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MATHEMATICAL MODELLING OF THE OBJECTIVE FUNCTIONS OF THE PRODUCTION PROCESS OF WOOD PELLETS

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ABSTRACT

The goal was to create a mathematical apparatus for process control of wood pellets production. Techniques of expert assessment and planning active industrial experiment were applied. Output objective functions of the process of biofuel production in the form of pellets are obtained. Plan of active industrial experiments was developed. It has taken into account the specific features of the used industrial equipment, technical specification and properties of raw materials. Objective information about the output technical and economic parameters of the process was get. Parameters, objectively changing according to the laws of probability in real rather wide ranges, were considered. The resulting equations of energy intensity changes and mechanical strength of the pellets, the temperature of the matrix, the performance of the used equipment, production costs were quite adequate to the real process. The average error is 0.562 % for the entire series of experiments for all of the above-mentioned objective functions. These equations make it possible to carry out single-criterion and multi-criteria optimization to enhance the effectiveness of the production process of pellets and analysis in industrial environment. It makes possible to optimize the possible modes and create mathematical apparatus for automatic control systems.

Keywords: equation, experiment, mathematic, modelling, pellet, process, wood.

INTRODUCTION

Problem of efficient utilization of resulting wood waste is always relevant. Increase of the useful output, improvement of the overall ecology of production, reduces of the cost of wood material and manufactured products in a given quality are also actual tasks (SAFONOV 2011). The relevance of these problems increases in proportion both to the increase of wood waste resulting from different technologies and the growth of world prices for fossil energy sources (SAFONOV *et al*. 2012a). World practice of wood waste utilization and obtaining the most demanded products from them has proved viability of alternative energy production in the form of chips, pellets, briquettes and other energy products (JANDAČKA 2011).

However, the technological processes of biofuels production from wood waste have considerable difficulties in control. It takes place despite the relative simplicity of the equipment and the regulation by changes of a number of operating parameters. Significant difficulties arise in determining the optimal characteristics of raw materials and its storage conditions. Also they arises in determining the levels of the control actions, technical equipment tuning, and synchronization of separate process operations connected by the transport sections (NIELSEN *et al.* 2009). Non-correct actions in the above-mentioned aspects are the reason of reducing the overall efficiency of pellets production. Indeed, many technical, technological, economic indicators are crucial in deciding the organization of such production on industrial scale. It is not possible to be succeeded at the present level of high and enough stable competitive environments in the market without having reliable information about the properties of the pelletizing process. Here research on actual operating industrial equipment plays an important role. The research is aimed at establishing dependencies of changes, mutual influence of various parameters, describing the production process of not only pellets, but other biofuels either. There are many examples of the use of high-performance, precise, modern equipment with automatic control systems at low overall efficiency of a number of indicators, characterizing the process. These indicators are independent of each other, their objective functions have extreme pointed in opposite directions. Receiving good, satisfying parameters of one group, the manufacturers, in some cases, due to lack of information on the relationship between the characteristics of the process, neglect parameters of other group. Thereby the overall efficiency of the process is reduced to an unacceptable level (SAFONOV 2002). For instance, we can obtain products with unacceptably low mechanical strength achieving the maximum productivity of the process of pellets production. High, uncompetitive cost of energy product can be obtained at maximum calorific value of the produced biofuels (GRANSTRÖM 2009, DZURENDA *et al.* 2001). This multi-objective problem can be solved by modern methods of active planning of industrial equipment. Mathematical analysis of obtained reliable results on the properties of the considered object, modelling indicators, characterizing the process with obtaining dependencies, adequate to actual process, are also used in this case.

METHODS

Plan of active industrial experiment is made on the basis of system analysis to obtain data for the mathematical modelling of the studied process. The basis of the system approach is the desire to explore the object as something integral and organized. It is in its entirety, and in the diversity of relationships in the object. This general principle focuses on the consideration of objects as systems. Methodology of systematic approach is based on the integrated use of the principles of modelling, and on the achievements of modern computing and mathematical modelling methods. This methodology let us go from complex physical model of pelleting (unsteady and irreversible one) to its formal mathematical model. Then we can go to its optimization.

