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Synthesis of a Fuzzy Model in Matlab for Automatic Control of the Drying Process

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***Abstract*— The paper considers the relevant issue of improving wood drying, reducing the energy intensity of these technol-ogies, primarily by means of automated process control systems based on modern information technologies. To take into account the uncertainties of the input parameters and the influencing factors the apparatus of fuzzy modeling was used. To complete the work, it was necessary to obtain the missing functional dependences of the wood moisture content and time of drying on the heating temperature and the equilibrium air humidity in the drying chamber based on fuzzy output, which was the purpose of this work. Methodologically, the work is based on the drying theory, wood science, the regulation of mathematical and fuzzy modeling, and in terms of checking the adequacy of the proposed fuzzy model, the methods of mathematical statistics and the theory of experiment were used.**

The results of the research are the obtained dependences of drying time and wood moisture content on the heating temperature and the equilibrium air humidity in the drying chamber, the synthesis of which is per-formed by means of Fuzzy Logic Toolbox of the Matlab application.

The scientific novelty of research can be seen in the development of models of drying process based on fuzzy modeling. The practical applicability of the results is the possibility of creating an intelligent system of automatic control of the drying process of lumber.

Keywords*— *wood drying; wood moisture; equilibrium air humidity; fuzzy modeling; fuzzy output

I. Introduction

In the context of the global problem of forest industry energy efficiency in-crease, the authors have previously considered drying wood as one of the most energy-intensive processes in forestry technologies. It is shown that this process can be improved most effectively by automatic control on the base of fuzzy logic. For this purposes it is necessary to develop appropriate fuzzy models. This concept is substantiated as a result of the analysis of the drying process research, the identification of uncertainties in the process pa-rameters and the substantive formulation of the task of fuzzy modeling of the main process parameters. The formalization of uncertainties allows us to complete the task, therefore the aim of these studies was to develop models of an intelligent system for managing the process of drying wood on the ba-sis of a fuzzy modeling apparatus.

The work provided for the following tasks.

1. Taking into account the results of formalization of the uncertainty of the present studies, the definition of fuzzy membership functions for the in-put and output variables of the problem (reduction to fuzziness).
2. Development of a base of rules for fuzzy products.
3. Synthesis of a fuzzy model of dependencies of humidity and drying time on input parameters by means of Matlab Fuzzy Logic Toolbox..

II. Fuzzy Modeling Application Overview

The analysis of theory on the topic of wood drying shows the impossi-bility of obtaining a sufficiently complete and adequate model for managing the wood drying process by traditional statistical methods, primarily due to the conditions of uncertainty in the input parameters of the process. It is noted that such problems should be solved on the basis of the fuzzy sets theory and its applications, fuzzy logic and fuzzy modeling in particular. In this regard, it is necessary to note a new trend in scientific research – the emergence of isolated cases of the theory of fuzzy sets application for re-search and development of automatic control of drying equipment. For ex-ample, soft computing was used to analyze the parameters of heat and mass transfer of the rate of evaporation of moisture, the effectiveness of drying quality, and the temperature of the ambient air in solar drying chambers [1]. It is indicated that mathematical models are generated in the MATLAB sys-tem, which in this case turned out to be quite adequate.

An attempt to develop a fuzzy controller to control the power of a so-lar-powered drying chamber is given in work [2].

In domestic and foreign editions, the topic of applying the theory of fuzzy sets in problems of modeling various processes is widely covered.

Examples of the practical use of TFS are thoroughly considered in the Russian edition [3]. The theoretical basis of fuzzy modeling and works in the FuzzyTECH computer program are outlined.

The work of Vasilyev VI, Ilyasov B.G. [4] can be considered a signifi-cant contribution to the development of TFS in terms of the use of intelligent systems based on fuzzy logic to control aircraft.

One of the fundamental works, which has both theoretical and practical significance for fuzzy modeling, is the research by Professor A. Pegat of the University of Warsaw [5]. According to leading experts, "... this is an out-standing book, which has almost no equal in existing literature".

In evaluating the technical condition of building concrete structures, the authors Shtovba S., Rotshtein A., Pankevich O. [6] suggested the use of fuzzy logic.

The section of the computer mathematics system MATLAB [7], where a fairly detailed theoretical part on the creation of fuzzy modeling systems is given, is of great practical importance for developers. Examples, allowing analogically create models of objects of any nature, are proposed.

As the creator and authors of a number of applied methods of fuzzy modeling should be mentioned Prof. Zadeh L.A. [8], his student and follower Kosko B., authors Mamdani E.H., Takagi T., Sugeno M.

