Development of models for forecasting and classification of a printing quality of a low cost 3D printer

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Abstract. At the present, the actual task is using 3D printers for the manufacture of certain objects with a given level of price / quality ratio. In many cases, it is economically feasible to use a low cost 3D printer. Therefore, it is necessary to have models that predict and classify the printing quality of such printers. The work has involved the development and assembly of a low cost 3D printer. For this purpose, the creation of geometric models of the component parts and the printer itself was carried out, and engineering calculations and optimization of the received designs were performed. It has been developed a printer control system. An experiment was conducted to produce cubes with different printing parameters on such printer. Based on regression analysis, linear and logistic regressions were constructed. Linear regression will allow to assess the quality level of the result depending on the printing parameters, and the logistic regression will allow to classify and predict the probability of manufacturing objects with a given quality level. The influence of each of the print parameters on the quality and result of the classification was analyzed.

1. Introduction
Today additive technologies are becoming increasingly importance in various sectors of the national economy. There is a large number of applications of these technologies in medicine (for example, [1, 2]), automotive industry and aircraft building (for example, [3, 4]), construction (for example, [5, 6]), food industry (for example, [7, 8]), materials science (for example, [9, 10]). These technologies appeared on the market relatively recently, but in the dynamics of development, they outstrip the rest of the production branches. Thus, their average annual growth is estimated at 27% and is projected to reach 26.7 billion US dollars by 2019, compared with 11 billion in 2015.

One of the directions of using additive technologies is the creation of models and prototypes of various objects and products. In particular, production companies spend up to 10% of the profit on prototyping the goods. For the prototyping, 3D printers are used.

In the industry, 3D printing can be used to manufacture molds for castings. In [11], Kafara M. et al. present results of research on the evaluation the influence of the binder quantity used in 3D-printing on dimensional accuracy and resilience of manufactured test specimen. The optimum operating point as compromise between accuracy and resilience was determined [11].
Results of research [12] are intended for the food industry in the manufacture of food products of complex shape by means of 3D printing. This work explores questions of optimization of chocolate 3D printing by correlating thermal and flow properties with 3D structure modeling [12].

In [13], Yang F. et al. developed a new 3D printing food constructs based on lemon juice gel system and studied the effect of potato starch on the rheological properties and mechanical properties of lemon juice gels. In addition, it has been investigated the influence of printing parameters (nozzle height, nozzle diameter, extrusion rate and nozzle movement speed) on the quality of printed products [13].

The development of a new 3D printing food constructs based on fish surimi gel system and study of the influence of NaCl addition on rheological property, gel strength, water holding capacity, water distribution and microstructure of surimi gel to be used as a material for 3D printing which were conducted in [14]. Also in this work, authors investigated the effects of the printing parameters on the geometrical accuracy and dimension of the printed surimi gel [14].

Using 3D printing to fabricate small model geogrids for geotechnical experiments, with the aim of scaling their geometry and tensile behavior under operational conditions was given in [15].

A number of studies are devoted to optimizing the parameters of 3D printing of biological materials. For example, in [16], Webb B. et al. developed a simple method of assessing the bioprint results from a range of printing parameters in a standardized manner applicable to extrusion-based bioinks. The method has been used the parameter optimization index, which could be a useful method across a wide range of 3D bioprinting research and development applications [16].

There are studies aimed at improving the quality of 3D printing and optimizing this process. In [17], Ware H. O. T. et al. describes using of the developed technology Continuous Liquid Interface Production, which has alleviated the main obstacles surrounding 3D printing technologies: production speed and part quality. Based on the technology it has been developed the μCLIP process to allow for 3D printing of biomedical devices with high precision [17].

Different approaches to optimization concept are identified in [18]. Main aspects for topological optimization are exposed and then analyzed on different software [18].

In [19], questions are investigated related to optimal methods of tuning and parametric calibration of inexpensive 3D printers. In this work, autors obtained that the infill density and the extrusion multiplier mostly affected the dimensional accuracy of the components. Both parameters highlight the influence of the slicing software on the planning and quality of the models [19].

At the same time, a number of issues related to 3D printing remain open.

In general, it can be noted that the actual task is to research the life cycle processes of low cost 3D printers and get a model for assessing the print result quality. In particular, such studies will allow creating equipment that will measure up the requirement of the criterion of maximum price / quality ratio.

The aim of the work is the development of a low cost 3D printer and the creation of models for forecasting and classification of the quality of the result of manufacturing products on it. To achieve this goal, the following tasks were solved in the work.

1. Development of design and model of 3D printer.
2. Creating a 3D printer and his control unit.
3. Conducting a series of experiments to assess the quality of 3D printing. Collecting of data on the results of experiments.
4. Regression analysis of the obtained data. The development of a model for determining the optimal 3D print parameters by the criterion of maximizing quality.

