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Multifactor analysis of experiment parameters on the example of the biomass cutting process

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Abstract. The paper presents a multifaceted analysis of variance of the biomass cutting process parameters. First of all, the results of the cutting process were presented as the obtained output based on the change in parameters in the form of knife sharpening angle, knife rake angle and moisture content of cutter material. These parameters constituted input factors for the analysis of their impact on the output value in the form of cutting force and analysis of the impact of each of the factors (parameters) on the interaction between the other factors (parameters). For this purpose, the ANOVA multifactor analysis method implemented in the Design-Expert software was used. The analysis made is an example of showing the impact of particular parameters on the cutting force, but also proves the possibility of limiting the number of experiments, giving the possibility of forecasting (determining) the output for parameter values not taken into account in the experiment. This allows to establish and determine new answers without the need to perform new experiments, but also to plan new, better-oriented goals in the form of finding the right answer value, which would be the value of the cutting force in relation to the discussed experiment.

1. Introduction

In recent years, specialized software was developed to ease the burden of time consuming mathematical calculations on many researchers worldwide and allowing to implement the methodology referred to as „design of experiment”. A number of software was developed to assist researchers at the design stage of the experiment as well as analyzing its results. Such software includes, among others, Statistica, Minitab and Design Expert. However, users of the previously mentioned software are facing a serious decision to select the correct model for planning or optimizing the course of the experimental study or analyzing its results [1–3]. The Design-Expert software facilitates designing experiments. It allows to develop an evaluate the planned experiment as well as provides comprehensive analytic functionalities [1]. Among them is the multi-factor analysis of variance ANOVA [4, 5]. This paper presents an analysis of interactions between the variable parameters obtained in the course of experimental study of the cutting process of biomass in form of straw. Cutting biomass is an important stage in the process of briquetted biofuel manufacture from the standpoint of process energy consumption [6–10]. In the industry, cutting processes are employed for other, less conventional materials, which is discussed in other studies [11–13].

Due to a growing demand for bioenergy, there is an increased demand to manufacture biofuels [14–16]. Straw, among others, is one of the major sources of biofuel [17–19]. Through compaction, it is formed into briquette or pellet [20]. The piston-based agglomeration method is also employed with other materials, as presented in other papers [21–23]. The geometrical characteristics of machine components and assemblies have a material influence on their operation, this matter is discussed in papers [24–27].

2. Research

The research of the cutting process is carried out on a specialized station as provided in figure 1. It comprises two main assemblies (figure 1). The first one is an assembly of knives for cutting biomass material. The straw intended for cutting is transported to the cutting knife zone by the roller assembly 2, which draw the material in and press it (figure 2a). In the cutting zone, blades and counter blades cut the material. The cutting knife assembly 1 is driven by a three-phase electric motor 3 with P = 2.2 kW power output and maximum rotation speed n = 2850 rpm. Motor 3 control is achieved via inverter 9 type MX pro 4V2.2 by Schneider Electric [28].

Figure 1. Testing station for the examination of the straw biomass cutting process:
1 – cut biomass material, 2 – cutting assembly, 3 – electrical motor driving the cutting assembly in a rotating motion, 4 – roller assembly, 5 – reduction gearbox of the roller assembly, 6 – electrical motor driving the roller assembly, 7 – scale-dryer, 8 – electrical motor inverter for the roller assembly, 9 – electrical motor inverter for the cutter assembly, 10 – PC registering the working parameters of the cutter assembly electrical motor, 11 – PC registering the working parameters of the roller assembly electrical motor [28].