In the fuzzy modeling field, there is a large publication activity in Rus-sia and abroad. Works on the development of the mathematical apparatus for accounting for fuzziness, uncertainty, other aspects of this concept [9,10] are known, as well as many applied studies in various technical [11,12], humanitarian areas, in law, economics and medical sciences.

Summarizing the overview, we can draw the main conclusions in the context of the present research.

1. The results of the existing studies do not fully provide a solution to the problem of the automatic control of the wood drying process, primarily due to uncertainties in the technological process data.
2. Issues of research of wood drying processes based on fuzzy modeling have not previously been considered.
3. For the practical implementation of fuzzy models, the Matlab system of computer mathematics [7] is mainly used, which is provided by the Fuzzy Logic Toolbox application designed for this purpose.

III. Methodology and Research

The methodological basis of the theoretical studies was constituted by the theory of wood drying, wood science, mathematical and fuzzy modeling, and in carrying out experimental studies to verify the adequacy of the pro-posed fuzzy model, methods of mathematical statistics and theory of exper-iment were used.

The development of fuzzy inference functions was carried out according to the well-known method [3-5] in the sequence given below. This technique was also used by the authors to solve other problems [13,14].

In addition, in the previous studies of the authors, the formulation of the fuzzy modeling problem of the drying process was carried out in a gen-eral form, and the input and output variables of the problem were substantiated.

To further solve the problem, it is necessary to define fuzzy member-ship functions and a base of fuzzy product rules.

A. Definition of fuzzy membership functions for input and task output variables

Let us define the values of the input variables. The temperature t in the convection-type chamber for conditional lumber is set over 8 steps in the range from 69 ºC to 83 ºC.

The value of the equilibrium humidity u according to experimental stud-ies [15] takes values from 4 to 12.5%.

The output values of the problem are the humidity W and the drying time of lumber T.

Drying in this problem is considered from a humidity of 60% and ends at 8%.

Drying time should be considered only as indicative and only for condi-tional lumber. Table 1 shows the experimental data from [15].

Taking into account the physical values of the quantities, the linguistic variables of the problem should be defined.

In the fuzzy sets universum in this case it would be reasonable to accept five values of the input and output linguistic variables. The term sets of lin-guistic variables are represented by triangular fuzzy numbers, and at the boundaries of the domain of definition by sigmoidal fuzzy intervals. For the term "Big" of the variable "Equilibrium humidity", a trapezoidal fuzzy num-ber is assumed, due to the increased range of values in this region. Graph-ically, the linguistic variables are shown in Fig. 1.

Fig. 1a, 1b show the membership functions of the input variables "Temperature t" and "Equilibrium humidity U"; fig. 1c shows the fuzzy function of the linguistic output variable "Humidity W", fig. 1d - "Time T".

As the notation of linguistic variables for the proposed functions, the following values are used: - “Minimum” - Min; “Small - S; "Average" - Av; "Big" - B; "Maximum" - Max.

In terms of the theory of fuzzy sets, linguistic variables are defined by term sets with the following values:

- “Temperature t” {Min, M, Av, B, Max};
- "Equilibrium humidity U" {Min, M, Av, B, Max};
- “Humidity W” {Min, M, Av, B, Max};
- “Time T” {Min, M, Av, B, Max}.

B. Formation of the rule base of the fuzzy inference system

For fuzzy derivation of the membership function, we use one of the most common methods – the Mamdani method [3,5]. The use of this method in-volves the development of a base of rules for fuzzy production.

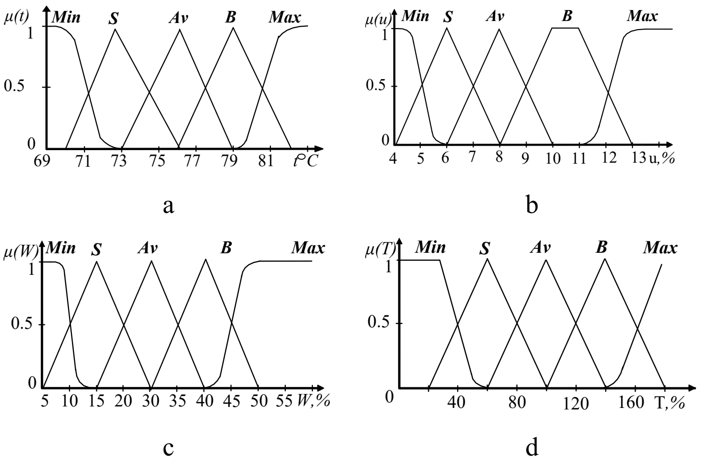

Fig. 1. Fuzzy membership functions of linguistic variables for the derivation of the function W = f(t, U): a – "Temperature t"; b – "The equilibrium humidity U"; c – "Humidity W"; d – "Time T"

Let us describe the effect of some combinations of input actions on the output parameter.

