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12. DEVELOPMENT SOFTWARE FOR STUDY THE WOOD DRYING CHAMBER BY USING A THREE-DIMENSIONAL MATHEMATICAL MODEL BASED ON CELLULAR AUTOMATA

The paper describes the study of the drying processes of capillary-porous materials by using the CAD model of wood drying chamber. The study involves the determination of temperature and humidity in the stack of dried wood by using cellular automata. To accomplish this task, we developed a three-dimensional mathematical model of heat transfer of wood in the drying process. In order to use this mathematical model in practice, we described the ways of representing the CAD model in the form of multidimensional arrays whose elements are 3D cubes, as well as special schemes of the relation between the edges of these 3D cubes. This representation allows us to make the most effective use of the developed mathematical model, which is described by an interconnected system of partial differential equations in time derivatives and spatial coordinates. Also in this paper, the results of the calculations in the form of graphs of change in the temperature and humidity of the stack of dried wood according to time iterations are shown. In order to take simpler results, we developed a radial basis artificial neural network.

12.1. INTRODUCTION

This type of work involves modeling and investigating methods of drying wood in forestry chambers. The object of the study in this case is aerodynamic processes. To calculate the parameters of the wood drying agent, SolidWorks Flow Simulation software application will be used with the theory of cellular automata. In the second case, it is supposed to represent the investigated CAD model in 2D von Neumann neighborhoods. In this work, we also develop software that is based on well-designed algorithms using the

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SolidWorks API. In addition, we develop a radial basis artificial neural network that will determine the parameters of the wood drying agent in a given face of the selected 3D cube and at a given point in time.

12.2. CAD MODEL AND ITS PRESENTATION IN 2D NEIGHBORHOOD OF VON NEUMANN

12.2.1. CAD MODEL OF THE CHAMBER

This paper investigates the CAD model of a wood drying chamber that we previously designed in SolidWorks environment. This CAD model consists of several components, including walls, doors and ceiling of the wood drying chamber, stacked lumber, humidifying nozzles, water heaters and axial fans. All components are combined into one large assembly (Fig. 12.1).

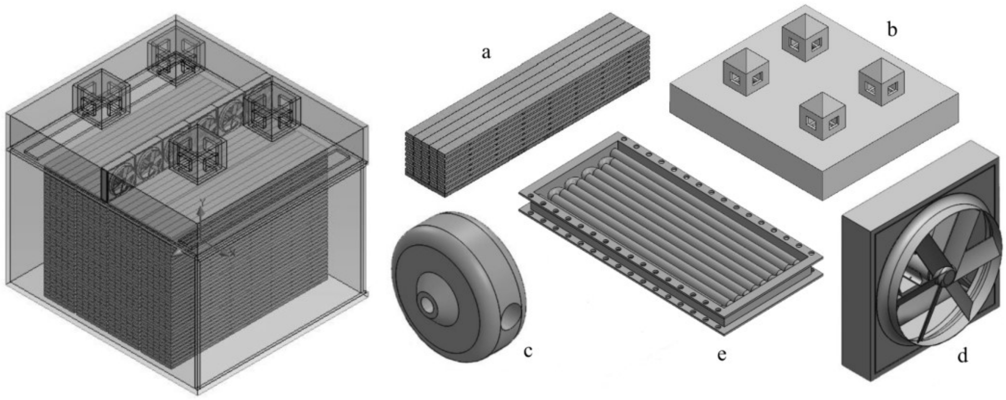
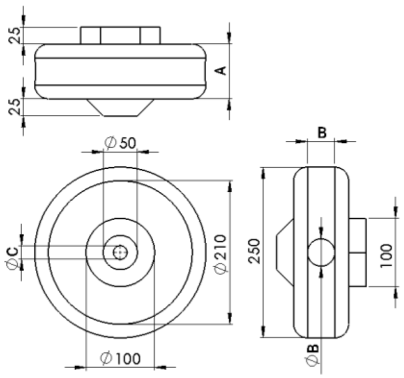


Fig. 12.1. Investigated CAD model in SolidWorks environment (a – stack of lumber; b – ceiling of the drying chamber; c – moisturizing nozzle; d – axial fan; e – water heater)

In total, we can have five types of water heaters, humidifying nozzles and axial fans. The choice of the type of equipment required depends directly on the physical dimensions of the wood drying chamber. Various types of equipment differ in geometric dimensions, capacity heater, the maximum volume of air that passes per minute and other.

