Науковий вісник НЛТУ України
Scientific Bulletin of UNFU
https://doi.org/10.36930/40330607
Article received 13.10.2023
Article accepted 21.12.2023
UDC 004.[94+42]
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ISSN 1994-7836 (print)
ISSN 2519-2477 (online)

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SOFTWARE TOOLS FOR CALCULATING THE MAIN PARAMETERS OF THE DRYING PROCESS OF ANISOTROPIC MATERIALS

Modern technologies for processing anisotropic materials require an integrated approach to controlling the drying process, which significantly affects the quality and properties of the material. This paper investigates the development of software tools for calculating the main parameters of the drying process of anisotropic materials. The use of cellular automata in this context allows modeling and controlling the distribution of temperature, moisture content, and stresses in the dried material. The work includes the development of a structural diagram and a modeling algorithm, in particular, taking into account the anisotropy of the physical and mechanical characteristics of wood. One of the key features of the work is the possibility of extending the existing transition rules for the cellular automaton model, which allows determining the initial moisture content in the cells based on its gradient at the boundaries and in the center of the wood. Software tools implemented in C++ programming language using the cross-platform environment "Code::Blocks" and the library "wxWidgets" provide the user with an intuitive and user-friendly graphical interface. The user can define input parameters, including geometric dimensions of the material, dryer characteristics, and other process parameters. An important function of the program is the output of results in the form of graphs illustrating the distribution of temperature, moisture content and stresses at different stages of drying. The user can also specify parameters for detailed analysis and export data for further research in Microsoft Excel. The study was conducted on pine wood material, taking into account various drying parameters. The modeling results demonstrate a significant effect of time and process parameters on the distribution of moisture and stresses in the material, which is in line with real-world conditions.

Keywords: modeling; cellular automata; anisotropy; physical-mechanical characteristics of wood; heat and mass transfer; stresses; moisture content.

Introduction / Вступ

Setting the research task. The process of drying lumber is an important problem in the forest and woodworking industry, which requires advanced methods to improve the quality and stability of the final products. Although existing methods offer efficient models of anisotropic materials drying, this research aims to address the need for accurate, but not overly complex, models. In particular, it is proposed to use cellular automata as a basis for modeling the drying process of anisotropic materials. Focusing on the anisotropy of the physical and mechanical characteristics of the material, the research is aimed at the development of a software tools capable not only of setting up simulations, but also of deriving graphic dependencies of the main drying parameters, in particular with the possibility of their export.

Characterization of the research problem in the global scientific literature. In the world scientific literature, the issue of modeling heat and mass transfer during drying of anisotropic materials arouses the interest of respected experts in this field. Outstanding researchers L. M. Hirnyk, Ya. I. Sokolovskyi, T. Hannes, V. Tamme, J. G. Salin, P. Muiste, L. Hong-Hai and many others have significantly advanced the understanding of this issue and either introduced or improved the fundamental methods of such modeling.

The relevance of the research. Modern anisotropic materials processing technologies set requirements for improving drying processes, which have a decisive impact on the quality and properties of wooden materials. Attempts to upgrade these processes through the development and implementation of software tools become particularly relevant in the field of timber drying and woodworking industry. This work is dedicated to creating such a system for calculating the main parameters of the drying process of anisotropic materials, specifically using cellular automata methods.

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Цитування за ДСТУ: Овсяк О. В., Дендюк М. В. Програмні засоби для розрахунку основних параметрів процесу сушіння деревини. Науковий вісник НЛТУ України. 2023, т. 33, № 6. С. 55–61.
Citation APA: Ovsiak, O. V., & Dendiuk, M. V. (2023). Software tools for calculating the main parameters of the drying process of anisotropic materials. *Scientific Bulletin of UNFU*, 33(6), 55–61. https://doi.org/10.36930/40330607

Object of research – the process of drying wood.

Subject of research – development of a software tools based on the method of cellular automata for modeling the main parameters of the drying process of anisotropic materials.

The purpose of the work – development of an effective software tools that provides means for calculating and visualizing the main anisotropic materials drying parameters.

To achieve this purpose, the following *main research objectives are identified*:

1. Extending the transition rules for the cellular automata model to consider the initial moisture content in the cells, taking into account its gradient at the edges and in the center of the wood.
2. Creating a software tool for modeling the drying process taking into account the anisotropy of the physical and mechanical characteristics of wood and displaying the results with the possibility of exporting them.

