Quality Function Deployment and Design Risk Analysis for the Selection and Improvement of FDM 3D Printer

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Abstract. Currently, the use of additive technologies is becoming relevant instead of traditional production technologies. The market offers a fairly large selection of 3D printers with different designs and kinematics. Each design and kinematics has its own disadvantages and advantages. The article demonstrates various versions of the kinematics of FDM 3D printers, the main units and parts, as well as their impact on the quality of 3D printing of parts. The results of structuring the quality function (QFD) and analysis of the types and consequences of potential inconsistencies (FMEA) of an FDM 3D printer for prototyping and manufacturing parts and assemblies for unmanned aerial vehicles are presented. A qualimetric assessment of the quality of FDM 3D printers with various kinematics design based on the QFD interconnection matrix was carried out. The aim of the study is to analyze the design and kinematics of FDM 3D printers for the manufacture of high-quality parts and assemblies for unmanned aerial vehicles without further post-processing based on the application of the QFD methodology. Based on the results of the study, recommendations and proposals for improving the design of FDM 3D printers were developed.

1. Introduction

Today, additive manufacturing is one of the most promising and relevant technologies [1]. The creation of objects using 3D printers allows to reduce various influences at the stages of technological process development, production preparation and production, including the influence of the human factor. Additive technologies are increasingly used in the aerospace industry and require constant improvement.

The use of modern and proven robust approaches to quality management allows you to improve product quality and reduce the time and cost of preparation for production, including with the use of additive technologies.

2. Quality function deployment methodology and risk analysis

2.1. Quality function deployment QFD

The quality function deployment (QFD) methodology, developed in Japan by engineer Yohji Akao, has long been successfully used all over the world and is one of the most effective modern approaches of robust design and quality management [2, 3, 4].

The goal of QFD is to determine the direction for improving products and processes at each stage of the product life cycle and, ultimately, obtaining a result that meets the requirements and expecta-
tions of the consumer. The main tool of the methodology is the matrix, which, in accordance with the form, is called the HoQ quality house (fig. 1).

![Figure 1. S HoQ QFD schematic.](image)

The importance of improving the component / characteristics / process \( Q_j \) is calculated by the formula (1) [2]:

\[
Q_j = \sum (p_i \times h_{ij}),
\]

where \( p_i \) – is the significance of the consumer's requirement, \( h_{ij} \) – is the degree of influence of the component / characteristics / process on the fulfillment of the consumer's requirement (fig. 1).

The significance of the consumer's requirement \( p_i \) is usually established by the questionnaire method on a 10-point scale with reduction to a relative value. The degree of influence \( h_{ij} \) is determined expertly using a scale: 1 - weak, 3 - medium, 9 - strong influence.

Application of the methodology in the design of products and preparation of production allows to reduce the time and costs for preparation of production up to 30-50% [2].

3. Failure mode and effects analysis FMEA

The method for failure mode and effects analysis FMEA inconsistencies, developed in the United States initially for the aerospace and defense industries, is an effective tool for improving the quality of developed technical objects [5, 6].

The method is aimed at assessing and preventing nonconformities and / or reducing their negative consequences at the early stages of design. The method is used to analyze the modifications and improvement of structures and processes, allows you to analyze potential defects, their causes and consequences, assess risks and take measures to eliminate or reduce the likelihood and damage from their occurrence.

The risk assessment is the value of the priority risk number (RPN), obtained by the formula (2):

\[
RPN = S \times O \times D,
\]

where \( S, O, D \) - respectively, the scores of significance, occurrence, detection, established by experts on a 10-point scale.

A schematic application of the FMEA method is shown in fig 2.
At the stage of the initial design of a complex technical product, it is possible to envisage the most modern solutions at the achieved technical level and prevent further modifications. This ensures the reduction of potential losses associated with failures in operation, control in production and re-equipment of production. At the same time FMEA is a method of continuous improvement (fig. 1) and is applied on a regular basis.

4. Analysis and improvement of the design of an FDM 3D printer

4.1. Study of FDM 3D Printer Design

To conduct a QFD study of the FDM (Fused Deposition Modeling) 3D printer design, the design and types of kinematics of 3D printers are considered. Currently, there is a fairly large selection of 3D printers on the commercial market with different designs and kinematics. Each design and type of kinematics has its own disadvantages and advantages. Below are the main units and parts of FDM 3D printers, types of kinematics, as well as their advantages and disadvantages.

**FDM 3D-printer design.** Despite the different design of FDM 3D printers on the additive equipment market, the following main components and parts can be distinguished:

a) extruder;
b) a desktop, or platform for 3D building;
c) movement mechanisms and guides;
d) control system;
e) power supply;
f) frame.

**Extruder.** The main component of any 3D printer is an extruder. (see Fig. 3). An extruder is an electromechanical component designed to melt and extrude material to build a 3D model on the desktop of a 3D printer.
Figure 3. Dual extruder FDM 3D printer.

The extruder consists of two parts:
1) cold end - a mechanism for feeding material for 3D printing;
2) hot end - a mechanism for melting the material for 3D printing.

There are currently two kinds of extruder design: bowden extruder and direct extruder. The difference between the two types of extruder design is as follows: in the bowden extruder, the material feeding mechanism is related to the material melting mechanism and is located on the frame of the 3D printer.