The roller assembly 2 drive system includes a three-phase electrical motor 6 with power P = 3 kW and maximum rotation speed n = 1430 rpm together with a reduction gearbox 5. Rotation speed control for motor 6 is achieved via inverter 8 type 4V4.0 by Schneider Electric. The registration of working parameters of motors 3 and 6 is achieved through dedicated software installed on PCs 10 and 11, with each PC communicating, respectively, with inverters 8 and 9. This enabled to register data including the change of torque value M (Nm) on the shafts of electrical motors 3 and 6, the change of current value I (A) and voltage U (V) of the respective motors. The cutting module 1 allows for the installation of blades with variable rake (application) angle of the cutting surface α (figure 2a) and blade angle β (figure 2b). The angle α and β values were: α = 5°, 15° and 30° and the angle β = 90°, 45° and 30° respectively [28].

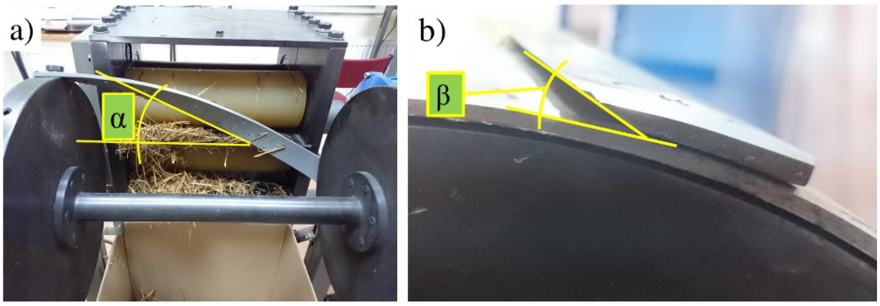

Figure 2. The testing station for the process of cutting of biomass material in form of straw: a) α – rake angle, b) β – blade angle [28].

The cut straw was characterized by two levels of moisture, respectively: 16.94 % and 28.75 %. The first value applied to straw transported directly from the field, the second value was achieved through conditioning. The moisture content value was established by using a scale-dryer. For every value of the angle α and β as well as each moisture level, twenty samples were cut, after prior weighing. Each sample weighed 36.5 g ± 1 g. It needs to be pointed out that conditioned samples were weighed before carrying out the process. Table 1 presents averaged results from all the tests as cutting force, determined from the measurement of torque on the shaft of the cutter assembly 1 (figures 1 and 2) [28].

Table 1. Variable parameter values together with the cutting force output expressed as an average value obtained from torque measurements.

Blade angle α (deg)	Rake angle β (deg)	Moisture (%)	Cutting force *P* (N)
30	15	16.94	407
45	30	28.75	458.4
45	5	28.75	453.5
45	30	16.94	346.8
90	30	16.94	353.1
90	15	28.75	360.6
30	5	16.94	387
45	15	16.94	277.5
90	15	16.94	457.7
30	30	28.75	425.9
45	5	16.94	347.1
90	5	16.94	324.6
30	15	28.75	456.7
30	30	16.94	334.7
90	30	28.75	457.8
30	5	28.75	414.5
90	5	28.75	457.8
45	15	28.75	340.3

3. Analysis of experiment parameters

The presented variable parameters and obtained output in form of the cutting force value were utilized in the experiment analysis in the context of searching for different shear force values for input parameters not assumed in the examination as variables (table 1). The below analysis is an example of utilizing the Design Expert software which enables various models to determine the output value of the system not obtained in the course of the experimentation due to equipment limitations or otherwise, which can be determined without expanding the scope of the experiment.

The Design Expert software was employed for designing the model of interactions between the coefficients presented in table 1, together with the output in form of the cutting force value. The software enables a selection of model to search specific parameter output values with possibly lowest error. After selecting a model, the software performs an evaluation. The results reflect the design possibilities in relation to a specific model. Hence, for the polynomial model expressed in equation (1), it is possible to calculate force value for other parameters not included in the experimental study:

$$\begin{aligned} \mathrm{P} = {} & 530.01 - 5.27 \cdot \mathrm{A} + 79.2 \cdot \mathrm{B} - 29.13 \cdot \mathrm{C} - 3.86 \cdot \mathrm{A} \cdot \mathrm{B} + 1.2 \cdot \mathrm{A} \cdot \mathrm{C} + 2.01 \cdot \mathrm{B} \cdot \mathrm{C} - 0.046 \cdot \mathrm{A}^2 - \\ & - 2.93 \cdot \mathrm{B}^2 - 0.057 \cdot \mathrm{A} \cdot \mathrm{B} \cdot \mathrm{C} + 0.046 \cdot \mathrm{A}^2 \cdot \mathrm{B} - 0.006 \cdot \mathrm{A}^2 \cdot \mathrm{C} + 0.131 \cdot \mathrm{A} \cdot \mathrm{B}^2 - 0.033 \cdot \mathrm{B}^2 \cdot \mathrm{C} - \\ & - 0.00145 \cdot \mathrm{A}^2 \cdot \mathrm{B}^2 - 0.000159 \cdot \mathrm{A}^2 \cdot \mathrm{B} \cdot \mathrm{C} + 0.00087 \cdot \mathrm{A} \cdot \mathrm{B}^2 \cdot \mathrm{C} + 0.0000096 \cdot \mathrm{A}^2 \cdot \mathrm{B}^2 \cdot \mathrm{C} \end{aligned} \quad (1)$$

where P – cutting force (N), A – blade angle (deg), B – rake angle (deg), C – moisture (%).

The above equation, with utilization of assumed and determined values of actual parameters not included in the examination, may be used to estimate the output in form of cutting force value. For this form of the equation, the values of each parameter are to be introduced with the correct unit for that parameter. At this point, we would like to remind that the experiment assumes the following parameter values (table 1) A = 30, 45, 90 (deg), B = 5, 15, 30 (deg), C = 16.94, 28.75 (%). Figure 3 presents the model graph (Eq. 1) in form of a three dimensional plane which demonstrates the interdependence between the variable parameters A and B for a constant moisture value C = 16.94 %, arrived upon in the course of experimental testing of the cutting process.

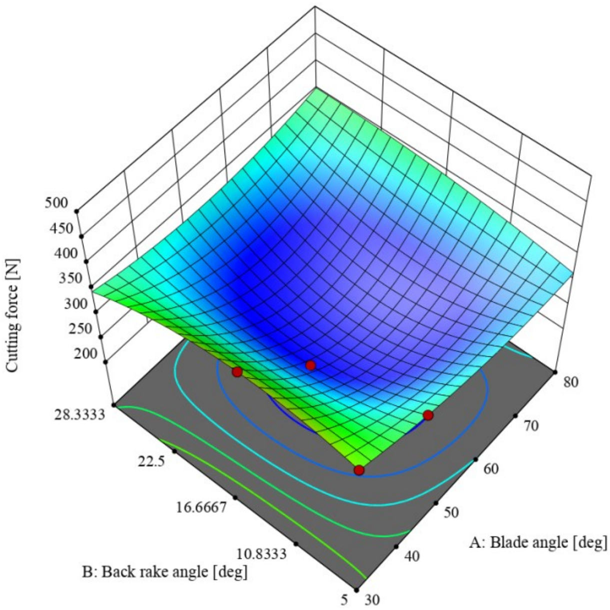

Figure 3. The cutting model graph obtained from results of experimental study presenting dependences between the values of blade angle A and rake angle B at moisture value C = 16.94 %.