Analysis of current research and publications. Existing wood processing technologies require a complex approach to managing the drying process, which significantly affects the quality and properties of the obtained material. Various researchers have carried out the modeling of the drying process of anisotropic materials for more than 30 years [7]. During this time, many emerging problems have been solved, and solutions have been found to such complex problems as external heat and mass transfer, as well as modeling moisture leading to stresses. They emphasize the evolution of modeling, in particular its extension from one-dimensional to multidimensional cases, which defines positive developments towards solving important problems in the field of wood drying. Despite this, research is still ongoing, in particular, in [11], the authors try to optimize the drying process of pine wood using two independent approaches. Firstly, they focused on the diffusion coefficient determined by experiments, and secondly, they investigated the effect of air humidification on the drying process itself. The authors compared the experimental data with the data obtained as a result of modeling using the TORKSIM v5.11 program, and as a result, they found relatively good agreement. Another important issue is the stress that occurs during wood drying, which can lead to various drying defects [12]. Its study is made possible by studying the microstructure of wood and the dynamics of heat and mass transfer during drying, which can be obtained by using a cellular automata model. In turn, some authors focus their research [2] on assessing the evolution of the physical and mechanical properties of pine subjected to drying and thermal modification. Thus, they manage to obtain a high dispersion after heat treatment and drying. At the same time, weight loss and moisture content decrease in proportion to the intensity of the treatment, which is associated with changes in the cell wall and thermal degradation due to the interaction of wood and water. In turn, in [3], the authors also suggest using their own software climate control system in the drying chamber to ensure optimal drying conditions and avoid errors that may occur at later stages of the process. It is clear that this approach will help improve the efficiency and quality of production, and the use of a virtual model will help in selecting the optimal equipment and adjusting the parameters of the drying process of anisotropic materials. All these works confirm the relevance of this study, and the software tools developed in this work can be useful in calculating the main parameters of the drying process of anisotropic materials, with the possibility of their further analysis and control.

Research results and their discussion / Результати дослідження та їх обговорення

Determination of the initial moisture distribution in modeling the non-stationary process of moisture transfer during anisotropic materials drying and extension of the existing transition rules for the cellular automata model. In previous works [4, 5], a cellular automaton model was developed and studied to determine the change in moisture content in lumber during drying. The transition rules developed in these works used constant values of the initial moisture content of lumber, for example, $U_0 = 0.35$, which were assigned to all cells without exception. Unfortunately, this approach did not take into account situations in which the initial moisture content of the lumber on its surface and in the middle is different. In this case, the use of constant values loses its expediency. In this regard, it is proposed to update the transition rules to be able to take into account such moisture differences. To make changes to the transition rules, first we need to update the list of input parameters that the user enters, such as U_{in} (moisture level in the middle of the lumber) and U_{out} (moisture level on the surface of the lumber). The updated transition rules will look like this:

IF $U_{in} = U_{out}$ **THEN** $U_0 = U_{out}$

ELSE $U_0 = U_{in} - (1 - C_x) \cdot (1 - C_y) \cdot (U_{in} - U_{out})$

Where: C_x, C_y are the coefficients of cell distance from the center of the lumber according to the selected direction, which can be determined as follows:

$$C_x = 1 - \left(\frac{S_1 h - 0.5a}{0.5a}\right)^2, \qquad C_y = 1 - \left(\frac{S_2 h - 0.5b}{0.5b}\right)^2. \qquad (1)$$

Where: h is the size of one cell, a is the width of one lumber, b is the thickness of one lumber, S_1, S_2 are the coordinates of the location of the cell on the cellular automatic field, where $S_1 \in [1; S_x]$, $S_2 \in [1; S_y]$, with $S_x = a/h$, $S_y = b/h$.

For example, if we select a cell $[S_1; S_2]$ with coordinates [42; 10] at $a = 50$ sm, $b = 3$ sm, $h = 0.2$ sm, $U_{in} = 0.35$, $U_{out} = 0.28$, then its initial moisture content value U_0 can be calculated as follows:

$U_0 = 0.35 - (1–0.559) \cdot (1–0.888) \cdot (0.35–0.28) = 0.346.$

Development of a structural scheme for controlling the main parameters of the drying process depending on the condition of the dried lumber. Developing a structural scheme for controlling the main parameters of the drying process for lumber is an important task from several perspectives. Firstly, it affects the quality of the product, as uncontrolled drying parameters can cause damage to the material or make it impossible to use it at all. Secondly, due to this structural control scheme, these parameters can be systematically determined and monitored, which helps ensure high product quality. Thirdly, drying often requires high temperatures, so its control with the help of a structural diagram helps to avoid risks and ensure the safety of the process. In addition, the development of a structural control scheme (Figure 1) helps to ensure the stability of the production process, which is extremely important, as even small changes can significantly affect the quality and cost of the final product. According to this scheme, the following notation can be applied: G_n – amount of steam entering through humidification tubes; t_n – temperature of steam in the heater; *PO* – control valve; *BM* – actuator; *T* – temperature transducers; *PW* – humidity controller; *PT* – temperature controller; $D_1 \ldots D_n$ – moisture sensors; $P_1 \ldots P_n$ –

output sensors of moisture meters; t_k – temperature of the heater; $t_м$ – temperature of the wet thermometer; t_c – temperature of the dry thermometer.