Research methodology is based on using assumptions of the theory of active experiments planning. Active experiment involves intervention of the experimenter in process control. It provides wide varying intervals of controllable parameters up to the required limits, taking into account the specifics of production and safety conditions. Also, the subjectivity of research is excluded. Active experiment planning was to choose the number and conditions of experiments which are necessary and sufficient for the task with required accuracy. At this, we should be guided by the following principles (SAFONOV *et al.* 2012b):

1. Desire to minimize the total number of production tests;
2. Simultaneous variation of all control actions, defining the nature of the process according to specific rules;
3. Use of the mathematical apparatus formalizing many of the actions of the experimenter and reducing human error values across the series of industrial experiments;

4. Selection of clear strategy that helps to make informed decisions after each industrial experiment.

Hartley plan was chosen to plan active industrial experiment. The advantage of this type of plan is getting reliable information about the object of study with a minimum number of experiments. At the same time the specific features of production was considered in order to avoid creation of emergency situations or breakdown of used equipment.

Mathematical modeling was performed using the software package «Statistica Advanced». This allowed to make statistical and correlation analyzes of the results. At the same time adequate equation were obtained.

EXPERIMENTAL PART

Research of the production process of wood pellets is to develop a plan of active experiment and its implementation on industrial equipment. A number of indicators can be defined to obtain reliable information about the studied process. These indicators are used to determine the importance of all parameters describing the technology by expert assessments method, (PETROVSKY *et al*. 2000). The indicators have been arbitrarily divided into groups by types: adjustable or operating objectively changing disturbances, technical and economic indicators. The essence of the method of expert assessments was in the survey of scientific, technical and engineering employees of enterprises and research organizations. The survey was conducted in the form of a questionnaire. Each parameter, influencing the pelleting technology has a score from 1 to N, just in accordance with its importance. N is a number of parameters in each of three groups. As a result of this assessment it turned out that technological process of pellets production can be characterized by the following parameters, factors, indicators presented in Table 1.

Tab. 1 The most important characteristics of production process of wood pellets.

№	Parameter name	Units	Designation
	Input controlled parameters, X_i		
1	Amount of supplied wood raw material	$kg \cdot h^{-1}$	X_1
2	Humidity of supplied wood raw material	%	X_2
3	Fractional composition of supplied wood raw material	Mm	X_3
4	Lignin content (species composition)	%	X_4
5	The distance between the rollers and the matrix	Mm	X_5
6	Rotation frequency of matrix	min^{-1}	X_6
7	Steam temperature	°C	X_7
8	Cooling temperature of pellets	°C	X_8
	Uncontrollable disturbances, F_j		
1	Temperature of atmospheric air	°C	F_1
2	Humidity of atmospheric air	%	F_2
3	Temperature of raw materials	°C	F_3
	Output technical and economic indicators, Y_n		
1	Specific calorific efficiency	$MJ \cdot kg^{-1}$	Y_1
2	Mechanical strength	%	Y_2
3	Matrix temperature	°C	Y_3
4	Performance at clean granules considering fine fraction dropping out after pressing	$kg \cdot h^{-1}$	Y_4
5	Production costs	RUB/t	Y_5

In general, the process of pellet production consists of the following stages:

1. Transportation of raw materials from the storage to the chipper for grinding.
2. Grinding of raw materials in chippers to produce particles.
3. Wood particles drying in the aggregates of the drum, belt or other types.
4. Transportation of chopped dry wood to the dispenser.
5. Dosing of chopped wood when feeding in the pellet press.
6. Granulation of wood pulp to give pellets.
7. Cooling of finished pellets in a cooling chamber.
8. Transportation and packaging of pellets.

Each technologically controllable parameter X_i can take multiple values in a series of experiments, in particular the minimum, average and maximum one. Varying levels of operating parameters were defined taking into account the views of engineering and technical staff. Characteristics of the used pellet press were paid special attention. These levels are shown in Table 2.

