schmidt 2006; Van den Bulcke et al. 2011; Reinprecht 2016).

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The research papers (Tjeerdsma et al. 2000; Boonstra, Tjeerdsma 2006) stated that thermal modification (TM) was successful in improving dimensional stability and fungal attack resistance, and caused the reduction of the mechanical properties of wood.

The researchers reported that TM of wood at different temperatures and duration decreased the equilibrium moisture content (*MC*), increased dimensional stability, mass loss (*ML*), and biological durability, and decreased some mechanical properties, as well as the wettability of wood, although in some studies the latter two parameters were found to increase (Tiemann 1920; Hakkou et al. 2005; Boonstra 2008; Esteves, Pereira 2009; Kaboorani, Englund 2010). TM process is characterized by various processing parameters, including temperature, wood type, and process duration. Determining the optimal process parameters by using optimization techniques is a continuous engineering task with the main aim to reduce the production cost and achieve desired product quality (Kuzman 2001; Byon, Hwang 2003). Wood processing and testing technologies, which have been applied for many years in a certain conventional form, can innovate the application of knowledge in the field of modelling, simulation, optimization, process theory, and computer technology. The optimization methods have been improved by the development of applied mathematics, statistics, the design of experiments, simulation, and computational methods (Jurković 1999; Jurković et al. 2006). Today, there are different optimization methods. The use of existing methods depends on the required degree of model accuracy, type of process, and necessity of optimization. The research (Hodžić, Hasanagić 2017; Hasanagić 2018; Hasanagić et al. 2020) investigates the influence of structural timber on the tensile strength as an output variable using stochastic modelling. The idea of genetic programming (GP) came as a generalization of a genetic algorithm (GA). Considering the fact that we can manipulate chromosomes in GA, which represent binary natural or real numbers, it is possible to form chromosomes that represent computer programs over which we could perform crossover and mutation operations and thus come up with a computer program that would solve a particular problem (Koza 1992). In GP, chromosomes in a population have the form of a hierarchical structure composed of primitive functions and terminals for individual problem areas. The set of primitive functions that create a chromosome consists of arithmetic operations, mathematical functions, Boolean logical operators and special functions specific to certain problems. The set of terminals that also create the structure of chromosomes is usually composed of input process parameters and various numerical constants. Symbolic expressions are represented as a binary tree, where the root and other internal nodes of the binary tree are marked with functions. The algorithm defined in this way searches for a solution to the problem in the space of all possible compositions of functions, which are recursively generated from the available primitive functions and terminals (Hrnjica, Danandeh Mehr 2018). In GP, a population composed of chromosomes reproduces according to Darwin's principle of survival and reproduction of the most adjusted, through genetic reproduction (crossing) of operations adapted to mating computer programs. GP as well as GA begins by initializing the initial population with randomly selected computer programs composed of functions and terminals. Every computer program (chromosome) in the population is evaluated in terms of how well it solves the problem. Analogous to GA, this measurement is called chromosome objective function measurement. The research focused on the effect of TM on fir, linden, and beech wood, at different temperatures and durations, on mechanical properties of wood, weight loss and prediction of the mechanical properties of thermally modified wood based on tensile strength using stochastic modelling and genetic programming. It is important to say that this paper presents optimization and modelling with GP that has not been yet applied to parameters of TM and is the first of its type in the field of TM of structural wood.

MATERIAL AND METHODS

Wood specimens. The study examined the mechanical tensile performance of three different types of wood that were thermally modified at different temperatures and durations at maximum temperature. Mechanical tensile testing was performed on a SIL-50kN testing machine (Shimadzu, Japan), with a single working cylinder, located in the upper part of the testing machine used for testing. The tensile strength (σ) in parallel to the fibres was carried out according to the Standard EN 408+A1, where the wood of full cross-section of length 9 is the thickness of the tested samples (Figure 1).

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The tensile strength (σ) was determined using the following Equation (1):

$$\sigma = \frac{F_{max}}{A} \quad (1)$$

where:

A – cross-sectional area (mm);

F_{max} – maximum load (N).

The group of selected materials of ten samples for each type of thermally modified wood consisted of beech (*Fagus* sp.), linden (*Tilia* sp.) and fir (*Abies* sp.). The average bulk density of the modified tensile specimens was 0.353 g·cm^{-3} for fir, 0.455 g·cm^{-3} for linden, and 0.655 g·cm^{-3} for beech specimens. Ten samples without visible defects, full cross-section, free from knots and resin pockets, with the dimensions 162 × 22 × 18 mm were prepared for tensile strength parallel to the grain test in the Standard BAS EN 408+A1. All specimens were cut according to the sawing pattern shown in Figure 2.