As a result, a method for monitoring the current state of dried lumber is proposed, which includes:

1) control of the parameters of the drying agent;
2) measuring the value of moisture content in lumber;
3) control of the calculated values of moisture content with the real data;
4) calculation of stresses using existing models.

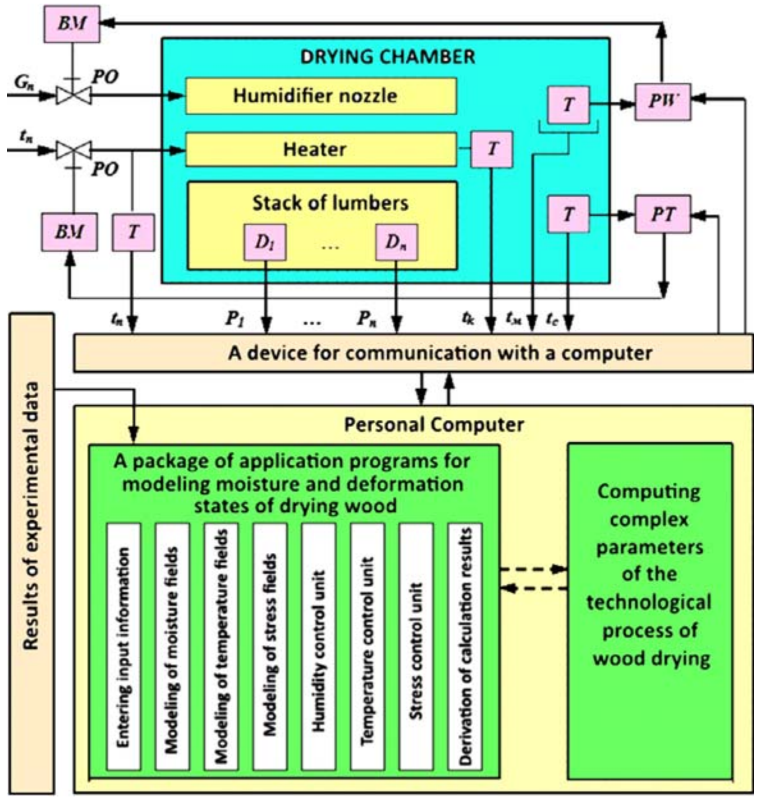

Fig. 1. Structural diagram of control of the main parameters of the drying process / Структурна схема контролю основних параметрів процесу сушіння

In real drying chambers, the control of drying agent parameters is carried out on the basis of existing automated systems with parallelization of the output values of parameters to a computer communication device, which makes it possible to determine the values of moisture transfers coefficients based on the current state of the drying agent parameters. In this case, the earlier developed [4, 5] cellular automaton model will be used, which makes it possible to determine the main parameters of the drying agent, which include relative humidity and temperature. One of the conditions for the adequacy of the calculated parameters of the states with the real ones is the condition that lumber with identical physical and mechanical characteristics must be placed in the drying chamber. In this case, we are interested in a package of application programs for modeling changes in the main parameters of dried wood.

Development of a block diagram of the software algorithm. The developed model of cellular automata makes it possible to conduct simulations and obtain graphs of the temperature and moisture content distribution in the dried lumber. Nevertheless, such results do not allow us to determine the stress values, which are the main constraint to intensifying the drying process and the determining criterion for the final quality of lumber. In this regard, the improvement of existing anisotropic materials drying technologies urgently raises the issue of using universal mathematical models of heat and mass transfer processes in dried lumber. The solution to this issue is complicated by the fact that wood belongs to the class of physically nonlinear hydrophilic polymers characterized by significant variability in structural properties. Nevertheless, there are currently sufficient mathematical models to determine the stresses in dried lumber, taking into account the characteristics of wood. At the same time, the use of numerical methods does allow solving the two-dimensional problem of stress calculation within the framework of elasticity theory. However, in this work, it is proposed to control these values relative to the values of moisture content, which is calculated on the basis of the developed cellular automata model. To use the cellular automata model, it is necessary to develop software that should be able to create a cellular automata field and use the developed transition rules. However, first, it is necessary to develop an algorithm (Figure 2) for calculating the main parameters of the drying process of anisotropic materials.