2. Development of design and model of 3D printer

Before creating a 3D printer, you need to develop 3D models of the printer and its components, as well as carry out an engineering analysis of the design of the printer. For this, we use CAD and CAE systems of COMPASS-3D.

The main components of the developed 3D printer are a frame, a heated table, a power supply unit, a control unit, four stepper motors, an extruder (see figure 1).

In the CAE system, using the APM FEM library, we perform strength analysis of construction components of the printer, which allows us to evaluate both the correctness of the geometric model of the printer and its durability during operation. To do this, we need to specify bindings for the object under study, the applied loads and the finite element grid.

Let us show the result of the strength analysis of the "Guide" detail. We shall fix the bindings from the ends of the part and apply a linear load $F_l = 9.8 \text{ H}$. The value of this load is set based on the fact that the printer table weighs $m = 2 \text{ kg}$ moves along two guides, and, taking into account the uniformity of load distribution, in accordance with Newton's second law:

$$F_l = mg/2 = 9.8 \text{ H}.$$ 

We choose the material for the production of guides – aluminum. We can distinguish the following properties, which affect the strength of the structure and the distribution of loads: yield stress – 195 MPa; density – 2712 kg/m3; thermal conductivity – 202 W / (m·C); yield stress – 110 MPa; relative extension – 12 %.
The results of the analysis showed that the equivalent Mises stress is equal to 4.3 MPa, the minimum yield point is greater than the value at which the deformation would continue to grow without increasing the voltage by 54.5 times; the minimum safety factor for strength is higher by 95.2 times. According to these data, we conclude that in the design of a 3D printer we can use guides with smaller diameters or smaller wall thickness. By calculating the total linear displacement, the maximum value of which is 0.03 mm, it can be concluded that it is possible to use a more flowable metal. In figure 2 as an example, the safety factor for strength diagram.

3. Creating the 3D printer and his control unit

Taking into account the results of modeling and engineering analysis of the structure, we will make the components of the 3D printer. The frame is made of plywood with a thickness of 10 mm, the guides are made of aluminum, fixing angles are made of 2 mm steel. We use threaded studs with metric thread M10 and linear bearings with a diameter of 10 mm under the aluminum guides. The transformation of the rotational motion of the motor into the translational motion is carried out by a belt drive using a belt GT2 with a width of 6 mm.

The printer control unit is implemented based on the Arduino Mega 2560 controller and the Ramps 1.4 expansion card. Arduino Mega 2560 manages the work of a 3D printer through commands in G-code. On Ramps 1.4 we install the drivers of stepper motors A4988 with permissible current up to 2 A and connect stepper motors Nema17, heating table, extruder, thermistors and limit switches. We use a power supply unit with a voltage of 12 V and a power of 240 W. The 3D printer assembled from the manufactured components is shown in figure 3.

![Figure 2. Manufactured 3D printer.](image)

Work with the manufactured printer is carried out through the program Repetier-Host. After loading in the Repetier-Host 3D model of the product for manufacturing in the Slic3r slicer, this model is cut into layers and a control program is created in the G-codes, which is sent to the Arduino Mega 2560.

4. Experiments to evaluate the quality of 3D printing

In order to build an analytical model of the dependence of the evaluation of the quality level on the printing parameters, it is necessary to identify the factors (predictors) and the dependent variable
We set the following factors: the height of the print layer \( h \), the temperature of the extruder \( T \), the filament feeding speed (plastic thread) \( U \) and the response make the number of defective layers \( w \) and the percentage of defective layers \( y \) of the total number of layers of the manufactured product. The dependent variable is also the printing time \( t \).

As a manufactured product in this experiment, we shall use a cube in the size of 20x20x20 mm\(^3\).

The essence of the experiment is the production of cubes for different values \( h \), \( T \), \( U \): \( h = \{0.1; 0.25\} \), \( T = \{210; 215; 220; 225; 230; 235; 240; 245; 250\} \), \( U = \{30; 40; 60\} \). Experiments will be conducted at a room temperature 22 °C. The temperature of the heating table in all experiments is 105 °C. A total of 32 cubes were produced. Each cube counted the number of defective layers and determined the percentage of defective layers.

The analysis of the data obtained as a result of the experiment can be performed in the package R. We estimated the correlation coefficients between the selected variable \( h \), \( T \), \( U \), \( t \), \( w \), \( y \) (see table 1). We see that all the selected variable affect the percentage of defective layers. Levels of relations between respectively the height of the print layer, the filament feeding speed and the percentage of defective layers are positive. Levels of relations between respectively the temperature of the extruder, the time of printing and the percentage of defective layers are negative. It can be noted that the level of relations between the respectively the height of the print layer, the time of printing and the number of defective layers are low.