TM was performed according to a commercial procedure (Silvapro®, Silvaprodukt, Slovenia), with an initial vacuum in the first step of treatment (Rep, Pohleven 2001; Rep et al. 2004) in the "Kambic" climatic chamber. The samples were heated to maximum temperatures in the range of 170–220 °C and treated with different maximum duration of the TM procedure at different time intervals of 1.3, 2, 3, 4, 4.5 hours, depending on the type. At the end of each treatment period, the samples were removed from the furnace and cooled in a desiccator containing silica gel. Afterwards, weights and dimensions were determined to get the weight change. The lowest mass loss (*ML*) was recorded for linden samples at a temperature of 170 °C and duration of 180 min while the highest *ML* was recorded for beech wood at a temperature of 210 °C and duration of 240 minutes. This indicates that degradation of cell-wall polymers was very low at this temperature. It is expected that mostly hemicellulose and lignin were degraded at this temperature leading to the *ML* as cellulose tends to have higher resistance to thermal degradation in comparison with hemicellulose and lignin (Hasanagić et al. 2021). It is noticeable from the diagrams (Figure 1) that the *ML* increased with increasing temperature and treatment time. It was found out in this paper that the weight loss was inversely proportional to the increase in temperature and length of thermal treatment, which is in line with the findings of previous researchers (Hasanagić et al. 2021).

The mass loss (*ML*) was determined using the following Equation (2):

$$ML\,(\%) = \left(\frac{M_o - M_t}{M_o}\right) \times 100 \quad (2)$$

where:

M_o – oven-dry weight of specimens before treatment (g);

M_t – dry weight of specimens after thermal treatment (g).

Stochastic modelling. Mathematical modelling in this study was performed using a rotatable central composite plan with five levels (coded: –1.6817, –1, 0, +1 and +1.6817) and rectangular arrays with three levels (coded: 1, 2 and 3) of three parameters of the thermal modification process (Table 1). The required number of experimental

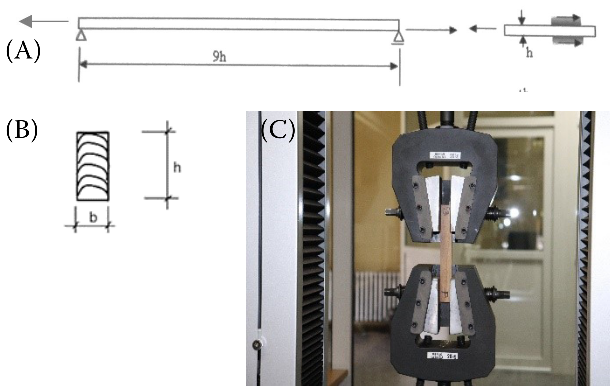

Figure 1. Mechanical tests: (A) Tensile test and dimensions of samples of rectangular cross-section b/h, (B, C) Tensile testing on Shimadzu testing machines (BAS EN 408)

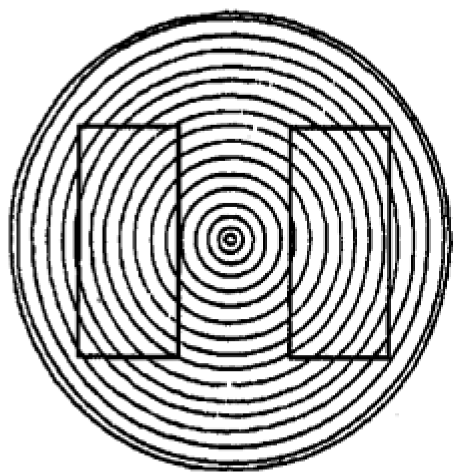

Figure 2. Sawing pattern of tensile test specimens

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points in this study is $N = 2^3 + 6 + 6 = 20$ (Table 2). There are eight factorial experiments (three factors at two levels, 2^3) with 6 replications at the central point of the plan.

Optimization by classical mathematical analysis. The obtained mathematical model is optimized by classical mathematical analysis (stochastic modelling) so that the parameters of the thermal modification process temperature (T), process duration (t) and wood density (ρ) can assume optimal values, when the objective function, expressed through the maximum tensile strength, gets the maximum value of $F_c = \sigma$.