If t = "Minimum" and u = "Minimum", then W = "Minimum" and T = "Average";

If t = "Minimum" and u = "Maximum", then W = "Maximal" and T = "Maximum";

If t = "Maximum" and u = "Minimum", then W = "Minimum" and T = "Minimum";

If t = "Large" and u = "Minimum", then W = "Small" and T = "Small";

If t = "Average" and u = "Average", then W = "Average" and T = "Av-erage";

If t = “Maximum” and u = “Small”, then W = “Small” and T = “Small”.

TABLE I. COMPOSITION OF THE BASE OF RULES OF FUZZY PRODUCTS FOR MODELING W = F(T, U)

Values of the linguistic variable "Temperature t"	The values of output fuzzy subsets "Humidity W" with a change in the fuzzy function "The equilibrium humidity U"				
	Min	**S**	**Av**	**B**	**Max**
Min	Max	Max	Max	Max	Max
S	B	B	Max	Max	Max
Av	Av	B	B	Max	Max
B	S	Av	B	B	Max
Max	Min	S	Av	B	Max

Similarly, we obtain a rule base for deriving the drying time function (Table 3).

TABLE II. COMPOSITION OF THE BASE OF RULES OF FUZZY PRODUCTS FOR MODELING T = F(T, U)

Values of the linguistic variable "Temperature t"	The values of output fuzzy subsets "Time T" with a change in the fuzzy function "The equilibrium humidity U"				
	Min	**S**	**Av**	**B**	**Max**
Min	Av	B	B	Max	Max
S	Av	Av	Av	Max	Max
Av	S	Av	Av	B	Max
B	Min	S	S	Av	B
Max	Min	Min	S	Av	B

The fuzzy inference of the resultant function is made according to the Mamdani method [3,5]. Diagram of output in Matlab-format is shown in Fig. 2.

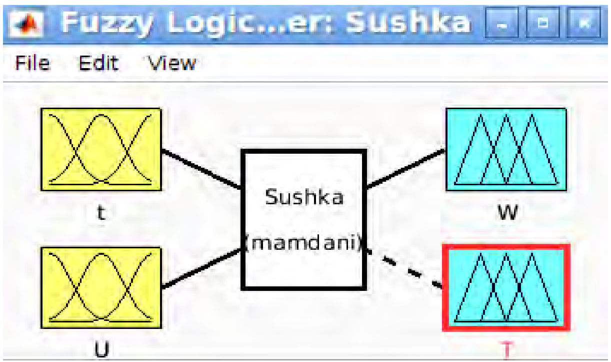

Fig. 2. The scheme of fuzzy output in the Matlab environment [34]

IV. RESULTS

A. Synthesis of fuzzy models of dependences of humidity and drying time of wood on temperature and equilibrium humidity

The formal formulation of the fuzzy inference problem is implemented in the computer program Fuzzy Logic Toolbox of the Matlab application [7]. The output procedure is shown in Fig. 3. In this case, the algorithm was used according to the well-known [3.5] method:

1. Fuzzification (introduction of fuzziness), (Fig. 3,a-3,c);

2. Forming the base of rules for fuzzy products (Fig. 3,d);
3. Fuzzy inference (Fig. 3,e);
4. Defuzzification (reduction to clarity), (Fig. 3,e);
5. Receipt of the final function of a fuzzy inference (Fig. 3, f).