In this case, block 2 is used to enter the initial data, including: species, initial moisture content of wood, geometric dimensions of the lumber cross-section, parameters of the drying agent (relative humidity, temperature and speed), coefficients of moisture conductivity, moisture exchange, etc. Also, in this block, the user should enter the dimensions of the cells into which the lumber is divided, as well as the time characteristics. In block 3, the matrices are initialized. In block 4, a cell-automatic field is created, the dimensions of which will depend on the specified cell size. In block 5, an iterative time cycle is started according to the specified time step. In blocks 6, 8, and 10, the cycle of using transition rules is carried out. In these cycles, adjacent cells are selected between which interaction will be performed. In blocks 7, 9, and 11, the developed transition rules are applied, which determine the changes in cell values for specific parameters of the lumber. Block 12 stores the intermediate modeling data for each of the involved cells in the corresponding database fields. In block 13, the matrices are reinitialized and the actions are repeated, but at a different iteration. In block 14, the modeling results can be obtained according to the desired parameters.

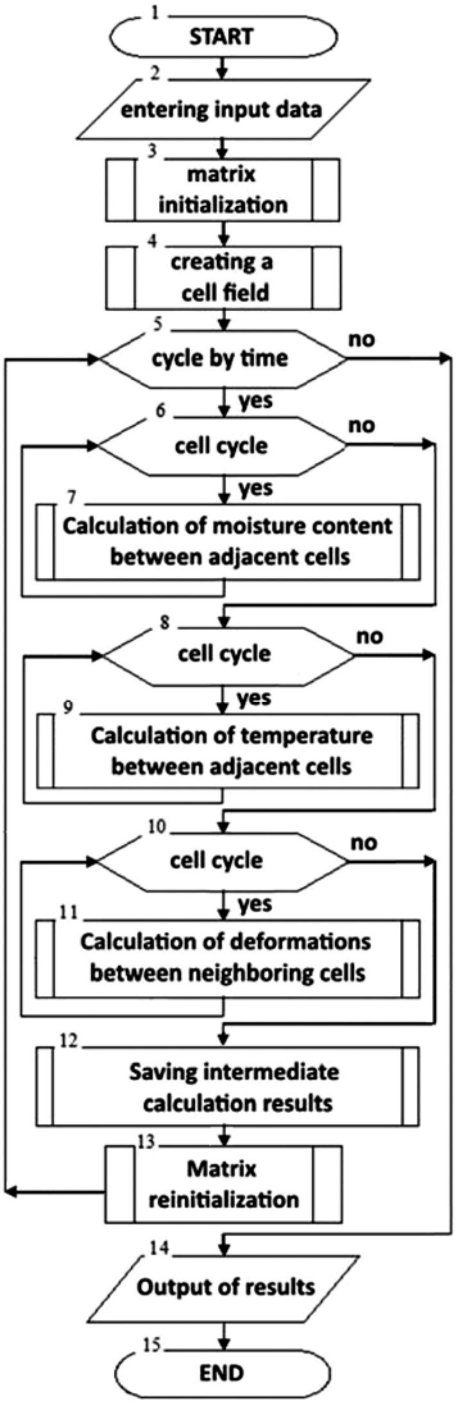

Fig. 2. Block diagram of the algorithm for calculating the main parameters of the drying process of anisotropic materials using the cellular automaton method / Блок схема алгоритму розрахунку основних параметрів процесу сушіння анізотропних матеріалів з використанням методу клітинних автоматів

Overview of the GUI and functionality of the software. For the purpose of practical application of the algorithm, the corresponding software was developed using the C++ programming language. To write the program code, the multi-platform software development environment "Code::Blocks" was used, which includes the library "wxWidgets". The GUI of the software is represented by a system of interconnected dialog windows for setting the input data of the modeling, including geometric parameters of wood, parameters of the drying agent, parameters of each stage of the technological process, coefficients, etc. To set the physical characteristics of the dried lumber and the parameters of the drying process, according to the developed algorithm, the program load is followed by calling the initial dialog window (step 1 of 6). In this window, the type of lumber, its transverse dimensions, and the dimensions of the cells to be placed on the cellular automata field are specified. Also, in this window (Figure 3), the user enters the number of process steps and the speed of the drying agent, which will not change during the modeling process.

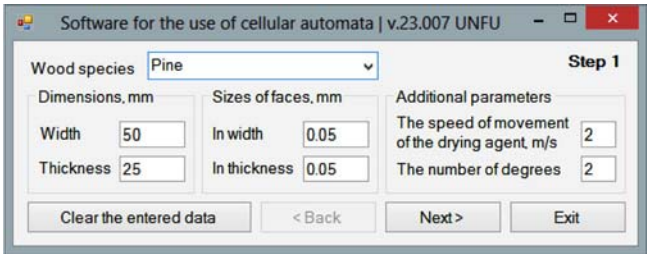

Fig. 3. Window for entering the main characteristics of dried lumber and parameters of the cell-automatic field (step 1) / Вікно введення основних характеристик висушуваних пиломатеріалів і параметрів клітино-автоматного поля (крок 1)

At the second step (Figure 4), the user enters parameters for each stage of the technological process, including the moisture content of the lumber, the temperature of the drying agent, its relative humidity, and the temperature difference.