Objective function $F_c = \sigma(X_1, X_2, X_3)$ for the range of $-1.682 < X_i < 1.682$ gets the maximum $F_c = \sigma$ for coded values $X_1 = X_{10}, X_{12} = X_{20}, X_3 = X_{30}$ or physical values $T = T_0$, $t = t_0$, $\rho = \rho_0$. Determination of the extreme values of the maximum tensile strength comes down to differentiating the mathematical model of the tensile strength.

Modelling and optimization of processing processes by evolutionary algorithm. Modelling by genetic programming (GP) was performed on experimental data. Based on the obtained GP model, the tensile strength prediction will show how much the model can contribute to predicting

Table 1. Physical and coded values of thermal modification parameters for experimental designs

Parameters / levels	Lowest	Low	Center	High	Highest
Coding – classical experimental design (X_i)	–1.682	–1	0	1	1.682
Temperature (°C) $X_1 = T$	170	180	195	210	220
Process duration (h) $X_2 = t$	1.3	2	3	4	4.6
Density (g·cm^{-3}) $X_3 = \rho$	0.33	0.43	0.58	0.73	0.83

X_i – coded value of the experimental plan

Table 2. Design of experiment with experimental and model results

No.	Modeling matrix and input parameters of TM process						Ex. results $Y_j = \bar{\sigma}_t$ (N·mm^{-2})	Ex. results $Y_j = \ln \bar{\sigma}_t$	Standard deviation of ex. results
	T (°C) ↔ X_1		t (h) ↔ X_2		ρ (g·cm^{-3}) ↔ X_3				
	temperature	coding	time	coding	density	coding			
1	180	–1	2	–1	0.43	–1	6 758.76	8.819	0.83
2	210	1	2	–1	0.43	–1	5 522.66	8.617	0.76
3	180	–1	4	1	0.43	–1	3 791.34	8.240	0.92
4	210	1	4	1	0.43	–1	2 717.57	7.907	0.57
5	180	–1	2	–1	0.73	1	6 331.91	8.753	1.20
6	210	1	2	–1	0.73	1	6 939.23	8.845	0.86
7	180	–1	4	1	0.73	1	5 140.26	8.545	0.75
8	210	1	4	1	0.73	1	3 043.39	8.021	1.04
9	195	0	3	0	0.58	0	6 042.38	8.707	0.66
10	195	0	3	0	0.58	0	6 823.26	8.828	0.71
11	195	0	3	0	0.58	0	6 428.42	9.039	0.97
12	195	0	3	0	0.58	0	6 762.49	8.819	0.81
13	195	0	3	0	0.58	0	5 977.69	8.696	1.05
14	195	0	3	0	0.58	0	7 936.65	8.979	0.88
15	170	–α	3	0	0.58	0	3 031.01	8.819	0.54
16	220	α	3	0	0.58	0	2 530.19	8.617	0.84
17	195	0	1.3	–α	0.58	0	3 795.24	8.240	0.57
18	195	0	4.6	α	0.58	0	2 823.68	7.907	0.73
19	195	0	3	0	0.33	–α	5 037.08	8.753	0.74
20	195	0	3	0	0.83	α	6 173.45	8.845	0.98

TM – thermal modification; Y_j – experimental results; $\bar{\sigma}_t$ – average of tensile strength; α – symmetrically placed points around the center of the experiment plan

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the tensile strength for the parameters of the solid wood heat treatment process outside the experimental plan and within the allowed interval. The genetic software tool GPdotNET (Version 4, 2018), i.e., software for modelling, optimization and prediction of experimental results of tensile strength testing of thermally modified wood using genetic programming methods and genetic algorithm, will be used in modelling, optimization and prediction of experimental data.

RESULTS AND DISCUSSION

Tensile strength and mass loss (*ML*) of thermally modified samples. The results have shown a growing trend of *ML* with increasing TM temperature from 170 °C to 210 °C in tensile test samples (Figure 3).

The lowest *ML* was recorded for linden tensile test samples at a temperature of 170 °C and duration of 3 hours. This indicates that degradation of cell-wall polymers was very low at this temperature. It is expected that mostly hemicellulose and lignin were degraded at this temperature leading to the *ML*, as cellulose tends to have a higher resistance to thermal degradation in comparison with hemicellulose and lignin (Tjeerdsma et al. 1988; Tjeerdsma, Militz 2005; Esteves et al. 2008). It is noticeable from Table 2 that the *ML* increases with increased temperature. In this paper it was determined that the weight loss was inversely proportional to the increase in temperature, length of thermal treatment and mass loss, which is in line with the findings of previous researchers (Esteves et al. 2008; Gunduz et al. 2009).