**Table 1.** The correlation coefficients between the variable \( h \), \( T \), \( U \), \( t \), \( w \), \( y \).

|   | \( h \) | \( T \) | \( U \) | \( t \) | \( w \) | \( y \) |
|---|---|---|---|---|---|---|
| \( h \) | 1.00 | 0.00 | 0.00 | -0.93 | -0.19 | 0.49 |
| \( T \) | 0.00 | 1.00 | -0.48 | 0.16 | -0.39 | -0.34 |
| \( U \) | 0.00 | -0.48 | 1.00 | -0.36 | 0.82 | 0.66 |
| \( t \) | -0.93 | 0.16 | -0.36 | 1.00 | -0.12 | -0.72 |
| \( w \) | -0.19 | -0.39 | 0.82 | -0.12 | 1.00 | 0.68 |
| \( y \) | 0.49 | -0.34 | 0.66 | -0.72 | 0.68 | 1.00 |

We shall construct regression models that describe the effect of the selected indicators on the number of defective layers in the cube and the percentage of their total number. In doing so, we shall perform a multicollinearity check and other prerequisites for the linear model.

Since the task is to build models for evaluating the print quality, it shall be expedient to convert the dependent variable \( y \), in particular, the extraction of the square root. Such a transformation is dictated by the fact that the value of the variable \( y \) is less than 0.25 and extracting the square root, we increase these values, approximating to 1, and the smaller the value, the more it is strengthened. Thus, when constructing the regression model, we will use \( y^2 = y^{0.5} \) instead of \( y \).

We created the following models:

\[
w(h, U) = a_0 + a_1 \cdot h + a_2 \cdot U, a_1 < 0, a_2 > 0, a_0 < 0, p(a_1) < 0.1, p(a_2) < 0.001
\]
has a $R^2 = 0.7133 \ (F(2, 29) = 36.07, \ p < 0.001)$.

$$y_2(h, U) = b_0 + b_1 \cdot h + b_2 \cdot U, \ b_1 > 0, \ b_2 > 0, \ b_0 < 0, \ p(b_1) < 0.001, \ p(b_2) < 0.001, \ p(b_0) < 0.1$$

has a $R^2 = 0.7326 \ (F(2, 29) = 39.72, \ p < 0.001)$.

We shall estimate the importance of independent variables in models. To do this, before constructing the regression model, we perform transformations of all variables so that their average values are 0, and the standard deviation is 1. In this case, the coefficients obtained as a result of the regression analysis are standardized. Because of such transformations, we have obtained that in the model $w(h, U)$ the importance of the variable $U$ practically in 4 exceeds the importance of the variable $h$. In the model $y_2(h, U)$ the importance of the variable $U$ in 1.4 exceeds the importance of the variable $h$.

Using these models, we can evaluate the contribution of each variable to print quality and the presence of defects.

We shall implement the construction of a logistic regression, which will allow forecasting and classifying the quality level of the manufacturing result. To do this, we introduce a quality level for the percentage of defective layers. If the percentage of defective layers exceeds this value, the product will be deemed to be of low quality, otherwise it will be qualitative. Accordingly, the variable $y_k$ describing the quality level will have 2 levels: 0 – if the product is of low quality and 1 – if the product is of high quality.

We created the following model:

$$y_k(h, U) = 1/(1+e^{-[c_0 + c_1 \cdot h + c_2 \cdot U]}), \ c_1 < 0, \ c_2 > 0, \ c_0 < 0, \ p(c_1) < 0.01, \ p(c_0) < 0.1$$

has a AIC = 32.436.

This model allows to correctly classify the quality of the printed cubes depending on the parameters of their printing in 81% of cases when using the threshold level of 0.52.

Using these models, we can proceed to the price / quality ratio. The costs will be determined not only by the consumption of the material, but also by machine time. The last parameter will be determined by the printing time.

5. Conclusion

Considering the actuality of the task of using 3D printers for the manufacture of certain objects with a given level of price / quality ratio, the work has involved the development and assembly of an low cost 3D printer. For this purpose, the creation of geometric models of the component parts and the printer itself was carried out, and engineering calculations and optimization of the received designs were performed. It has been developed a printer control system.

An experiment was conducted to produce cubes with different printing parameters on such printer. By counting the normal and defective layers, a conclusion was made about the quality of each cube when it is printed with one or the other parameters.

Based on regression analysis, linear and logistic regressions were constructed. Linear regression will allow to assess the quality level of the result depending on the printing parameters, and the logistic regression will allow to classify and predict the probability of manufacturing objects with a given
quality level. The influence of each of the print parameters on the quality and result of the classification was analyzed.

Further work in this direction implies the inclusion of more factors in the model, as well as the use of machine learning methods to improve the accuracy of predicting the result of 3D printing, depending on the printing parameters.

6. References

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