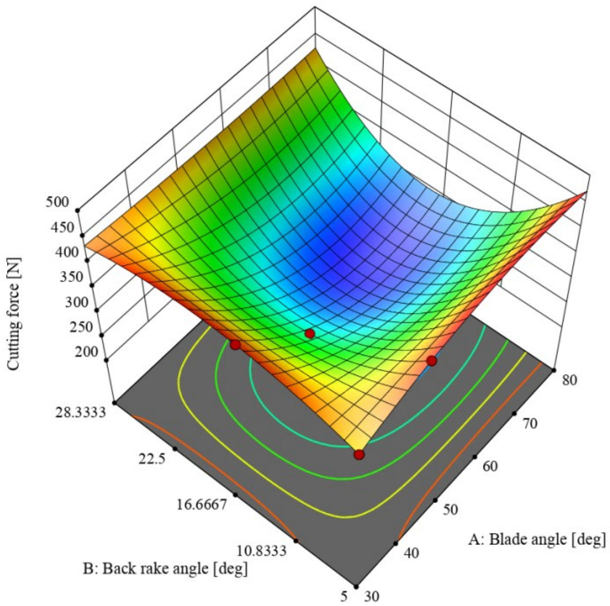

Figure 4. Cutting model graph obtained based on results of experimental study demonstrating the dependence between the values of blade angle A and rake angle B values for moisture C = 28.75 % with marked points denoting A and B parameter values examined in the experiment.

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Points on the graph above mark the examined parameters of the cutting process. These points limit the area on the graph surface. In order to estimate the output as cutting force for different values of parameters A and B, it is more reliable to rely on the area limited by these points. Analysis of graph points outside this area require experimental verification. This requirement can be referred to as experiment plannability using Design Expert software. The figure 4 presents a three dimensional graph plane demonstrating the interrelation between parameter values A and B and cutting force value at moisture 28.75 %, the influence thereof on the value of cutting force was determined in the course of the experiment.

Figure 5 presents example graphs showing estimated interrelation between parameter A and B values bearing on the cutting force value for intermediate values of moisture not included in the experiment. These values are, respectively, C = 20 % and C = 25 %. This distribution of graph points is beyond the area denoting values examined in the course of the experiment; therefore, it is suggested to utilize them as a basis for planning further experimentation focusing the study effort on obtaining a specific target function, which can be, for example, minimum cutting force value.

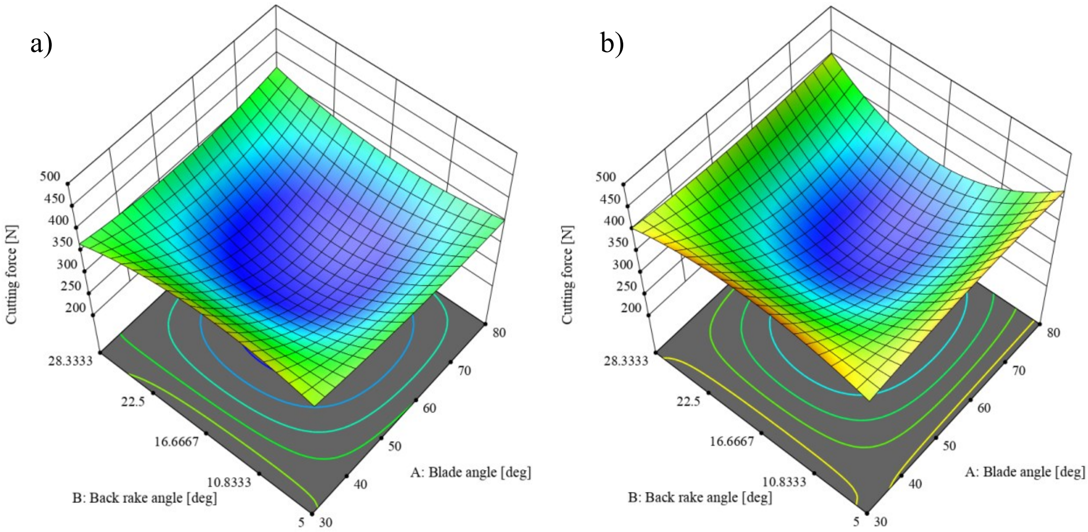

Figure 5. Cutting model graph obtained based on results of experimental study demonstrating the dependence between the values of blade angle A and rake angle B for moisture values: a) C = 20 %, b) C = 25 %, the influence of these values were not accounted for in experimental studies.

The points located outside the area denoted by points limiting the plane examined in the experiment stand for the inadequate model values; therefore, there is a high risk of error resulting from the determination of sought values based on the proposed model.