Figure 4 shows the decrease in σ of the modified samples for different temperatures, durations, and densities. Based on the analysis of the results, it is clear that there is a decrease in σ when wood is processed at higher temperatures. In addition, the loss of tensile strength depends a lot on the maximum duration of the TM process.

Prediction of the tensile strength model of thermally modified specimens. The design of the experiment (Table 2) is a powerful tool for modelling and analysing the influence of process parameters. Based on the performed experiment, we can represent the functional relationship between the response of thermal wood process, in this case the tensile strength, and the investigated independent parameters by the following mathematical model form [Equation (3)]:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + \\ + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3 \quad (3)$$

or in coding form where all the constants, including interactions, can be estimated. Table 2 shows the experimental design matrix $N = 2^{k-p} + 2k + n_0 = n_k + n_\alpha + n_0 = 20$ for the experimentally determined values of the tension force, based on the expressions [Equations (4–7)]:

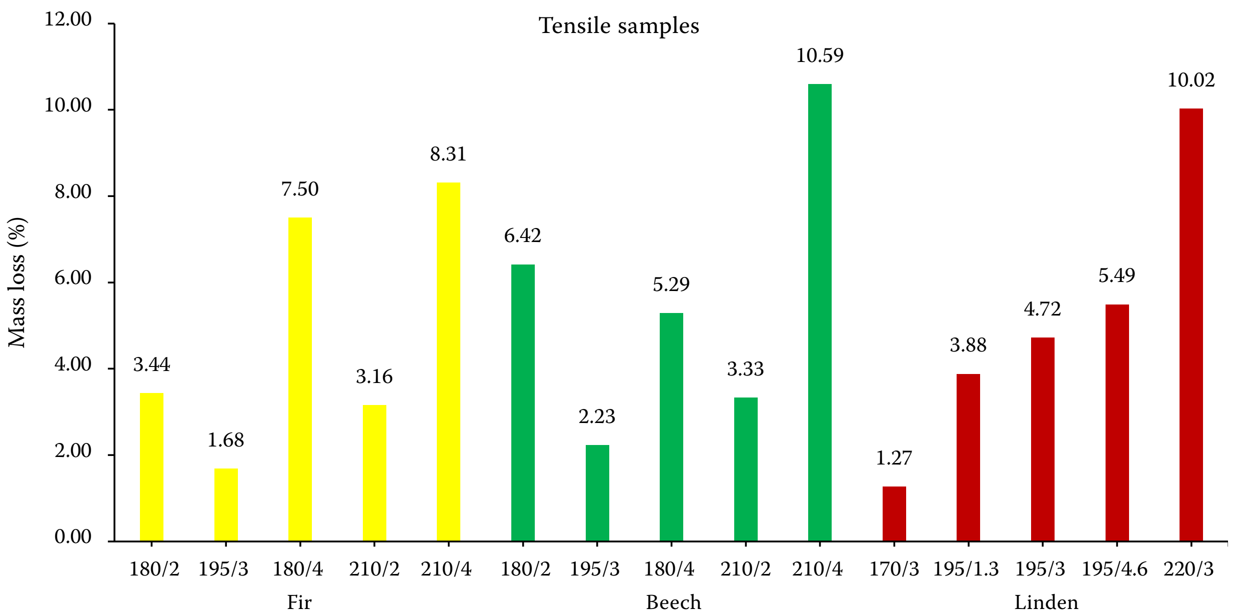

Figure 3. Average mass losses in fir, linden and beech wood samples treated with heat from 170 °C to 210 °C