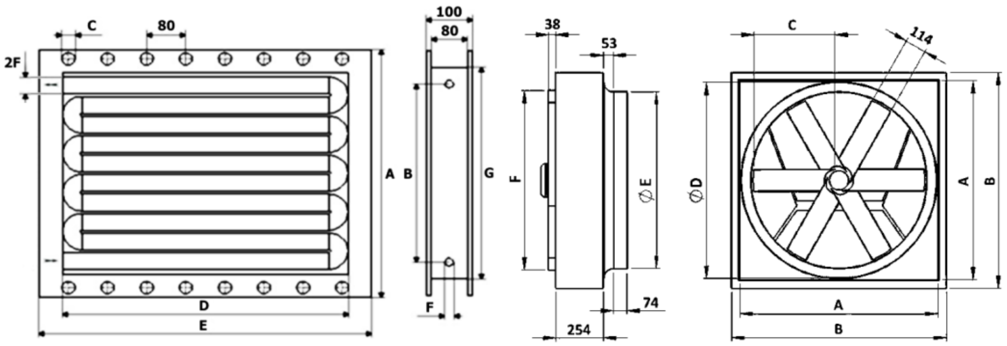
The basic geometric dimensions and drawings of moisturizing nozzles used in this CAD model of the wood drying chamber are shown in Figure 12.2 and characteristics of water heaters and axial fans shown in Figure 12.3.

In this paper, the focus will be on the stacks of lumber, for which we developed a corresponding three-dimensional mathematical model of heat transfer of wood in the drying process [1].



Type	A, mm	B, mm	C, mm
AN#1	60	30	10
AN#2	70	35	15
AN#3	80	40	20
AN#4	90	45	25
AN#5	100	50	30

Fig. 12.2. Characteristics of moisturizing nozzles



Type	A, mm	B, mm	C, mm	D, mm	E, mm	F, mm	G, mm	N
DRH#1	528	375	26	602	680	18	450	16
DRH#2	555	402	26	730	808	19	477	20
DRH#3	582	429	26	858	935	20	504	24
DRH#4	609	456	26	1014	1092	21	531	28
DRH#5	636	483	26	1239	1316	22	558	32

Type	A, mm	B, mm	C, mm	D, mm	E, mm	F, mm
VO#1	654,10	743	232,2	638,9	538,5	652,5
VO#2	754,10	843	282,2	738,9	638,5	752,5
VO#3	854,10	943	332,2	838,9	738,5	852,5
VO#4	954,10	1043	382,2	938,9	838,5	952,5
VO#5	1054,10	1143	432,2	1038,9	938,5	1055,5

Fig. 12.3. Drawings and characteristics of axial fans and water heaters

12.2.2. MODEL IN 2D NEIGHBORHOOD OF VON NEUMANN

To study the proposed CAD model of a wood drying chamber by using cellular automata, it is necessary to present it in the form of 2D neighborhood von Neumann 1st order. In Fig. 12.4, an example of a graphical breakdown of one stack of lumber is shown where it is unfolding in 2D neighborhood von Neumann [2].

In a similar way, all existing components of the CAD model of the wood drying chamber are broken down. In order to use cellular automata to investigate the parameters of the wood drying agent in the CAD model under study, in addition to splitting it into 3D cubes, it is also necessary to develop links between these 3D cubes. For this task, we used the connections on the tangent faces of different 3D cubes. Fig. 12.5 shows a general view of making such connections using the example of one of the lumber [3].