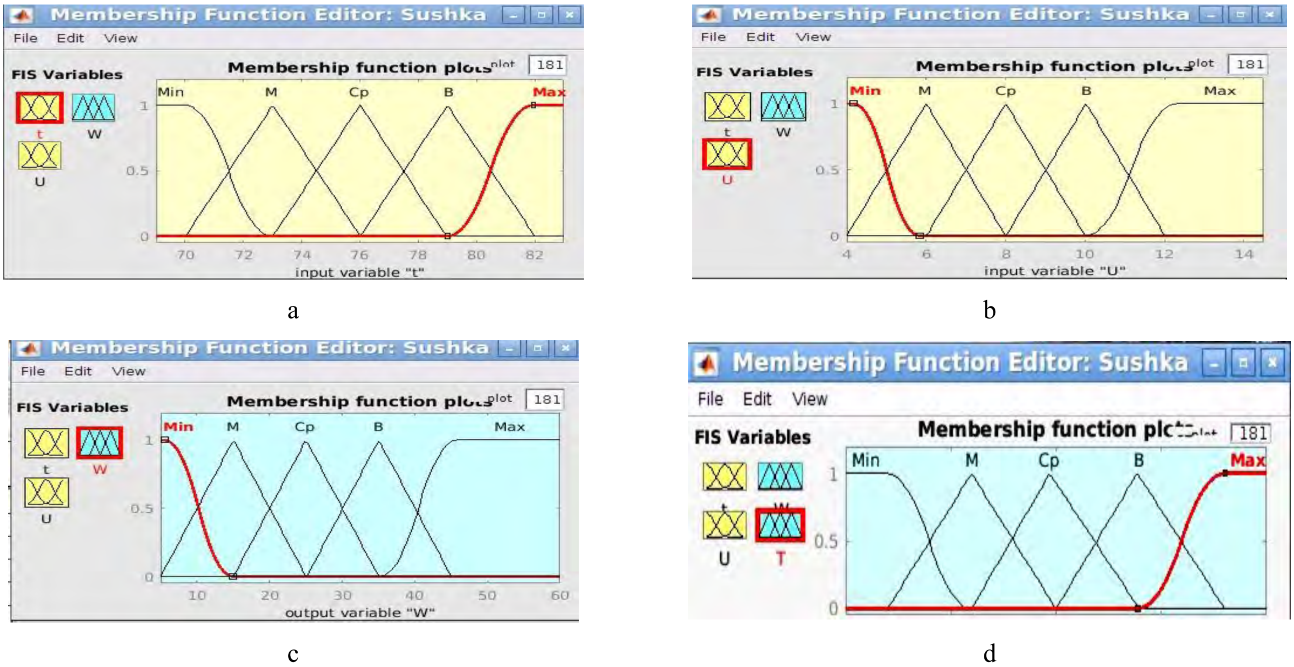

Fig. 3. . Fuzzy function in the Fuzzy Logic Toolbox environment of the Matlab application: a - fuzzy function of belonging to the linguistic variable "Temperature t"; b - fuzzy function of belonging to the linguistic variable "The equilibrium humidity U"; c - fuzzy membership function of the variable "Humidity W"; d – fuzzy function of belonging to the linguistic variable "Time T"

The functions resulting from fuzzy inference are mathematically cor-rect enough and can be used to predict moisture values and wood drying time. Comparison with experimental data [15] shows their adequate adequa-cy.

B. Results analysis

The results are considered in terms of differences from current re-search, analyzing their compliance with the following criteria of scientific value:

- difference from known results;
- scientific novelty;
- practical applicability.

The main difference between the results is that, as was shown, there are not enough full-scale studies on the processes of drying wood that are devoted to fuzzy modeling of wood drying to develop automated process control systems using fuzzy logic neither in Russia nor abroad.

The conditions of uncertainty in the initial parameters of the drying process lead to situations where traditional methods are ineffective due to the lack of sufficiently reliable knowledge about the object of control. The proposed approach and the results obtained, unlike the existing methods, allow solving this problem in relation to the process of drying lumber.

Scientific novelty follows from the distinctive features of the results, i.e. for the first time, a theoretical approach was proposed for estimating the moisture parameters and wood drying time on the basis of fuzzy modeling. Another element of scientific novelty is the established functional depend-ences of humidity and drying time of wood on temperature and equilibrium air humidity in the drying chamber. The adequacy of the obtained depend-ences is confirmed in the results of experimental studies [15]

The practical applicability of the results lies in the possibility of creat-ing a system for automatic control of the process of drying wood. Results in the form of a functional relationship derived from a fuzzy inference are nec-essary for the development of a fuzzy drying chamber control controller.