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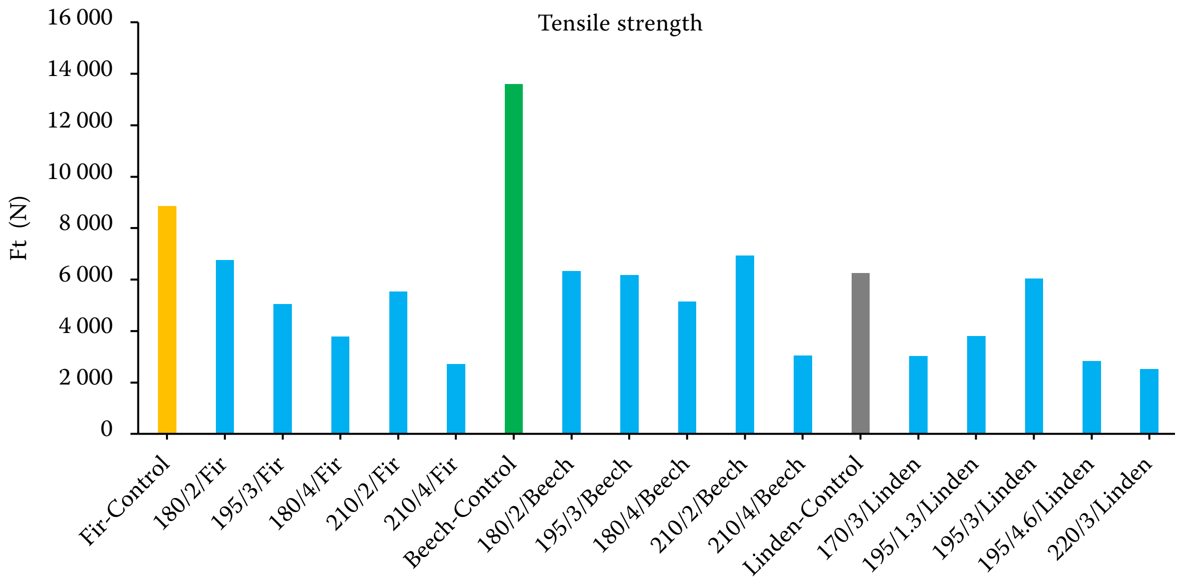

Figure 4. Average tensile strength of thermally modified and unmodified wood

$$b_0 = a_1 \times \sum_{j=1}^{N} y_j + a_2 \times \sum_{i=1}^{k}\sum_{j=1}^{N} X_{ij}^2 y_j \quad (4)$$

$$b_i = a_3 \times \sum_{j=1}^{N} x_{ij} y_j \text{ for } i = 1, 2, 3 \ldots, k \quad (5)$$

$$b_{im} = a_4 \times \sum_{j=1}^{N} X_{jxmj} y_j \text{, for } 1 \le i \le m \le k \quad (6)$$

$$b_{ii} = a_5 \times \sum_{j=1}^{N} X_{ij}^2 y_j + a_6 \times \sum_{j=1}^{k}\sum_{j=1}^{N} X_{ij}^2 y_j + a_7 \times \sum_{j=1}^{N} y_j \quad (7)$$

for $i = 1, 2, 3, \ldots$

The obtained mathematical model has the following form [Equation (8)]:

$$Yj = 8.857 - 0.093X_1 - 0.215X_2 - 0.067X_3 - 0.292X_1^2 - 0.259X_2^2 - 0.046X_3^2 + 0.093X_1X_2 + 0.0128X_1X_3 + 0.031X_2X_3 - 0.060X_1X_2X_3 \quad (8)$$

After the transformation of Equation (8), σ model as a function of logarithmic temperature, duration of TM process (t), and wood density (ρ) has the following physical form [Equation (9)]:

$$Y_j = \sigma = -42.346 + 1.339t - 0.259t^2 + 0.508T - 0.00131T^2 \quad (9)$$

For the 95% confidence level, $R^2 = 0.99$ shows a good interdependency of the input parameters (T, t, ρ) and response (σ). Accordingly, σ model [Equation (9)] describes the experimental results within a range of experiments accurately enough (the model explains 99% of the variability in tensile strength) (Figure 3).

Tensile strength modelling by genetic programming. The modelling of the maximum tensile strength in thermally modified solid wood using the method of genetic programming (GP) was performed through this chapter. The aim of the experimental research was to obtain a GP model of tensile strength (σ), and, after testing, genetic modelling was conducted. The computer program GPdotNET was used to determine the GP model of the maximum tensile strength of thermally modified specimens. The following GP parameters were used during modelling: Set of functions $F = \{+, -, \times, /\}$; Input variable vectors X_1, X_2, X_3; Set $T = \{T, t, \rho\}$ – set of terminals, temperature (T), time (t) and density (ρ); R makes a set of randomly generated constants that can be found in the expression ($R1$ = 4.177400112; $R2$ = 2.497699976; $R3$ = 4.95705986; $R4$ = 0.987389982; $R5$ = 2.526469946; $R6$ = 7.715789795); Size of population – G = 500; Initial depth of binary wood – 5; Depth of wood at mutation and crossing – 7; Probability of crossing – 90%; Probability of mutation – 5%; Probability of reproduction – 20%; Selection method, Elite se-

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lection; "Ramped half-and-half" method of initialization of mixed population; Number of iterations (evolutions) 1 000. The criterion function of chromosome goodness testing (computer programs) is defined by multiple regression [Equation (10)]:

$$R = \sqrt{1 - \frac{\sum (y_i - \tilde{y}_i)^2}{\sum (y_i - \overline{y}_i)^2}} \tag{10}$$

where:

y_i – values of experimental data;

$\overline{y}_i$ – mean value of experimental values;

$\tilde{y}_i$ – model values.