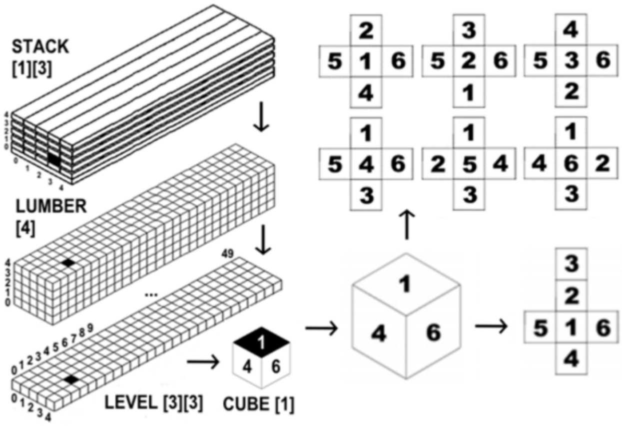


Fig. 12.4. View of a graphical breakdown of a stack of lumber

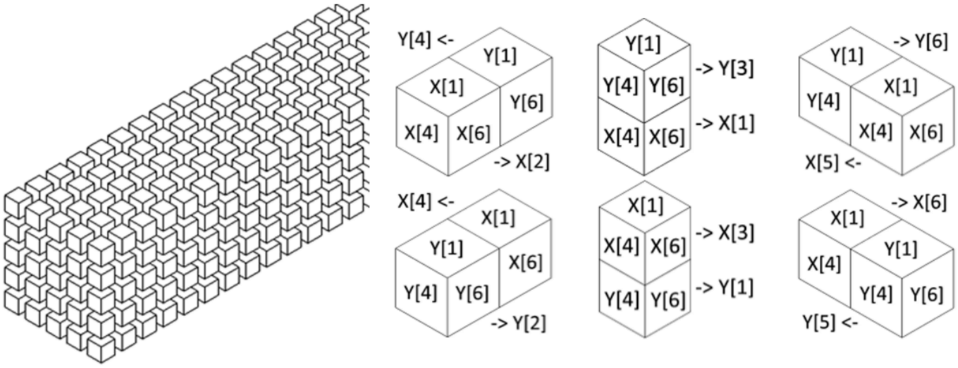


Fig. 12.5. The process of making connections between adjacent 3D cubes

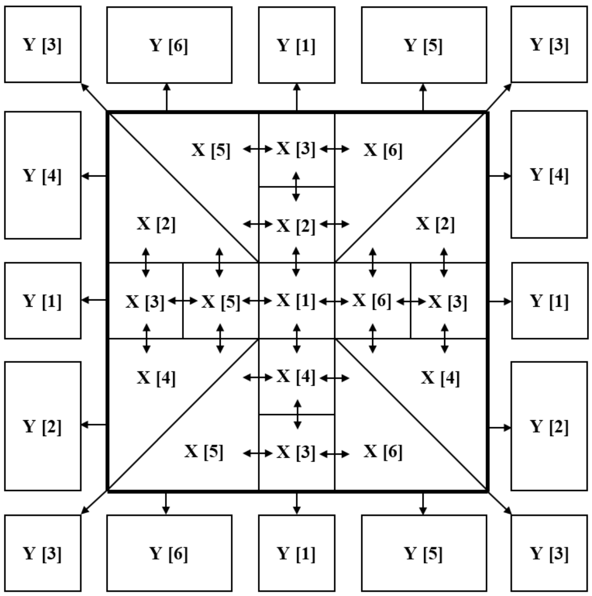


Fig. 12.6. The scheme of the relationship of the faces between two adjacent 3D cubes

With a graphical way of making connections between adjacent 3D cubes, we developed an appropriate diagram of the relationship between all faces of two adjacent 3D cubes (Fig. 12.6). The notations *X* and *Y* are two adjacent 3D cubes, and the numbers adjacent to them are responsible for the faces of this 3D cubes [4].

12.3. DEVELOPMENT OF 3D MATHEMATICAL MODEL OF HEAT TRANSFER IN THE DRYING PROCESS

12.3.1. DESCRIPTION OF THE DEVELOPED MATHEMATICAL MODEL

To determine the parameters of the wood drying agent, a three-dimensional mathematical model of heat transfer of wood in the drying process was constructed. This three-dimensional model is described by an interconnected partial differential system of partial time derivatives and spatial coordinates and has the following form

$$\begin{cases} c\,\rho\,\dfrac{\partial T_i}{\partial t} = \lambda_1 \dfrac{\partial^2 T_i}{\partial x^2} + \lambda_2 \dfrac{\partial^2 T_i}{\partial y^2} + \lambda_3 \dfrac{\partial^2 T_i}{\partial z^2} + \varepsilon\,\rho_0\,r \dfrac{\partial U_i}{\partial t}, \\ \dfrac{\partial U_i}{\partial t} = a_1 \dfrac{\partial^2 U_i}{\partial x^2} + a_2 \dfrac{\partial^2 U_i}{\partial y^2} + a_3 \dfrac{\partial^2 U_i}{\partial z^2} + a_1 \delta \dfrac{\partial^2 T_i}{\partial x^2} + a_2 \delta \dfrac{\partial^2 T_i}{\partial y^2} + a_3 \delta \dfrac{\partial^2 T_i}{\partial z^2}, \end{cases} \tag{12.1}$$

where $(x, y, z, t) \in \Omega$, domain $\Omega = \{0 \le x, y, z \le l; 0 \le t \le \tau\}$, $T_i = T_i(x, y, z, t)$ – temperature, $U_i = U_i(x, y, z, t)$ – moisture content, c – specific heat, ρ – density, i – serial number of 3D cube, t – time, x, y, z – coordinates of the 3D cube location, $\{\lambda_1, \lambda_2, \lambda_3\}$ – coefficients of thermal conductivity, ε – phase transition coefficient, ρ_0 – basic density, r – specific heat of vaporization, $\{a_1, a_2, a_3\}$ – humidity coefficients, δ – thermo gradient coefficient.