Tab. 2 Varying levels of operating parameters of the production process of wood pellets.

Name of operating parameter	Units	Smallest observation (-)	Mid-value (0)	Largest observation (+)
Amount of supplied wood raw material X_1	$kg.h^{-1}$	900	1550	2200
Humidity of supplied wood raw material X_2	%	8	10	12
Fractional composition of supplied wood raw material X_3	mm	1	3	5
Lignin content (species composition) X_4	%	21	24	27
The distance between the rollers and the matrix X_5	mm	0.4	0.6	0.8
Rotation frequency of matrix X_6	min^{-1}	100	120	140
Steam temperature X_7	°C	130	140	150
Cooling temperature of pellets X_8	°C	10	15	20

Planning of active industrial experiment involves active intervention of researcher in the production process of wood pellets. This planning includes choice in every industrial experience of those levels X_i of controlled parameters that are of concern.

Actual process of wood pellets production is affected by both controlled factors X_i and uncontrolled disturbances F_e. Uncontrollable factors can affect the reproducibility of the experiment, so they need to be considered when conducting research. Permissible level of fluctuations should be under precise control. At the output of the numerical values of uncontrollable factors a series of experiments need to be interrupted and resumed when achieving the set fluctuation range. Hartley plan for eight controllable parameters is given in Table 3.

Tab. 3 Hartley plan for active industrial experiments of production process of pellets.

№	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8
1	−1	−1	−1	−1	−1	−1	−1	−1
2	+1	−1	−1	−1	−1	−1	−1	−1
3	−1	+1	−1	−1	−1	−1	−1	−1
4	+1	+1	+1	−1	−1	−1	−1	−1
5	−1	−1	−1	+1	−1	−1	−1	−1
6	+1	−1	−1	+1	−1	−1	−1	−1
7	−1	+1	−1	+1	−1	−1	−1	−1
8	+1	+1	+1	+1	−1	−1	−1	−1
9	−1	−1	−1	−1	+1	−1	−1	−1
10	+1	−1	−1	−1	+1	−1	−1	−1
11	−1	+1	−1	−1	+1	−1	−1	−1

12	+1	+1	+1	−1	+1	−1	−1	−1
13	−1	−1	−1	+1	+1	+1	−1	−1
14	+1	−1	−1	+1	+1	+1	−1	−1
15	−1	+1	−1	+1	+1	+1	−1	−1
16	+1	+1	+1	+1	+1	+1	−1	−1
17	−1	−1	−1	−1	−1	−1	+1	−1
18	+1	−1	−1	−1	−1	−1	+1	−1
19	−1	+1	−1	−1	−1	−1	+1	−1
20	+1	+1	+1	−1	−1	−1	+1	−1
21	−1	−1	−1	+1	−1	−1	+1	−1
22	+1	−1	−1	+1	−1	−1	+1	−1
23	−1	+1	−1	+1	−1	−1	+1	−1
24	+1	+1	+1	+1	−1	−1	+1	−1
25	−1	−1	−1	−1	+1	−1	+1	−1
26	+1	−1	−1	−1	+1	−1	+1	−1
27	−1	+1	−1	−1	+1	−1	+1	−1
28	+1	+1	+1	−1	+1	−1	+1	−1
29	−1	−1	−1	+1	+1	+1	+1	−1
30	+1	−1	−1	+1	+1	+1	+1	−1
31	−1	+1	−1	+1	+1	+1	+1	−1
32	+1	+1	+1	+1	+1	+1	+1	−1
33	−1	−1	−1	−1	−1	−1	−1	+1
34	+1	−1	−1	−1	−1	−1	−1	+1
35	−1	+1	−1	−1	−1	−1	−1	+1
36	+1	+1	+1	−1	−1	−1	−1	+1
37	−1	−1	−1	+1	−1	−1	−1	+1
38	+1	−1	−1	+1	−1	−1	−1	+1
39	−1	+1	−1	+1	−1	−1	−1	+1
40	+1	+1	+1	+1	−1	−1	−1	+1
41	−1	−1	−1	−1	+1	−1	−1	+1
42	+1	−1	−1	−1	+1	−1	−1	+1
43	−1	+1	−1	−1	+1	−1	−1	+1
44	+1	+1	+1	−1	+1	−1	−1	+1
45	−1	−1	−1	+1	+1	+1	−1	+1
46	+1	−1	−1	+1	+1	+1	−1	+1
47	−1	+1	−1	+1	+1	+1	−1	+1
48	+1	+1	+1	+1	+1	+1	−1	+1
49	−1	−1	−1	−1	−1	−1	+1	+1
50	+1	−1	−1	−1	−1	−1	+1	+1
51	−1	+1	−1	−1	−1	−1	+1	+1
52	+1	+1	+1	−1	−1	−1	+1	+1
53	−1	−1	−1	+1	−1	−1	+1	+1
54	+1	−1	−1	+1	−1	−1	+1	+1
55	−1	+1	−1	+1	−1	−1	+1	+1
56	+1	+1	+1	+1	−1	−1	+1	+1
57	−1	−1	−1	−1	+1	−1	+1	+1
58	+1	−1	−1	−1	+1	−1	+1	+1
59	−1	+1	−1	−1	+1	−1	+1	+1
60	+1	+1	+1	−1	+1	−1	+1	+1
61	−1	−1	−1	+1	+1	+1	+1	+1
62	+1	−1	−1	+1	+1	+1	+1	+1
63	−1	+1	−1	+1	+1	+1	+1	+1
64	+1	+1	+1	+1	+1	+1	+1	+1
65	−1	0	0	0	0	0	0	0
66	+1	0	0	0	0	0	0	0
67	0	−1	0	0	0	0	0	0
68	0	+1	0	0	0	0	0	0
69	0	0	−1	0	0	0	0	0