After defining the parameters, we can start the evolution of computer programs. The choice of arithmetic operations that can be found in the mathematical model depends on the type of process and it is necessary to perform several tests with different sets of operations. After performing the modelling by genetic programming, the model data were obtained, which are closer to the model obtained by regression analysis. The following expression [Equation (11)] represents a mathematical model obtained by genetic programming, where the results of the model are presented in Figure 3 and compared with the experimental results and the obtained stochastic modelling results.

The correlation coefficient between the results of the obtained model [Equation (11)] and the training set is 0.96 (Training Data Set), while the correlation coefficient between the model and the validation set is 0.95 (Testing Data Set). It can be said that the model perfectly describes the process.

The tensile strength according to the experiment presented in Figure 5 (blue column) is the approximate value of the values calculated according to the analytical model [Equation (11)] for the maximum tensile strength (black column). From the previously presented results, the maximum tensile strength model describes the problem approximately well.

Tensile strength optimization of thermally modified specimens by classical mathematical optimization. In the classical mathematical analysis, the optimization of the parameters of the TM construction wood procedure was performed by deriving the obtained mathematical model (9). When it comes to the tensile strength model, the obtained mathematical model of tensile strength is optimized so that the parameters of the model assume optimal values, when the objective function, expressed through the tensile strength, gets the maximum value [Equation (12)]:

$$\frac{\partial F}{x_j} = 0 \; ; \left(j = 1,2,3,\ldots,n \right) \tag{12}$$

where:

F – function (tensile strength);

x_j – input values in the model.

The solution to the equation system provides the stationary point coordinates [Equation (13)]:

$$X_{10} = -0.088,\ X_{20} = -0.3625,\ X_{30} = -0.5912 \tag{13}$$

These are nonlinear equations and solutions (X_{10}, X_{20}, X_{30}), i.e., stationary points are obtained by iterative methods. If there is a minimum, maximum, bending or saddle point in the stationary point, it is necessary to examine the sign of the determinants Δ_1, Δ_2 and Δ_3. Since the value is $\Delta_1 < 0$, $\Delta_2 > 0$, $\Delta_3 < 0$, stationary point is the maximum of the objective function $F_c = f(T, t, \rho) \rightarrow F_{max}$ or [Equation (14)]:

$$\Delta_1 = -0.5859 < 0;\ \Delta_2 = 0.2953 > 0;\ \Delta_3 = -0.0268 \tag{14}$$

where:

Δ – determinant values.

Based on the calculated values of determinants Δ_i and criteria (Equations 7–9), the function of maximum tensile strength for $X_{10} = -0.088$; $X_{20} = -0.3625$;

$$Y_{gp} = \sigma = -\frac{R4}{R6 + X_2} - X_3 + \left[R3 + \left(R1 - R4 + 2R6\right) \times \left(R4 + R3 \times R6 - X_2\right)\right] \times \left(R6 - X_2 + \frac{R1 + X_3}{R2}\right) - \frac{\left(R2 - \frac{X_1}{R4}\right) \times \left(-R4 + 2R6 - 2X_2\right)}{\frac{R6}{X_2} + X_2 + \frac{R4 \times \left(R4 + R5 \pm R1 \times R5\right) \times X_2}{R2 - R3} + \frac{X_1}{R4 \times R6 - R3 \times R6 \times X_3}} \tag{11}$$

where:

R – a set of randomly generated constants that can be found in the expression;

X – input variable vectors.