The analysis of the above model indicates that is of low significance, therefore it is called for to limit the number of expressions of the model. The Design Expert software can be used to reduce the model expression by defining the level of significance $\alpha = 0.05$ as a typical limit value recognized in many areas of study. As a result of this operation, the model shall be materially limited to the form of a linear model in which the sole variable is the moisture value C. ANOVA analysis indicates that this model is significant due to the statistics value $F = 8.12$ and test probability $p = 0.0116$. Therefore, there is a 1.16% risk that model output achieves an error value. The simplified model equation is as follows:

$$P = 265.47 + 5.55 \cdot C \tag{2}$$

where P – cutting force (N), C – moisture (%).

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Figure 6 shows a model graph (Eq. 2) expressed as a three dimensional plane presenting and interdependence of variable parameters A and B for the constant moisture values C = 16.94 % and 28.75 %, obtained on the basis of the cutting process experimental study.

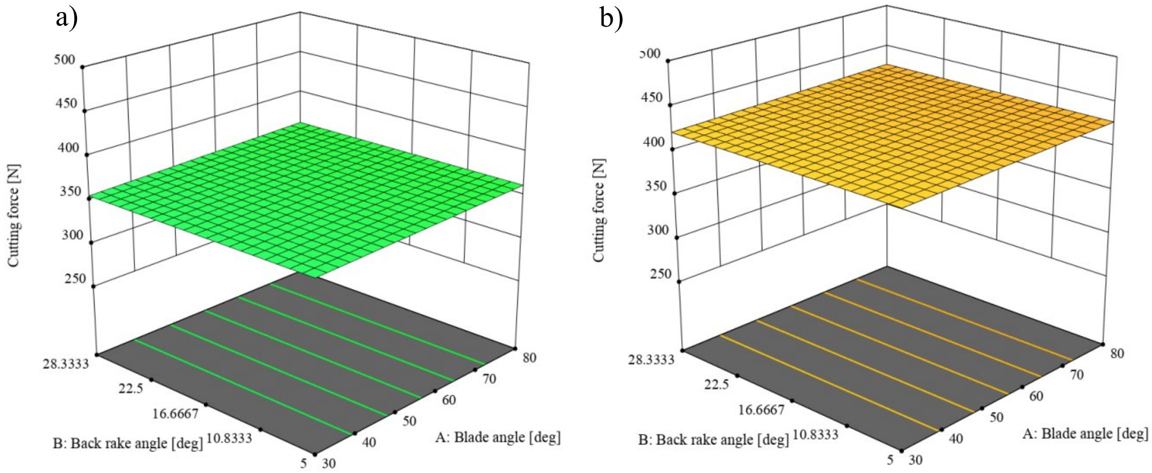

Figure 6. Cutting model graph (Eq. 2) obtained on the basis of experimental study results presenting a dependence between the values of blade angle A and rake angle B at moisture value: a) C = 16.94 %, b) C = 28.75 %.

It is possible to introduce a variable A (rake angle) to the above equation (2), the resulting model is expressed with the following equation:

$$P = 258.29 + 0.13 \cdot A + 5.55 \cdot C \tag{3}$$

where P – cutting force (N), A – blade angle (deg), C – moisture (%).

The above model is identified as significant due to the statistics value F = 3.87 and test probability p = 0.0442. This means that there is a 4.42 % risk that the model output achieves an error value. Figure 7 presents a model graph (dependency 3) in form of a three dimensional plane expressing the interrelation between the variable parameters A and B for constant moisture value C = 16.94 % and 28.75 %, obtained on the performed cutting process experiment.