Initial conditions that relate to a period of constant drying rate of wood have also been developed as follows

$$T_i(0, x, y, z) = T_0(x, y, z), \qquad U_i(0, x, y, z) = U_0(x, y, z). \tag{12.2}$$

In general, the developed mathematical model can be implemented by using finite element methods or differences.

12.3.2. BOUNDARY CONDITIONS ACCORDING TO THE CREATED 3D CUBES

For this three-dimensional model, we developed boundary conditions of the third kind, which correspond to each of the faces of the created 3D cubes. Such a representation makes it possible to apply this mathematical model in the study of the parameters of the agent of drying wood by using cellular automata [5].

Generally, the boundary conditions developed are as follows:

$$\begin{cases} \lambda_j \dfrac{\partial T_i}{\partial n}\bigg|_{\{x,y,z\} \in \partial\Omega} + \rho_0(1-\varepsilon)\cdot\beta\left(U_i\bigg|_{\{x,y,z\} \in \partial\Omega} - U_p\right) = \alpha\left(T_i\bigg|_{\{x,y,z\} \in \partial\Omega} - T_c\right), \\ a_j\delta \dfrac{\partial T_i}{\partial n}\bigg|_{\{x,y,z\} \in \partial\Omega} + a_j \dfrac{\partial U_i}{\partial n}\bigg|_{\{x,y,z\} \in \partial\Omega} = \beta\left(U_p - U_i\bigg|_{\{x,y,z\} \in \partial\Omega}\right), \end{cases} \tag{12.3}$$

where j – index ($j = 1, 2, 3$), α – coefficient of heat exchange, β – moisture exchange coefficient, l – the length of each face (all faces are equal to each other), $U_p(T_c, \varphi)$ – equilibrium humidity, T_c – ambient temperature, φ – relative humidity.

12.4. SOFTWARE DEVELOPMENT FOR RESEARCH OF CAD MODEL BY USING CELLULAR AUTOMATA

12.4.1. GRAPHICAL INTERFACE

To study the CAD model, a software in the Microsoft Visual Studio 2010 application using programing language C# was developed. This program has several tabs, one of which is responsible for working with cellular automata (Fig. 12.7).

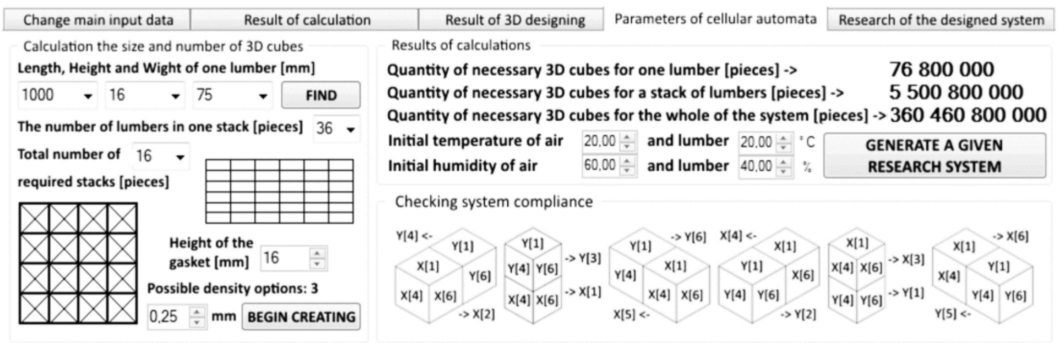


Fig. 12.7. View the tab of the developed software for working with cellular automata

With this software, the user can enter the size of the lumber, their number in one stack and the total number of stacks. Based on this data, the program can generate a three-dimensional array of data, the size of which will depend on the separation density of the studied CAD model, which is entered by the user. By manipulating the size of the separation density into 3D cubes, the user can get the most accurate calculation results [6].

12.4.2. UML DIAGRAMS

To work with the created three-dimensional array, we developed 12 classes, which can move objects of different classes among themselves. In this regard, instances of the developed classes have associative relationships, which are shown in the developed class diagram (Fig. 12.8).