70	0	0	+1	0	0	0	0	0
71	0	0	0	−1	0	0	0	0
72	0	0	0	+1	0	0	0	0
73	0	0	0	0	−1	0	0	0
74	0	0	0	0	+1	0	0	0
75	0	0	0	0	0	−1	0	0
76	0	0	0	0	0	+1	0	0
77	0	0	0	0	0	0	−1	0
78	0	0	0	0	0	0	+1	0
79	0	0	0	0	0	0	0	−1
80	0	0	0	0	0	0	0	+1
81	0	0	0	0	0	0	0	0

We obtained plan data of the change in output technical and economic indicators in the regulation of operating parameters and corresponding permissible levels of objectively changing factors. It allows us to pass to the modelling process of pellet production of wood waste. It should be noted that instrumentation, used in the active industrial experiments to determine the parameters of pelleting, met modern requirements in terms of accuracy and operation speed. Such instrumentation made it possible to obtain reliable information about the researched process.

In general, the equations of changes in technical and economic indicators of pelleting process depend on the operating parameters and objectively varying levels of uncontrolled factors. It can be represented as Taylor series taking into account squares and pairwise interactions (1):

$$Y_j = B_0 \cdot X_0 + B_1 \cdot X_1 + ... + B_n \cdot X_n + B_{11} \cdot X_1^2 + ... + B_{nn} \cdot X_n^2 + B_{F1} \cdot F_1 + ... + B_{Fk} \cdot F_k + \\ + B_{12} \cdot X_1 \cdot X_2 + ... + B_{n-1} \cdot X_{n-1} \cdot X_n \quad (1)$$

Getting the coefficients of the models of this form for each technical and economic indicator was carried out on the personal computer using standard application package «Statistica Advanced».

RESULTS AND DISCUSSION

As a result of mathematical modelling values of the coefficients were obtained. We based on varying intervals of operating parameters presented in Table 2. Also we took into account the corresponding levels of unregulated parameters, the average values of which were as follows for the series active industrial experiments: $F_{1\ average}$ = 2.2 °C, $F_{2\ average}$ = 46.5 %, $F_{3\ average}$ = 5.2 °C. Table 4 shows the numerical values of the coefficients for each technical and economic indicator or objective function, corresponding to each member of the equation.