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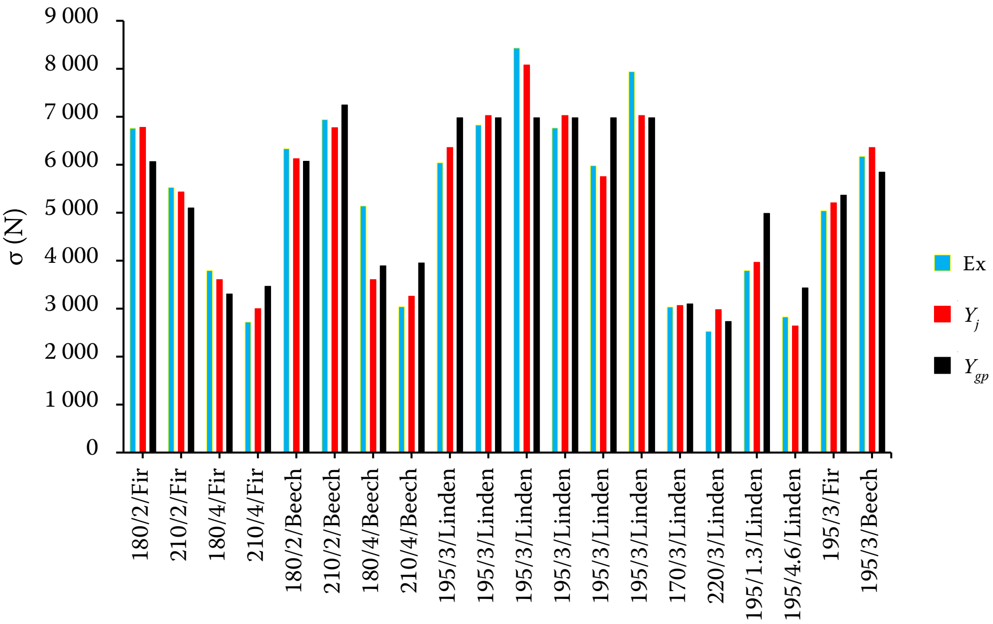

Figure 5. Comparative results of experiments (Ex), stochastic model (Y_j) and genetic programming (Y_{gp}) in tensile strength (σ)

X_{30} = –0.5912 has the maximum value $\sigma = \sigma_{max}$. The optimal maximum tensile strength was obtained for the physical variable parameters of the thermal modification process T = 193.67 °C, t = 2.63 h and ρ = 0.66 g·cm^{-3}.

The tensile strength curves are shown in Figure 6. The graphical representation next to the extreme point σ_{max} shows the intensity of the tensile strength change depending on the individual change of each of the analysed parameters of the tensile process.

The system of Equations (12–14) can also be represented graphically in the form of a curve that will show the behaviour of the maximum tensile strength function depending on the input variables. Individual diagrams would show the behaviour of a force dependent on one variable while the other is at rest, and vice versa. Orthogonal cross-sections of the objective function model $F_c = \sigma_t$ (9), through the point of the maximum tensile strength of thermally modified wood σ_t (X_{10}, X_{20}), the following mathematical models of tensile strength determined by one physical variable are obtained [Equations (15–16)]:

$$Y_T = -40.616 + 0.508T - 0.0013T^2 \quad (15)$$

$$Yt = 7.169 + 1.339t - 0.259t^2 \quad (16)$$

where:

Y – value of the function through the optimal point;
T – process temperature (°C);
t – duration of the process (h).

The curves of the maximum tensile strength are shown in Figures 7A and 7B. The graphical representation of the extreme σ_{max} shows the intensity of the tensile strength change depending on the individual change of each of the analysed parameters of the thermal modification process of wood.

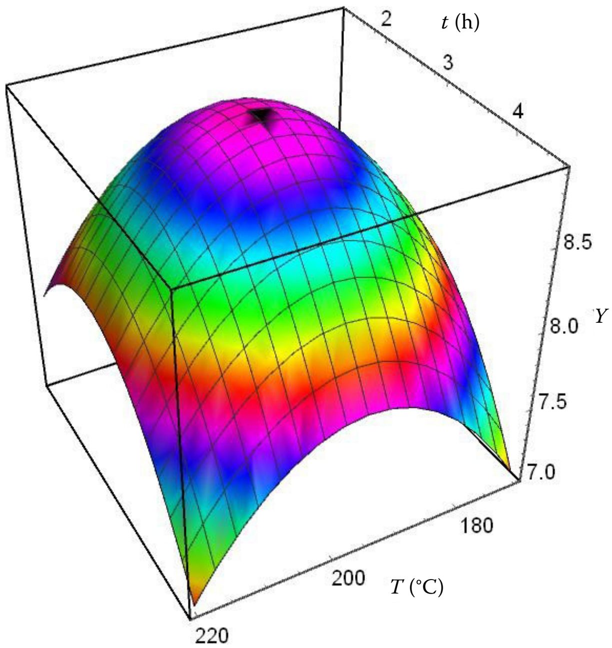

Figure 6. Graphical representation of the function $Y_{T,t}$ of the maximum tensile strength depending on the input parameters