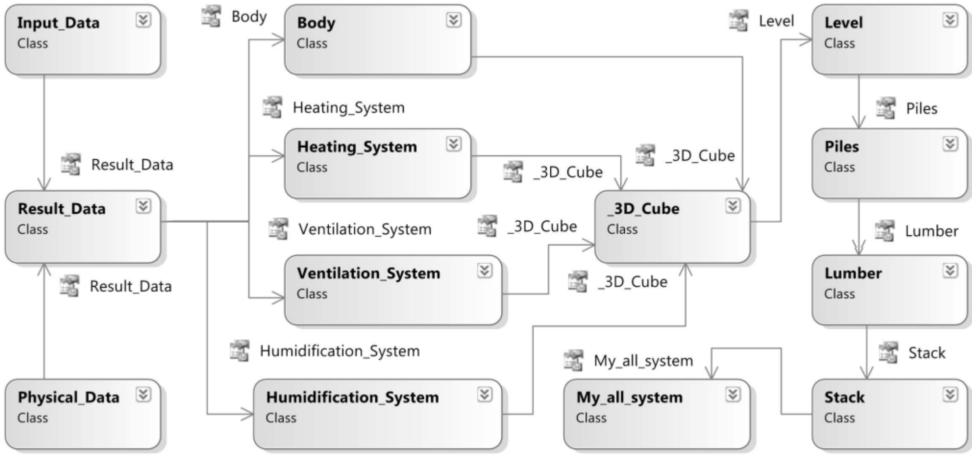


Fig. 12.8. The appearance of a class diagram

The sequence diagram (Fig. 12.9) shows the interaction of objects of the developed classes with each other. This diagram shows only those classes that are directly involved in investigating the parameters of a wood drying agent by using cellular automata [7].

To better understand all the functionality of the developed software, you can use the diagram of use (Fig. 12.10).