The resulting mathematical relationships were checked for adequacy by actual measured performance value for each industrial experiment. Determination of discrepancies or errors between the measured and calculated values was carried out according to the formula (2):

$$\Delta_j = \frac{|Y_{j\ measured} - Y_{j\ calculated}|}{Y_{j\ measured}} \cdot 100\ \%, \quad (2)$$

where $Y_{j\ measured}$ – actually measured or found value of objective function in the pelleting process for each industrial experiment; $Y_{j\ calculated}$ – the calculated value of the objective function in pelleting process for each industrial experiment.

Tab. 4 Values of the coefficients B_n for the objective functions of the production process of wood pellets.

Coefficient B_n	Y_1	Y_2	Y_3	Y_4	Y_5
B_0	−70.0925774	−344.1328890	−7.1290416	−7928,2119964	7454.1920629
X_1	0.0074325	0.0497485	−0.0013159	1.8451961	−2.3808111
X_2	1.4916658	8.2091928	−3.1707886	170.5844975	−54.0823055
X_3	−8.3801523	−27.1626658	−5.0316028	−533.5922940	203.3446725
X_4	3.3380655	17.0866288	12.1956044	254.9274881	−195.6927147
X_5	−32.4996967	14.6402634	−24.1085645	362.3173559	−54.5765030
X_6	1.7985215	0.8188500	−0.5499287	16.4172631	−5.9227328
X_7	−0.6364041	2.0257555	−0.0995506	41.5817931	−14.7805745
X_8	0.1089659	−0.3415808	6.0184559	6.8498623	12.3761029
F_1	−0.1297856	0.0713992	0.0170708	0.2890974	−1.2680305
F_2	0.0005279	−0.0171915	0.0228438	−0.2253399	0.2037297
F_3	0.1053026	0.1738054	−0.1802996	1.9828621	−2.3702815
X_1^2	0.0000009	−0.0000037	0.0000034	−0.0000566	0.0004550
X_2^2	0.0096095	−0.3095215	0.0576227	−5.4187526	2.7887022
X_3^2	0.0958474	−0.3224439	−0.4319973	−5.7156032	2.8126433
X_4^2	−0.0183968	−0.3924855	−0.3606549	−5.9962878	4.3410542
X_5^2	5.8342318	−33.7395422	−10.0600811	−555.6890844	329.1258317
X_6^2	−0.0013182	−0.0018174	−0.0065734	−0.0385924	0.0126983
X_7^2	0.0026923	−0.0092797	0.0005709	−0.1784685	0.0758432
X_8^2	0.0006675	−0.0378743	−0.1049171	−0.7334893	0.2882757
$X_1 \cdot X_2$	−0.0017144	−0.0061646	−0.0028901	−0.1160874	0.0495906
$X_1 \cdot X_3$	0,0019683	0.0064785	0.0025616	0.1196010	−0.0539607
$X_1 \cdot X_4$	0.0000860	0.0001154	0.0002558	0.0079861	0.0029242
$X_1 \cdot X_5$	0.0002593	0.0025111	−0.0003099	−0.0020221	−0.0552223
$X_1 \cdot X_6$	−0.0000013	−0.0000157	−0.0000207	0.0000553	0.0003849
$X_1 \cdot X_7$	−0.0000011	0.0000038	0.0000463	−0.0006542	−0.0005369
$X_1 \cdot X_8$	−0.0000225	0.0000543	0.0000414	−0.0000709	−0.0011999
$X_2 \cdot X_3$	0.5095572	2.0830457	0.9242220	38.2216510	−17.5135296
$X_2 \cdot X_4$	0.0309819	0.0461034	0.0463587	0.1538286	−0.8891291
$X_2 \cdot X_5$	0.1368019	1.0208996	−0.5733358	7.9859763	−16.3982130
$X_2 \cdot X_6$	−0.0041891	−0.0031638	0.0051949	0.0046740	0.0734944
$X_2 \cdot X_7$	−0.0062866	−0.0027368	0.0159574	−0.0721710	0.0033042
$X_2 \cdot X_8$	−0.0080663	0.0202756	0.0132780	0.2609343	−0.2455868
$X_3 \cdot X_4$	−0.0294996	−0.0553992	−0.0898507	−0.1742798	1.0836624
$X_3 \cdot X_5$	0.2392138	−1.2167495	−0.0249135	−8.0620571	20.8123509
$X_3 \cdot X_6$	−0.0016721	0.0047136	0.0006253	0.0137747	−0.0980662
$X_3 \cdot X_7$	0.0015823	0.0008124	−0.0225490	0.0947699	0.0522918
$X_3 \cdot X_8$	0.0075455	−0.0281932	−0.0083587	−0.4010384	0.3224820
$X_4 \cdot X_5$	4.4535632	1.5262585	−5.4485157	24.9035393	−12.8571838
$X_4 \cdot X_6$	−0.0453515	−0.0156492	0.0628729	−0.2698601	0.1537334
$X_4 \cdot X_7$	−0.0057778	0.0210346	0.0040351	0.3753247	−0.1853703
$X_4 \cdot X_8$	0.0004335	0.0067089	−0.0048994	−0.1212947	−0.2186440
$X_5 \cdot X_6$	−0.7233615	−0.0530105	1.2515709	−1.7560590	−0.6982152
$X_5 \cdot X_7$	−0.0165786	−0.0599021	0.2050768	0.0295234	1.3307489
$X_5 \cdot X_8$	0.0229080	−0.5633664	0.0532519	−11.1854518	4.5350966
$X_6 \cdot X_7$	0.0009390	−0.0000560	−0.0013771	−0.0091470	−0.0060163
$X_6 \cdot X_8$	0.0004730	0.0057599	−0.0011764	0.1150174	−0.0459915
$X_7 \cdot X_8$	−0.0008141	0.0054915	−0.0189083	0.0699946	−0.0696439