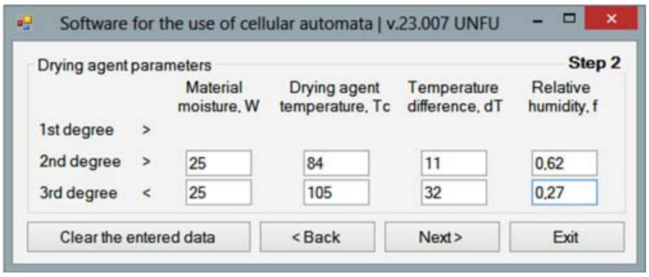

Fig. 4. The window for entering parameters for each of the technological process stages (step 2) / Вікно введення параметрів для кожної із стадій технологічного процесу (крок 2)

In the next step, the previously entered physical and mechanical characteristics of lumber, such as moisture conductivity and moisture transfer coefficients for different directions of wood anisotropy, are displayed from the database (Figure 5). However, the user can make changes to them as well as enter the moisture content on the surface of the lumber and the equilibrium moisture content.

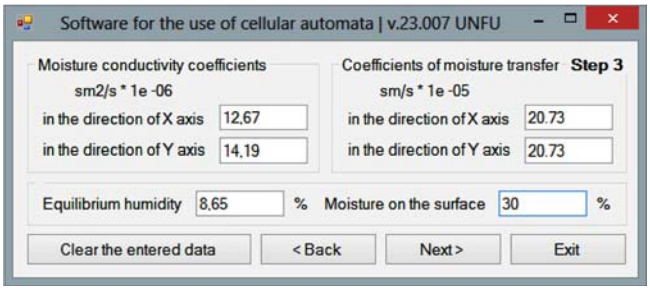

Fig. 5. Window for specifying physical and mechanical characteristics of lumber (step 3) / Вікно для задавання фізико-механічних характеристик пиломатеріалу (крок 3)

To monitor the stresses in wood, it is necessary to specify the relaxation kernel coefficients when modeling the drying process (Figure 6). These coefficients can be found in reference books [6]. To simplify the user's work, these values are loaded automatically from the database by the program. In general, these values could not be displayed in a separate window of the software, but this was done so that the user could change them if necessary, without having to open the database. Usually, at this step, it is enough to simply click the "Next" button.

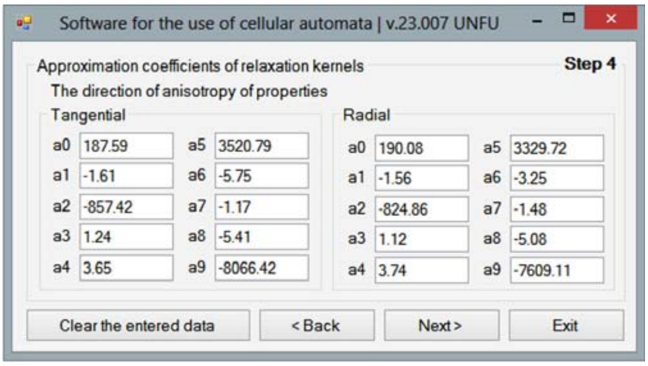

Fig. 6. Window for viewing and changing coefficients of relaxation kernels (step 4) / Вікно для перегляду та зміни коефіцієнтів ядр релаксації (крок 4)

Similarly, it is possible to view and change the coefficients of the elastic moduli. It can be done in the next step (Figure 7). In general, this window is also more informative, but it can be useful for a detailed study of the stresses that occur in wood during drying. In addition, at steps 4 and 5, it is possible to view and change the values of the coefficients in two directions of anisotropy, in particular in the tangential and radial directions.

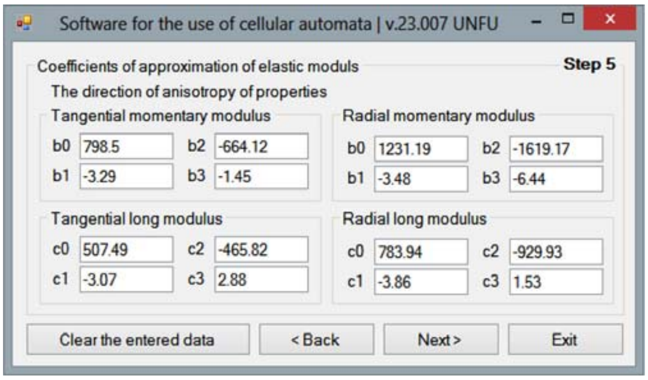

Fig. 7. Window for viewing and changing the coefficients of the elasticity modulus (step 5) / Вікно для перегляду та зміни коефіцієнтів модуля пружності (крок 5)

In the sixth step (Figure 8), the shrinkage coefficients for the tangential and radial axes of anisotropy and the duration of the process can be specified. Also, at this step, it is possible to set the time discretization step for calculating the moisture content, temperature, and stresses for each cell on the cellular automatic field at each time point.