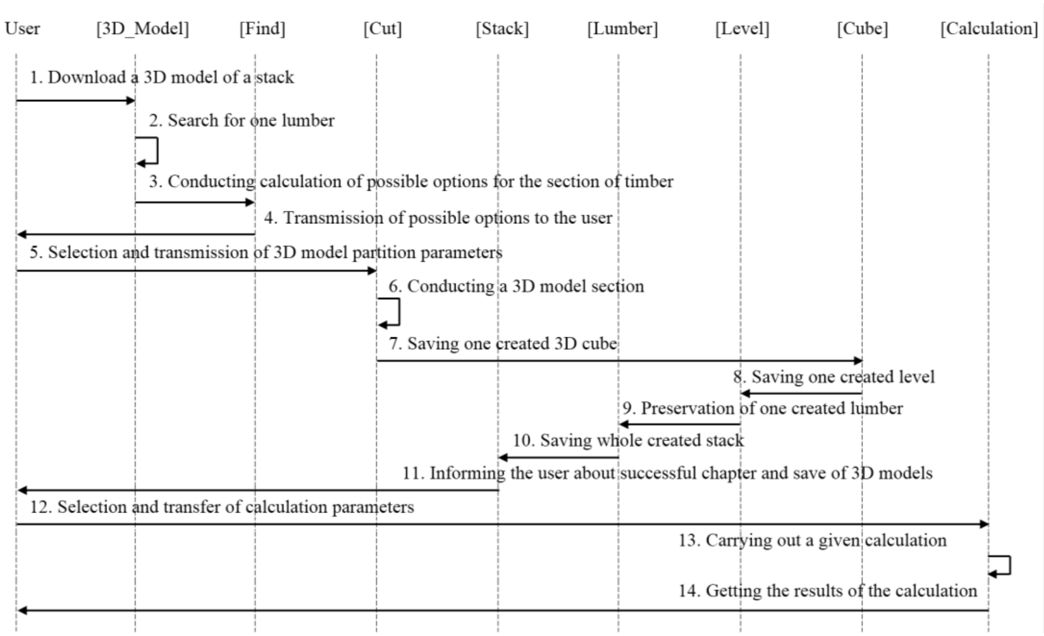


Fig. 12.9. The appearance of a sequence diagrams

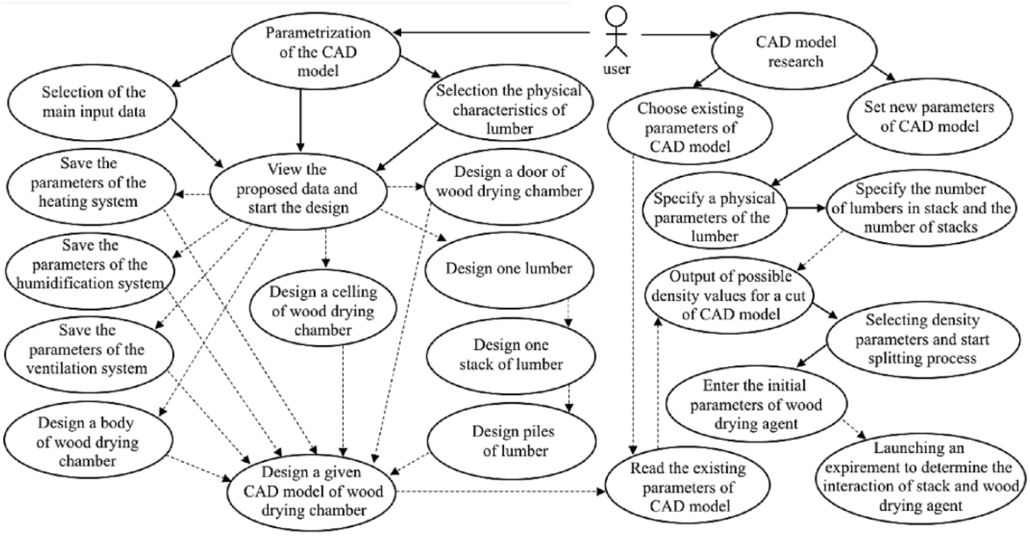


Fig. 12.10. The appearance of a using diagram

12.5. CALCULATION RESULTS

12.5.1. EXPERIMENT IN SOLIDWORKS FLOW SIMULATION

To determine the change parameters of agent timber, an experiment using SolidWorks Flow Simulation was carried out. As a result of this experiment, we obtained the numerical values of temperature and relative humidity of the air masses in the wood drying chamber. In addition, we obtained a trajectory of motion of air masses, based on which the surface of change of temperature and relative humidity in the upper layers of the CAD model were taken.

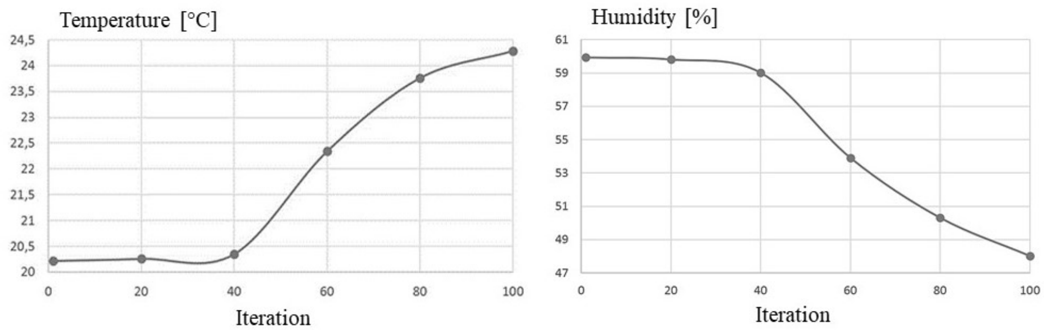


Fig. 12.11. Graph of temperature and humidity in wood

As a result of 100 iterations, we obtained average numerical values of the temperature and humidity. Based on these data, the corresponding graphs (Fig. 12.11) were constructed. These graphs show that the *Y* axis is responsible for the average values and the *X* axis for the iteration numbers. Based on the obtained data, we constructed graphs of temperature and relative humidity changes of the wood drying agent in space and time (Fig. 12.12).

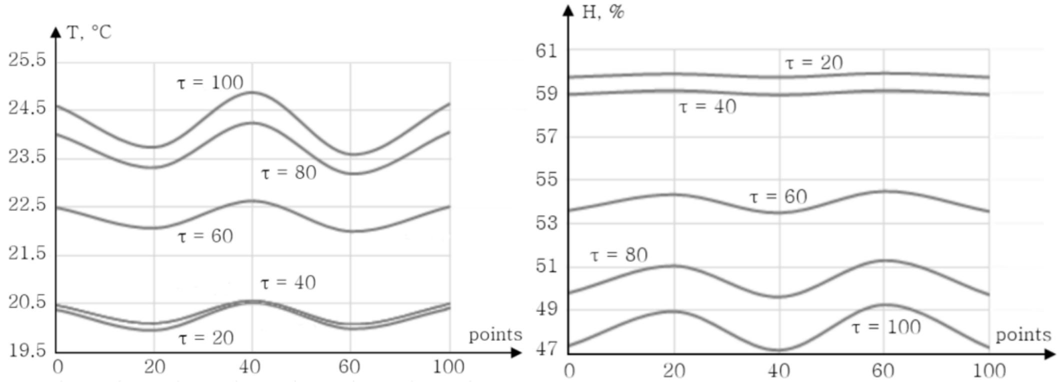
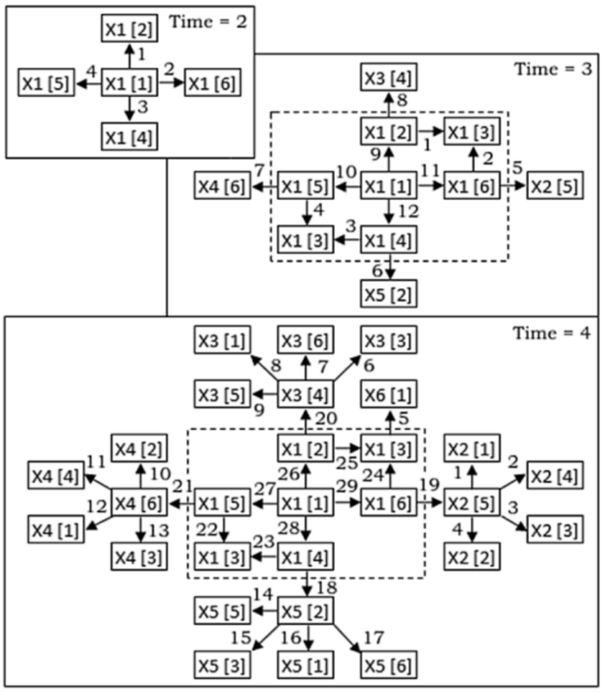