Table 5 presents the average values for each objective function. These values are shown when checking derived mathematical equations for the adequacy to the actual process for the entire series of industrial experimental studies.

Tab. 5 Average values of differences between the actual and calculated data of the objective functions of the production process of wood pellets.

Output target function of pelleting process	Average value of the error $\Delta_{j\ average}$, %
Specific calorific efficiency Y_1	1.067
Mechanical strength Y_2	0.367
Matrix temperature Y_3	0.547
Productivity on clean granules considering fine fraction dropping out after pressing Y_4	0.533
Production costs Y_5	0.297
Average value of the error for all objective functions	0.562

The previous studies of different authors are more concerned either modeling of some indicators of pelletizing process or modeling of logistics, demand, supply, transportation of raw materials and pellets. In comparison with it, it can be said that the presented results are new. They open opportunities for their use in created systems of pellet press control. At the same time there are no results of earlier works with simultaneous modeling of the most important technological, economic, operational parameters of considered process taking into account the mode parameters and objective factors. So works (STELTE *et al.* 2011, HOLM *et al.* 2011) concern the evaluation study of the impact of pellet length. Also they concern die temperature, biomass moisture content and particle size on the pelletizing pressure during fuel pellet production from biomass. It has been shown that the pelletizing pressure increases exponentially with the pellet length. A mathematical model, predicting the increasing pelletizing pressure was in good accordance with experimental data. The pelletizing pressure was shown to be dependent on biomass species, temperature, moisture content and particle size. An increasing temperature of the die during pelletizing, decreasing pelletizing pressure, and infrared spectra of the pellet surface indicated hydrophobic extractives for pellets. We mean pellets produced at higher temperatures that might have acted as a lubricant reducing the friction between biomass and steel surface. The influence of the biomass moisture content was ambiguous and depending on the biomass type. For woody samples, the pelletizing pressure dropped with increasing moisture content while it increased for wheat straw. The effect of particle size on the pelletizing pressure was more defined, showing that the pelletizing pressure increases with a decreasing particle size. An increasing pelletizing pressure is resulting in an increasing pellet density. It was shown that pressures above 250 MPa are resulted only in minor increase in pellet density. At the same time the other parameters, namely: the performances of the pelletizer, mechanical and economic indicators, characterizing the efficiency of pelletizing, have not been considered.