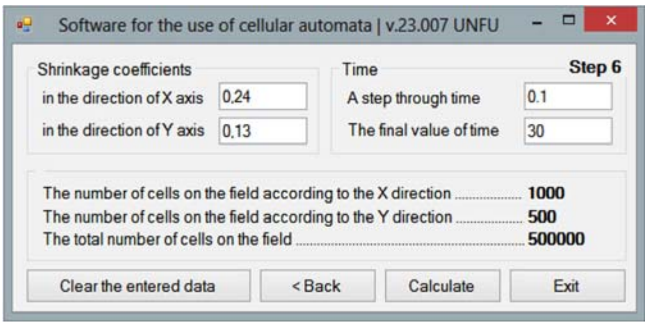

Fig. 8. Window for entering the final parameters of the simulation (step 6) / Вікно введення кінцевих параметрів моделювання (крок 6)

It is also worth considering the number of cells in the field that is displayed in this window. This number directly affects the speed and accuracy of calculations. It is recommended to always choose a compromise between these two parameters [1]. If necessary, it is always possible to resize the cells by returning to step 1. To perform calculations at this step, it is necessary to press the "Calculate" button, which calls the main program function, which, after performing calculations, calls a dialog window (Figure 9) to decide whether to display the calculation results or not. In any case, regardless of the choice of the user, all modeling results will be saved to the database. In the future, this data may be used to create corresponding graphs.

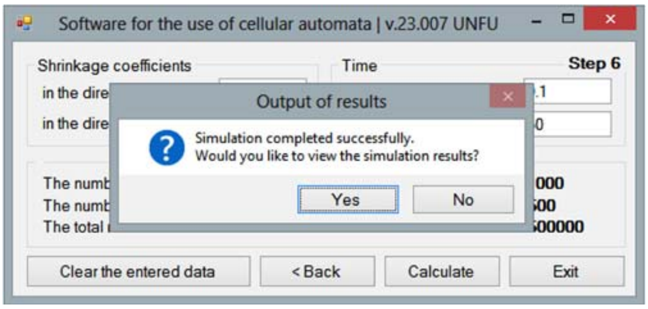

Fig. 9. The window that opens after the successful completion of the simulation / Вікно, що відкривається після успішного завершення процесу моделювання

In general, the functionality of the software provides for displaying graphs of temperature, moisture content and stresses for any selected cell. To build other graphs, the software provides the ability to export data from the database to ".xlsx" files, with the possibility of their further opening and analysis in Microsoft Excel, the version of which should not be earlier than 2010. If the user chooses to show the modeling results, a window opens in which the desired parameters can be specified. For example, it is possible to display the moisture distribution in the center of the lumber cross-section along its width (Figure 10). To do this, select the appropriate parameter in the drop-down list and click the "Display" button.

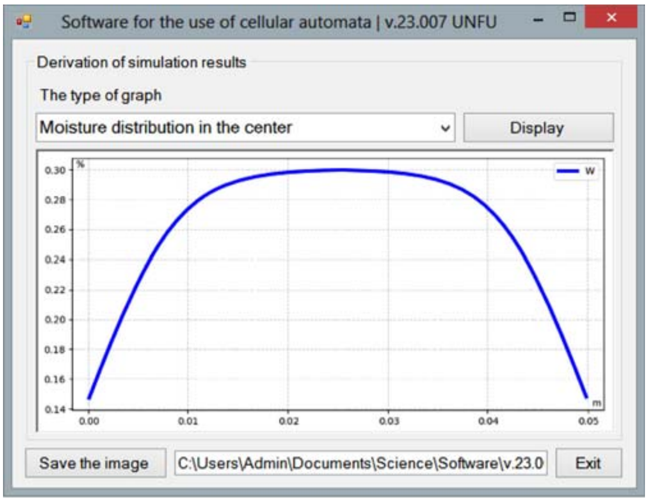

Fig. 10. Window of simulation results on the example of a graph of moisture distribution in the center of the cross section of lumber along its width / Вікно результатів моделювання на прикладі графіку розподілу вологи у центрі поперечного перерізу пиломатеріалу вздовж його ширини

Another functionality of the software is the ability to determine the moisture content and enthalpy (Figure 11). Depending on the drying method, in particular, when combusting coolants to obtain the required parameters of the drying agent, an algorithm for determining the moisture content and enthalpy, which are shown in the Idα diagram, was developed and implemented. It is worth noting that the input data for determining the moisture content and enthalpy of both the drying agent and the furnace gas blend, depending on the type of fuel, are temperature and relative humidity.