Fig. 12.12. Graphs of temperature and relative humidity changes in space and time

12.5.2. DYNAMIC EXPERIMENT BASED ON 3D CUBES

Therefore, at the beginning of the experiment, we have a huge number of 3D cubes whose faces have initial values. Next, we select one 3D cube, which in the course of the experiment will have a change in the numerical values of its faces according to the developed mathematical model. We will call this 3D cube $X1$ and denote the numbers of its faces in square brackets [8].



Time	0	1	2	3	4
X1 [1]	**20,00**	**20,03**	**20,05**	**20,09**	**20,12**
X1 [2]	20,00	20,00	20,03	20,05	20,09
X1 [3]	20,00	20,00	20,00	20,03	20,05
X1 [4]	20,00	20,00	20,03	20,05	20,09
X1 [5]	20,00	20,00	20,03	20,05	20,09
X1 [6]	20,00	20,00	20,03	20,05	20,09
X2 [1]	20,00	20,00	20,00	20,00	20,03
X2 [2]	20,00	20,00	20,00	20,00	20,03
X2 [3]	20,00	20,00	20,00	20,00	20,03
X2 [4]	20,00	20,00	20,00	20,00	20,03
X2 [5]	20,00	20,00	20,00	20,03	20,05
X3 [1]	20,00	20,00	20,00	20,00	20,03
X3 [3]	20,00	20,00	20,00	20,00	20,03
X3 [4]	20,00	20,00	20,00	20,03	20,05
X3 [5]	20,00	20,00	20,00	20,00	20,03
X3 [6]	20,00	20,00	20,00	20,00	20,03
X4 [1]	20,00	20,00	20,00	20,00	20,03
X4 [2]	20,00	20,00	20,00	20,00	20,03
X4 [3]	20,00	20,00	20,00	20,00	20,03
X4 [4]	20,00	20,00	20,00	20,00	20,03
X4 [6]	20,00	20,00	20,00	20,03	20,05
X5 [1]	20,00	20,00	20,00	20,00	20,03
X5 [2]	20,00	20,00	20,00	20,03	20,05
X5 [3]	20,00	20,00	20,00	20,00	20,03
X5 [5]	20,00	20,00	20,00	20,00	20,03
X5 [6]	20,00	20,00	20,00	20,00	20,03
X6 [1]	20,00	20,00	20,00	20,00	20,03

Fig. 12.13. Performing 0-4 iterations of the experiment when changing the temperature values

In the course of the experiment, the faces of $X1$ will transfer the change of their numerical values to adjacent faces of other 3D cubes, which we will call XN, where N is the ordinal number of 3D cubes. To determine the number of tangent faces in adjacent 3D cubes, we can use the developed scheme of relations, which is shown in Fig. 12.6.

An example of performing this experiment, when selecting the initial first face for $X1$ is shown in Fig. 12.13. Since the experiment involves a large number of iterations, we have shown only the first four. At the same time, we consider that at the first and second iterations (time = 1, 2) the numerical values of only the eigenvalues for $X1$ are realized. Beginning with the third iteration (time = 3), we can observe the process of transmitting numerical values for the faces of neighboring XN. In addition, this figure shows the temperature values for all involved faces of the selected 3D cubes [9].

12.5.3. USING A RADIALLY BASED ARTIFICIAL NEURAL NETWORK

In order to obtain numerical values in any 3D cube and at any time, we have created a radial basis artificial neural network. This network contains three layers. The first conventional input layer distributes the sample data for the first layer of weights.

The second layer contains hidden neurons with radially symmetric activation function. The third layer of the network is the source. Such a radial basis network with R inputs is presented in Fig. 12.14.