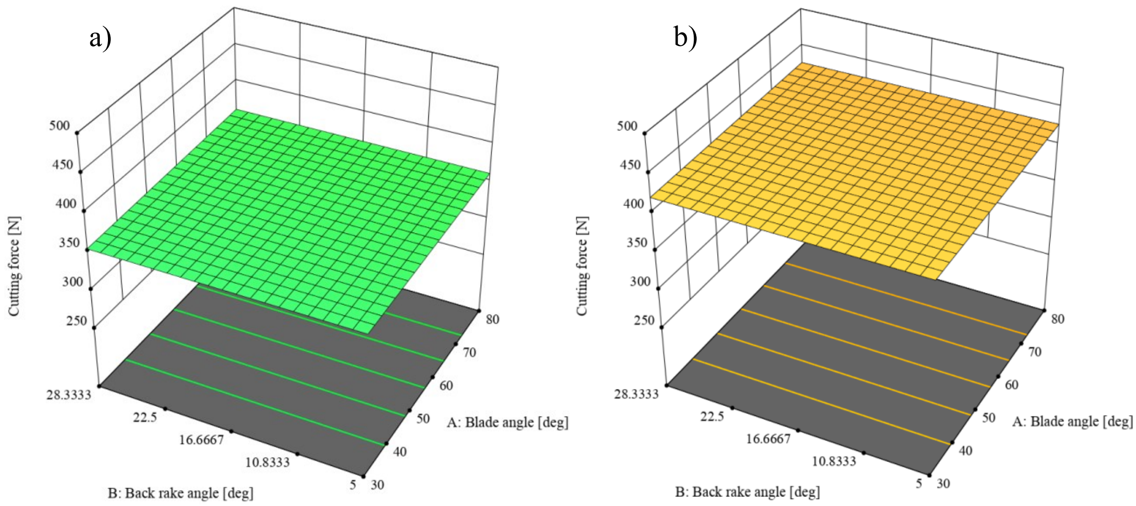

Figure 7. Cutting model graph (Eq. 3) obtained on the basis of experimental study results presenting a dependence between the values of blade angle A and rake angle B for moisture values: a) C = 16.94 %, b) C = 28.75 %.

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The model can interchangeably be expressed by the Eq. (2), and can be expanded by introducing a variable representing the rake angle value. This model is expressed with the equation:

$$P = 265.14 + 0.0196 \cdot B + 5.55 \cdot C \tag{4}$$

where P – cutting force (N), B – rake angle (deg), C – moisture (%).

In this case, the values F and p assume the values of F = 3.81 and p = 0.0460. This means that the risk of model output achieving an error value is 4.6 %.

Figure 8 presents the model graph (dependency 4) in form of a three dimensional plane expressing an interdependence of variable parameters A and B for a constant moisture value C = 16.94 % and 28.75 %, determined on the basis of the performed cutting process experiment.