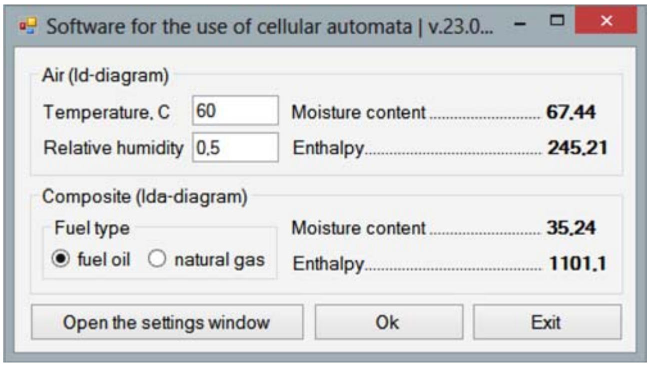

Fig. 11. Dialog window of the electronic version of Id and Idα-diagrams / Діалогове вікно електронної версії Id та Idα-діаграм

Analysis of the obtained results. For modeling was used pine lumber 1 m in length, 50 mm in width, and 25 mm in thickness. The density of the lumber is $\rho_0 = 400$ kg/m^3, the initial moisture content is $W_0 = 0,3$ % and the temperature is $t_0 = 20$ °C. In addition, the following drying process conditions were applied, such as the ambient temperature $t_c = 79$ °C, the relative humidity of the environment $\varphi = 77$ %, and the speed of the drying agent $v = 2$ m/s.

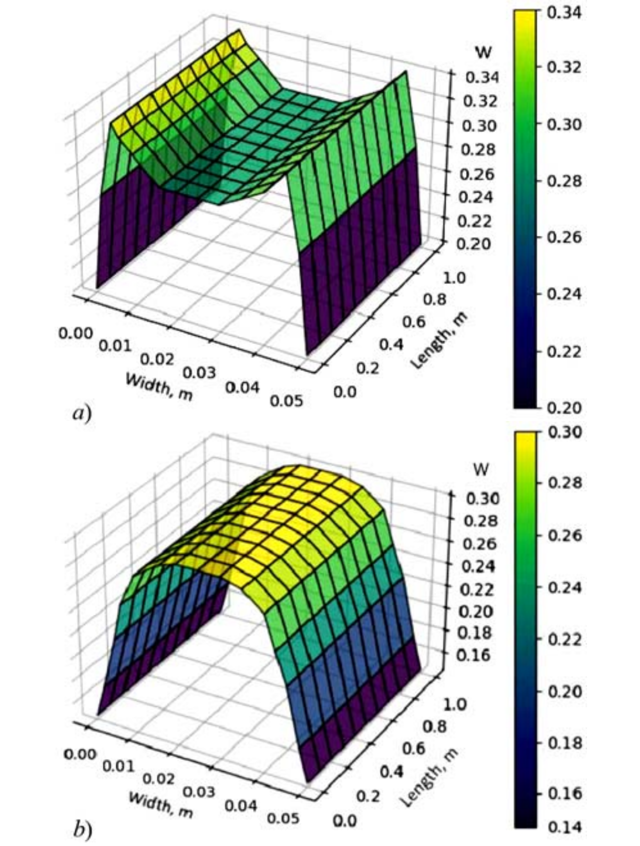

Fig. 12. View of 3D graphs of moisture distribution along the width of lumber at different moments of drying time / Вигляд 3D графіків розподілу вологи вздовж ширини пиломатеріалу у різні моменти часу процесу сушіння: a) after 0.5 hours / через 0.5 години; *b*) after 5 hours /через 5 годин

To create a cellular automatic field, rather small cells with a face size of 0.05 mm are used. In general, the finished field consists of 500,000 cells. The accuracy of calculations at such a density should be quite high, although it will take more time to obtain results. During the modeling process, two experiments were performed. In the first one, a total of 300 iterations were performed, which corresponds to a given time range of 30 minutes, with a step of 0.1 minute, i.e., one iteration is equal to 6 seconds. In the second experiment, 3000 iterations were performed, which corresponds to a time period of 5 hours. The modeling results are shown in the 3D graphs (Figure 12).

The analysis of the obtained results indicates that the simulation of the dynamics of moisture field distribution in the tangential cross-section of lumber using the cellular automata method shows that the simulation time is a significant factor. With an increase in the process duration, significant changes occur in the moisture distribution along the lumber. However, it is important to mention that the time step size (Δt) is not a decisive factor in cellular automata modeling. Therefore, its value can be increased to obtain results faster without losing significant accuracy, which is a key task in modeling. Similar modeling results were obtained for other types of lumber.