T – temperature; t – duration of the process

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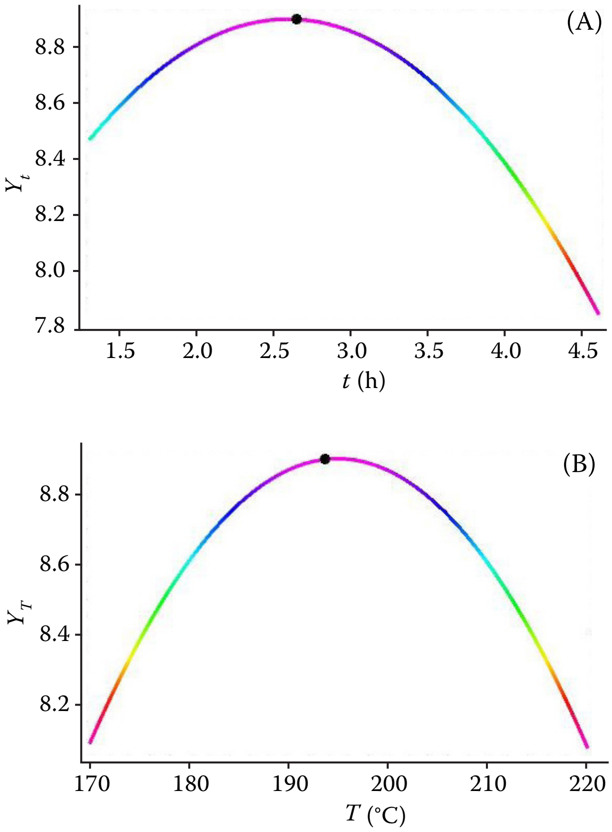

Figure 7. Graphical representation of the function: (A) Y_t tensile parameters of thermal modification depending on the duration of the process (t); (B) Y_T tensile parameters of thermal modification depending on the temperature (T) of the process

Conducted optimization also shows that the stochastic modelling method can be successfully applied to determine the maximum tensile strength and process parameters of TM wood. Defining the optimal parameters of TM, i.e., the maximum tensile strength, has a special significance in the exploitation of thermally modified wood in finished products (indoor furniture, outdoor furniture, manufactured boards, construction elements).

Optimization of tensile strength of thermally modified wood by genetic algorithm. The calculation in this part of the paper was conducted to find the optimal combination of GP model [Equation (11)] of the maximum tensile strength of thermally modified wood obtained by the method of genetic programming. The goal was to minimize production costs and total losses of maximum tensile strength while meeting the physical and mechanical properties of wood. Gene representation through real numbers was also used for this example.

Table 3. The comparison of the optimal results obtained

Method	Optimal thermal modification parameters		
	T (°C)	t (h)	ρ (g·cm^{-3})
Classic mathematical analysis	193.67	2.63	0.66
Genetic algorithm	197.99	2.00	0.62

The main influential GA parameters used for optimization are as follows: population size – 500; number of iterations – 281; probability of mutation – 5%; probability of crossing – 90%; probability of reproduction – 20%; rank selection method. The obtained maximum value of the mathematical model of tensile strength (11) for the parameters of the wood TM process T = 197.99 °C, t = 2 h and ρ = 0.62 g·cm^{-3} was σ = 6 195.577 N.

Comparison of the obtained results. The presented optimization approaches provide the same optimal values for the TM parameters and give accurate results (as indicated by the confirmation test) with small deviation between each other (Table 3).

CONCLUSION

The paper presents the application of different optimization approaches to find optimal parameters of thermal modification of wood. The paper shows that stochastic modelling and evolutionary algorithms can provide reliable results that are consistent with experimental data. The aim was to present the successful application of optimization by classical mathematical analysis and GA for experimental models that do not contain many experiments. Optimal values of temperature (T), duration of TM process (t) and wood density (ρ) were obtained by optimizing the obtained models of maximum tensile strength, using the method of classical mathematical analysis and evolutionary algorithm. The optimal parameters of the TM process by classical mathematical analysis and genetic algorithms have approximately the same value and represent an ideal treatment that can be applied to the wood where mechanical and physical properties are preferred. The optimization techniques presented (classical mathematical method and genetic algorithms) have a potential to improve initial process parameters of thermal modification of wood with high accuracy, which was also verified by the experiment.

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