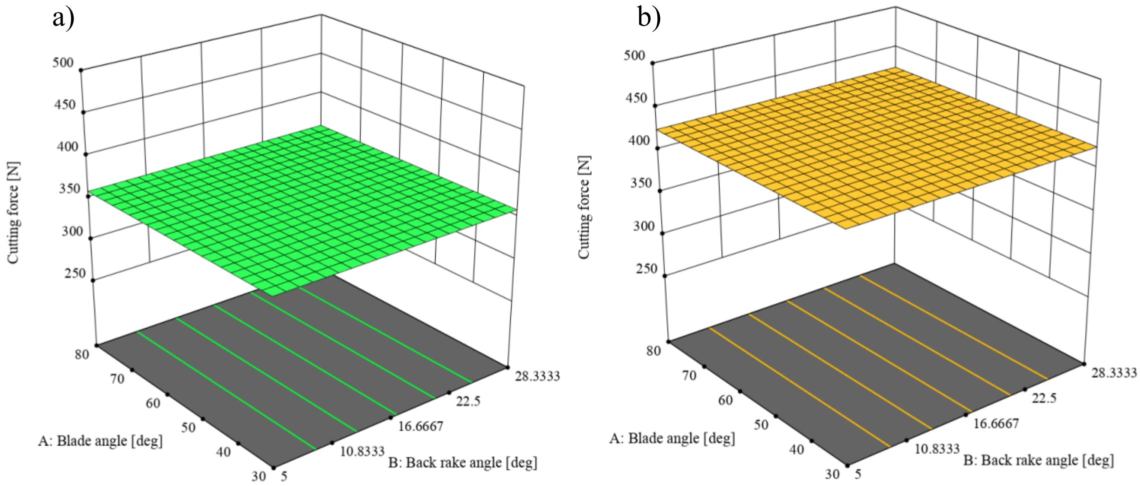

Figure 8. Cutting model graph (Eq. 4) obtained on the basis of experimental study results presenting a dependence between the values of blade angle A and rake angle B for moisture values: a) C = 16.94 %, b) C = 28.75 %.

In the case of both models expressed with equations (3) and (4), the software calculates the value of the Adequate Precision parameter which represents a signal to noise quotient. It compares the range of predicted values at points of calculation with an average prediction error. If its value is lower than 4, it means that the model is inadequate and should not be used to estimate the sought values (values not determined in the course of experimentation) from the area of points determinably by the model.

In case of the model expressed with the equation (2), the Adequate Precision value is 4.031, which means the model is usable in design space. Conversely, it is not possible for models expressed with equations (3) and (4), where the value is lower than 4.

4. Conclusions

The model expressed with the equation (2) meets the criteria specified above, allowing it to be used for predicting the value of the cutting force with assumed values of variables A, B and C which were not included in the experiment. The model may be considered as simplified as a result of transformation based on the Design Expert software outputs. In order to utilize the remaining models expressed by equations (1), (3) and (4), it is necessary to carry out verification which at the same allows to increase the area of surface limited by points of values from the experimental study (for the model expressed with the equation (1), figures 3 and 4) which may contribute to expanding the design area and therefore the model may become more adequate and usable in relation to the model expressed with the equation (2).

The utilization of software tools, i.e. Design Expert enables to evaluate an experiment on the grounds of correct direction of selected variables assumed in the experimentation. Variance analysis will allow to answer the question whether an experiment carried out has a sufficiently wide scope to allow to predict other vales based on the model obtained from the experiment, or is it necessary to broaden the range of the experimental study, directing the researcher to search for output values from the experiment in a correct area of variable parameters which affect it directly.