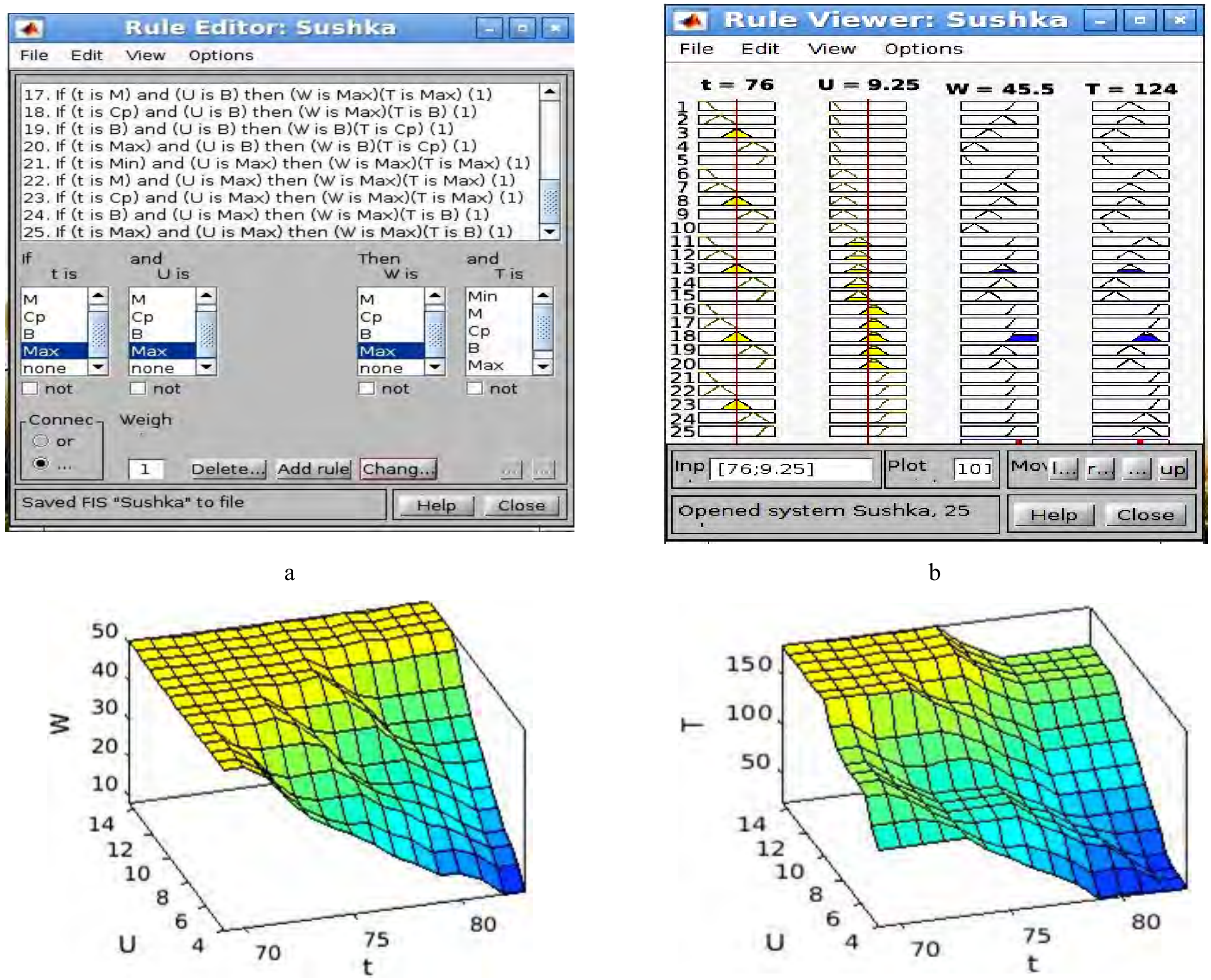

Fig. 4. . Fuzzy output of the function *W = f(t, U)* and *T= f(t, U)* in the Fuzzy Logic Toolbox environment of the Matlab application: a - base of rules of fuzzy inference; b - procedure of fuzzy inference and reduction to clarity; c - fuzzy inference func-tion of the "Humidity, W"; d - fuzzy inference function of the "Time, T"

V. CONCLUSION

Studies have led to the following conclusions:

1. Currently the improvement of research methods for the parameters of wood drying is impossible without the use of intelligent software systems and computer tools. The proposed formulation of the fuzzy modeling prob-lem and the implementation of the corresponding software in the Matlab en-vironment makes it possible to effectively use information technologies in research, modeling and improvement of drying chambers.

2. Analysis of studies of the drying process of wood led to the identification of fuzziness in the source data, to substantiate the informative setting of the fuzzy modeling task, taking into account the uncertainties. For conditions of problems of such sort, the apparatus of the theory of fuzzy sets and its ap-plications, in particular, fuzzy modeling, is most suitable. The proposed fuzzy models form a mathematically correct apparatus for estimating wood moisture and drying time, which allows us to recommend these results for use in the practice of designing systems for intelligent automatic control of drying chambers.

3. The proposed functions of humidity and wood drying time, built on the basis of fuzzy inference, take into account the main process parameters - the temperature in the chamber, the equilibrium air humidity, and a comparison of the simulation results with experimental data [15] shows that the devel-oped model is sufficiently adequate and allows you to implement a funda-mentally new approach to solving the problem of improving drying equip-ment, improving the quality of lumber and reducing the energy intensity of processes.

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