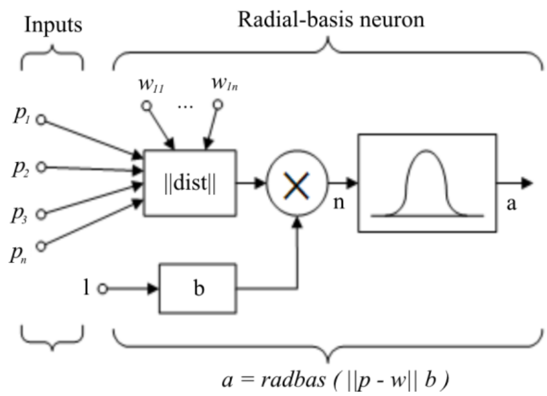


Fig. 12.14. Radial basis artificial neural network

The input of the activation function for a given artificial neural network is defined as the modulus of difference of the vector of weights w and the vector of input p multiplied by the displacement b. This function will have a maximum equal to one with zero input. As the distance between the vectors w and p decreases, the output of the radial basis function will increase. Therefore, the radial basis neuron will act as an indicator that generates a unit value when the input p is identical to the weight vector w. The offset b can adjust the sensitivity of neurons *radbas*.

In order to take full advantage of this artificial neural network, it is necessary to have arrays of the input training sample. These arrays are obtained by performing the first 100 iterations of the experiment. In general, we have the following arrays:

- Input - coordinates of the 3D cube, time, number of its face, type sought;
- Temperature - temperature values;
- Humidity - humidity values.

In total, each of the training sample arrays contain at least 600 datasets. These arrays are shown in Fig. 12.15.

Variables - input

Humidity × | Temperature × | Velocity × | input ×

input <600x4 double>

	1	2	3	4
100	2.8000	3.2000	2.8000	0
101	-4	-1.3000	-2.8000	20
102	2.8000	-1.3000	-2.8000	20
103	0.1000	0.2000	-2.8000	20
104	-1.2500	0.2000	-2.8000	20
105	-2.6100	0.2000	-2.8000	20
106	-4	0.2000	-2.8000	20
107	1.4600	0.2000	-2.8000	20
108	2.8000	0.2000	-2.8000	20
109	0.1000	1.7000	-2.8000	20
110	-1.2500	1.7000	-2.8000	20
111	-2.6100	1.7000	-2.8000	20
112	-4	1.7000	-2.8000	20
113	1.4600	1.7000	-2.8000	20
114	2.8000	1.7000	-2.8000	20

Variables - Temperature

Temperature × | Velocity ×

Temperature <600x1 double>

	1	2
100	20.2180	
101	18.3988	
102	18.3444	
103	18.3731	
104	18.6367	
105	20.5831	
106	18.4563	
107	18.3483	
108	18.3675	
109	18.5496	
110	19.2686	
111	24.1706	
112	18.5048	
113	18.4067	
114	18.3952	

Variables - Humidity

Humidity × | Temperature ×

Humidity <600x1 double>

	1	2
100	59.9400	
101	60.9911	
102	60.6799	
103	61.1059	
104	61.0152	
105	59.3555	
106	61.0187	
107	60.5760	
108	60.5307	
109	61.0516	
110	60.4537	
111	57.3406	
112	60.9992	
113	60.7495	
114	60.4262	

Fig. 12.15. The appearance of the training sample arrays

With a training sample, we have created a feature that allows the use of artificial neural network. This *Mynetwork* feature is as follows:

```
Function Result = Mynetwork (x, y, z, time, number, type, temperature, humidity)
    If type = = 'T'
        Net = newrbe (input', temperature');
    End
    If type = = 'H'
        Net = newrbe (input', humidity');
    End
Result = sim (net, [x, y, z, number, time]');
```

As a result of using this function, we obtain the required numerical value according to the given coordinates and the face number of the desired 3D cube [10]. The use of the developed *Mynetwork* function is as follows:

```
>>  res = Mynetwork (21, 18, 16, 214, 1, 'T', Temperature, Humidity)
res = 24.9542
>>  res = Mynetwork (21, 18, 16, 214, 1, 'H', Temperature, Humidity)
res = 61.0484
```

From this example, you can see that *x*=21, *y*=18, *z*=16, time=214 second and the face of select 3D cube is equal one. In addition, it can been seen that in the first case, we selected the temperature and in the second case, we selected the relative humidity. As a result of using developed *Mynetwork* function, the artificial neural network showed the following results: $T = 24.95°C$ and $H = 61.05\%$.

12.6. CONCLUSIONS

In this work, we performed a series of experiments in SolidWorks Flow Simulation, based on which we determined the parameters of the wood drying agent. In addition, to determine the parameters of a wood drying agent by using the theory of cellular automat, we developed a mathematical model. To use this theory, we presented a CAD model in the form of 2D Von Neumann neighborhoods in 1-order. Based on the obtained data, we got the graphs of aerodynamic flows in the CAD model. In addition, we developed and tested an artificial neural network that determine the temperature and humidity of any face of the selected 3D cube at a given point in time.

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