5. References

[1] Montgomery D C 2013 *Design and Analysis of Experiments* (Hoboken: Wiley)
[2] Wałęsa K, Malujda I and Talaśka K 2018 Butt welding of round drive belts *Acta Mech. et Auto.* **12** 115–126
[3] Wałęsa K, Malujda I, Górecki J and Wilczyński D 2019 The temperature distribution during heating in hot plate welding process *MATEC Web of Conf.* **254** 02033
[4] Chinyere Anyanwu R, Rodriguez C, Durrant A and Ghani Olabi A 2018 Optimisation of tray drier microalgae dewatering techniques using response surface methodology *Energies* **11** 2327
[5] Agresti A 2002 *An Introduction to Categorical Data Analysis* (Hoboken: Wiley)
[6] Xavier C A N, Moset V, Wahid R and Moeller H B 2015 The efficiency of shredded and briquetted wheat straw in anaerobic co-digestion with dairy cattle manure *Biosystems Engineering* **139** 16–24
[7] Bitra V S P, Womac A R, Chevanan N, Miu P I, Igathinathane C, Sokhansanj S and Smith D R 2009 Direct mechanical energy measures of hammer mill comminution of switchgrass, wheat straw, and corn stover and analysis of their particle size distributions *Powder Technology* **193** 32–45
[8] Warguła Ł, Adamiec J M, Waluś K J and Krawiec P 2018 The characteristics analysis of torque and rotation speed of working unit of branch grinder-introductory research *MATEC Web of Conferences* **157** 01021
[9] Wargula Ł, Krawiec P and Waluś K J 2019 Innovative research method of the fuel injector that allows to evaluate the efficiency of wood chip drive control systems *MATEC Web of Conferences* **254** 01010
[10] Talaśka K 2017 Analysis of the energy efficiency of the shredded wood material densification process *Procedia Engineering* **177** 352–357
[11] Wojtkowiak D and Talaśka K 2019 Determination of the effective geometrical features of the piercing punch for polymer composite belts *The International Journal of Advanced Manufacturing Technology* https://doi.org/10.1007/s00170-019-03746-7
[12] Wojtkowiak D, Talaśka K, Malujda I and Domek G 2018 Estimation of the perforation force for polymer composite conveyor belts taking into consideration the shape of the piercing punch *The International Journal of Advanced Manufacturing Technology* **98** 2539–2561
[13] Wojtkowiak D and Talaśka K 2019 The influence of the piercing punch profile on the stress distribution on its cutting edge *MATEC Web of Conferences* **254** 02001
[14] Tanger P, Field J L, Jahn C E, DeFoort M W and Leach J E 2013 Biomass for thermochemical conversion: Targets and challenges *Front. Plant Sci.* **4** 218
[15] Ben-Iwo J, Manovic V and Longhurst P 2016 Biomass resources and biofuels potential for the production of transportation fuels in Nigeria *Renew. Sustain. Energy Rev.* **63** 172–192
[16] Huang M, Chang C, Yuan M, Chang C, Wu C, Shie J, Chen Y, Chen Y, Ho C, Chang W et al. 2017 Production of torrefied solid bio-fuel from pulp industry waste *Energies* **10** 910
[17] Demirbas M F, Balat M and Balat H 2009 Potential contribution of biomass to the sustainable energy development *Energy Convers. Manag.* **50** 1746–1770
[18] Garrido M A, Conesa J A and Garcia M D 2017 Characterization and production of fuel briquettes made from biomass and plastic wastes *Energies* **10** 850
[19] Wilczyński D, Malujda I, Talaśka K and Długi R 2017 The study of mechanical properties of natural polymers in the compacting process *Procedia Engineering* **177** 411–418

[20] Berdychowski M, Talaśka K and Wilczyński D 2019 Evaluation of the possibility of using the Drucker-Prager-Cap model in simulations of the densification process of shredded natural materials *MATEC Web of Conferences* **254** 02018
[21] Górecki J, Malujda I and Wilczyński D 2019 The influence of geometrical parameters of the forming channel on the boundary value of the axial force in the agglomeration process of dry ice *MATEC Web of Conferences* **254** 05001
[22] Górecki J, Malujda I, Wilczyński D and Wojtkowiak D 2019 Influence of the face surface shape of the piston on the limit value of compaction stress in the process of dry ice agglomeration *MATEC Web of Conferences* **254** 06001
[23] Górecki J, Malujda I, Talaśka K, Wilczyński D and Wojtkowiak D 2018 Influence of geometrical parameters of convergent sleeve on the value of limit stress *MATEC Web of Conferences* **157** 05006
[24] Dudziak M, Kołodziej A, Domek G and Talaśka K 2017 Multi-angularity – identification of parameters and compatibility conditions of the axisymmetric connection with form deviations *Procedia Engineering* **177** 431–438
[25] Wałęsa K, Malujda I and Talaśka K 2018 Butt welding of round drive belts *Acta Mechanica et Automatica* **12** no. **2** 115–126
[26] Gawronska E 2019 A sequential approach to numerical simulations of solidification with domain and time decomposition *Applied Sciences* **9** 1972
[27] Sapietova A, Novak P, Saga M, Sulka P and Sapieta M 2019 Dynamic and stress analysis of a locking mechanism in the Ansys Workbench software environment *Advances in Science and Technology – Research Journal* **13** 23–28
[28] Wilczyński D, Talaśka K, Malujda I and Jankowiak P 2018 Experimental research on biomass cutting process *MATEC Web of Conferences* **157** 07016