Discussion of research results. Since this work develops software tools for calculating and visualizing the main parameters of drying anisotropic materials, the results can be compared with next works. For example, in [10], software tools for monitoring and visualizing the parameters of the wood drying process were improved. Of course, in this work it is not about ordinary software, it is about the software used for a polarization-type moisture meter that monitors the drying of wood by the method of electrical resistance. Nevertheless, these software tools allow to determine the main parameters of drying, which makes it similar to our study. Work [8] is also quite similar, as it develops software tools for analyzing moisture exchange during drying, but using CUDA technology. The developed program also has the ability to calculate and visualize the main parameters of drying, in particular wood. The difference lies in the use of CUDA technology, which allows for parallelization of calculations, thereby speeding them up. Simultaneously, in paper [9], software tools are also developed to calculate and visualize the main drying parameters, again using wood as an example. Unlike the previous two papers, the use of the cellular automata method is proposed here. All of these works make it possible to compare the results of research, although not to the fullest extent. In general, the research topic is relatively new, and therefore there are not enough sources to conduct a more detailed comparison of the results. In summary, these studies show the real state of the field, as they were published in the last few years.

So, based on the results of the work performed, it is possible to formulate the following scientific novelty and practical significance of the research results.

Scientific novelty of the obtained research results – improved the transition rules of the cellular automata model for determining the initial moisture content in the cells necessary for modeling the drying process of anisotropic materials, taking into account the anisotropy of the physical and mechanical characteristics of lumber.

Practical significance of the research results – the ability to use the software on different operating systems and the convenience of analyzing the distribution of temperature, moisture content and stresses, which can be exported for further analysis in other convenient environments, including Microsoft Excel.

Conclusions / Висновки

In the process of performing the work, the transition rules for the cellular automaton were improved, taking into account the initial moisture content of the cells. The values were updated to take into account the moisture gradient at the edges and in the center of the wood. This approach makes it possible to more accurately model the anisotropy of the material's physical and mechanical characteristics during drying. The obtained 3D graphs of the moisture distribution along the lumber confirm the adequacy of the new rules and the consideration of such a distribution. In addition, the results indicate the successful implementation of these aspects in a model that reflects the behavior of the material during drying.

In this work, a software tool was also created to calculate and visualize the main parameters of drying anisotropic materials. This tool is cross-platform, which allows it to be used on different platforms. The tool allows users to analyze the distribution of temperature, moisture content, and stresses. It is also possible to export the data obtained for further analysis in other programs, which increases the level of user convenience. To summarize, these developments represent an innovative approach to modeling the drying process that can be applied in the woodworking, forestry, and wood products sectors.

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ПРОГРАМНІ ЗАСОБИ ДЛЯ РОЗРАХУНКУ ОСНОВНИХ ПАРАМЕТРІВ ПРОЦЕСУ СУШІННЯ ДЕРЕВИНИ

Сучасні технології обробляння деревини потребують комплексного підходу до управління процесом її сушіння, який істотно впливає на якість та властивості матеріалу. У роботі розглянуто особливості розроблення програмних засобів для розрахунку основних параметрів процесу сушіння деревини. Застосування клітинних автоматів у цьому контексті дає змогу моделювати та контролювати розподіл температури, вологовмісту та напружень у висушуваному матеріалі. Робота містить розробку структурної схеми та алгоритму моделювання, зокрема із врахуванням анізотропії фізико-механічних характеристик деревини. Однією з ключових особливостей роботи є можливість розширення наявних правил переходів для моделі клітинних автоматів, що дає змогу визначати початковий вміст вологи у клітинах залежно від перепаду її значень на границі та в центрі деревини. Програмні засоби реалізовано мовою програмування C++ з використанням багатоплатформового середовища "Code::Blocks" та бібліотеки "wxWidgets", що надає користувачеві інтуїтивний та зрозумілий графічний інтерфейс. Користувач може визначити вхідні параметри, включаючи геометричні розміри матеріалу, характеристики агента сушіння та інші технологічні параметри. Важливою функцією програми є виведення результатів розрахунку у вигляді графіків, що відображають розподіл температури, вологовмісту та напружень на різних етапах сушіння. Користувач також має можливість визначити параметри для докладного аналізу, а також експортувати дані для подальшого вивчення в середовищі Microsoft Excel. Дослідження проведено на прикладі соснового пиломатеріалу, враховуючи різні параметри сушіння. Результати моделювання показують значущий вплив часу та технологічних параметрів на розподіл вологи та напружень у матеріалі, що в принципі відповідає реальним умовам.

Ключові слова: моделювання; клітинні автомати; анізотропія; фізико-механічні характеристики деревини; тепломасообмін; напруження; вологовміст.