As results of studies (KAWAKITA *et al.* 1971) mathematical relationships were derived including the pressure and volume factors (3):

$$\frac{P}{C} = \frac{1}{ab} + \frac{P}{a} \qquad (3)$$

where C = degree of volume reduction or engineering strain, a and b = Kawakita-Ludde model constants related to characteristics of the powder.

The linear relationship between $\frac{P}{C}$ and P allows the constants to be evaluated graphically. This compression equation holds true for soft and fluffy powders (DENNY 2002). Any discrepancies from this expression are sometimes due to fluctuations in the measured value of V_0.

Research (MANI *et al.* 2004) indicated that constant (a) is equal to the initial porosity of the sample, while constant $\frac{1}{b}$ is related to the failure stress in the case of piston compression. The paper (TUMULURU *et al.* 2010) refers to different models relating only pressure during pelletizing process. Developed mathematical models for countercurrent feed pellet cooler, moisture content for outlet pellets differs in the following results. Input - output model for the whole cooler can be used to calculate the temperature and moisture content of the outlet pellets, during steady state (ANDERSSON *et al.* 2008). This can be useful to indicate if something is wrong with the cooler. Other output indicators are not taken into account.

Group of authors published the results of modeling of pellets apparent density (ARZOLA *et al.* 2014). Derived model from experimental data is:

$$\rho_a = 2.077 - 0.0295\ SF + 0.00031\ SF^2 \qquad (4)$$

The expression of the empiric model for the behaviour of the pellets durability index DI in function of the experimental factors is

$$DI = 150.3 + 0.41BA^2 + 4.8W - 0.38W^2 \qquad (5)$$

where BA - binding agent content (%), W - moisture content (%).

The results obtained in this study allow the technical evaluation of the process scale-up at industrial production levels. However, they do not cover the entire list of parameters characterizing the pelletizing process.

There are scientific studies concerning only the economic component of the considered process (BRUGLIERI *et al.* 2008). In paper a linear programming model for running a biomass-based energy production process is described, with a real-world application. Model makes it possible to double the profit associated to traditional agricultural production. The financial benefit was so large that plant was able to self-finance the project without having to seek economic incentives.

The work of Iranian scientists examined the effects of moisture content, piston speed, die length, and particle size on the density of pellets only. In this research, artificial neural network was used for modeling the effect of independent variables on the density of the pellet. The results were compared with results of RSM method (ZAFARI *et al.* 2013). The results indicate that a properly trained neural network can be used to predict effect of input variable on pellet density. The ANN model was found to have higher predictive capability than the RSM model. Statistical analyses confirmed the following fact. The moisture content, speed of piston, and particle size significantly affected the pellet density while the influence of die length was negligible. The result of present research can be useful for designing and constructing a suitable pelleting machine for producing biomass pellets.

CONCLUSION

As a result of performed work the following results were obtained.

1. For the first time obtained equation of the objective functions changes of technical and economic indicators of the process of pellets production from wood waste were quite adequate to real conditions.
2. Error on series of active industrial experiments does not exceed the measurement error applied during the process of instrumentation and regulatory technical facilities of control system.
3. Obtained equations significantly describe the process of pelletizing. They can be effectively used in automatic control systems.
4. In the future, it is reasonable to define an additive utility useful function to be able to use in the production. This requires the use of methods of expertise and convolution of criteria, aimed at the simultaneous production of the extreme values of all technical and

economic indicators. This approach will enable to carry out single-criterion and multi-criteria optimization.

5. Analysis of the application of the obtained results in industrial conditions showed an increase in productivity of the equipment. Calorific efficiency of the products and mechanical strength of pallets increased. Temperature of the matrix decreased. Production costs reduced.

The developed methodology and the results are universal for all plants and applied equipment. But adjustments of coefficients, presented in Table 4, can be needed. All this can be used in conducting additional research taking into account specific features of industrial equipment. Also very important to consider the raw material properties, unregulated factors levels and other circumstances.

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