Each design has its own advantages and disadvantages. But the main advantage of the bowden extruder is the lower inertia and vibration in 3D printing due to the correlated cold end, which undoubtedly improves the quality of the printed parts.

Desktop, or platform for 3D building. The desktop, or platform for 3D building, is an integral part of the 3D printer, on which the part is formed, that is, the part is 3D printed (see Fig. 4). The desktop consists of an upper and a lower part. A part is formed on the upper part, and on the lower part it is intended for heating and fixing the desktop.

Figure 4. Desktop of FDM 3D printer.

Moving mechanisms and guides. To ensure the movement of the extruder and the working table, movement mechanisms and guides are used, which include stepper motors and rails (see Fig. 5). A system of pulleys, gears, belts and shafts is used to convert the rotation of the stepper motor shaft into the translational motion of an extruder or desktop.
Control system. The operation of all components of the 3D printer is controlled by a control system, which includes a control module, software (for example, Marlin software), a motherboard, intermediate boards and limit switches. Figure 6 shows the 3D printer control module and the limit switch.

Power Supply. The power supply converts the high voltage of the external network into low voltage for stable operation of the 3D printer.

Frame. All of the above components and mechanisms are placed in the frame of the 3D printer. The frame is made of aluminum profiles and sheets of ABS or organic glass.

Variants of FDM 3D-printer kinematics. The kinematics of a 3D printer is the pathway through which the extruder and the desktop of a 3D printer move. Currently, two types of kinematics are most widely used: Cartesian 3D printers and delta 3D printers. There are other types of kinematics of 3D printers, but due to their small distribution, they will not be considered in this article. Each type of kinematics has its own advantages and disadvantages.

Cartesian 3D printers. Cartesian 3D printers work based on a Cartesian coordinate system. The movement of the extruder relative to the desktop is set along three axes: X, Y and Z. Figure 7 shows the Flyingbear Tornado 2 PRO 3D printer.
The most common Cartesian 3D printers are the following two types:
1. The extruder moves along the X and Y axes, while the worktable moves along the Z axis;
2. The extruder moves along the Z axis, and the worktable along the X and Y axes.

The main advantages of Cartesian 3D printers are:
a) simplicity of design;
b) ease of calibration;
c) great possibilities for modernization of the structure;
d) manufacturing and assembly of 3D printers of any size and size;
e) Cartesian 3D printers are suitable for mass production of parts and assemblies.

The main disadvantages of Cartesian 3D printers are their slow printing speed and large dimensions compared to 3D printers with different kinematics.

*Delta 3D printers.* The extruder of delta 3D printers moves simultaneously along three axes along a complex trajectory according to the trigonometric function, the desktop remains stationary. The movement of the extruder is provided by the movement of the rods fixed on the three axes of the 3D printer.

The main advantages of delta 3D printers are high printing speed and small size.

The main disadvantages of delta 3D printers are:
a) high requirements for the precision of manufacturing and assembly of the structure;
b) the complexity of the calibration;
c) low possibilities for modernization of the structure;
d) the need to use motherboards with high computing power.

### 4.2. FDM 3D printer Quality and risks of the design analysis based on the QFD and FMEA methods

**Assessment of the quality of the kinematics of an FDM 3D printer.** Generalized requirements for a 3D printer are: dimensions of the working chamber; quality (accuracy and roughness) of printing; structural reliability; the ability to print with various materials; ease of use and maintenance; low cost of purchase and operation. Different types of kinematics are capable of meeting these requirements to varying degrees.

Below in Table 1, an assessment of the fulfillment of the requirements by various types of kinematics is given [7]. The significance of the requirements is determined on a 10-point scale from the point of view of the industrial consumer. If the printer was used privately or in an educational setting, the importance of specific characteristics would be different.

Compliance with the requirements was assessed by experts on a 5-point scale. The overall quality score was calculated by analogy with the methodology adopted in HoQ QFD as the sum of the products of assessments of fulfillment of requirements by the significance of the requirement.

| **Requirements** | Evaluation of the kinematics of a 3D printer (5-point scale, 0 - does not fulfill the requirement, 5 - the best) |
|------------------|----------------------------------------------------------------------------------------------------------|
| Significance to the consumer abs / rel | Cartesian H-bot | Cartesian CoreXY | Delta | Polar | Robotic | SCARA | “Ideal” |
| Dimensions of the working chamber | 8 | 11 | 3 | 3 | 4 | 4 | 5 | 4 | 5 |
The best rating (79.7%) belongs to 3D printers with Cartesian kinematics. CoreXY kinematic printers are cheaper and easier to use. We consider polar printers to be the worst (57.1%) at the moment. They are of limited use.

SCARA 3D printers have prospects, but they are still quite expensive.

**QFD FDM 3D Printer.** To assess possible directions for improving a 3D printer for subsequent prototyping and manufacturing of parts for unmanned aerial vehicles, a Level 1 QFD was carried out for the design of a Cartesian kinematics 3D printer (Table 2) and a generalized QFD (Table 3).

The main structural elements of a 3D printer are described above in section 3.1. The requirements and their significance for the consumer were obtained earlier (table 1).

According to the QFD level 1 results (Table 2), the most important are the following generalized characteristics of the FDM 3D printer in terms of prototyping and manufacturing of unmanned aerial vehicle parts with high quality requirements: Type and characteristics of kinematics (15%); Extruder type and characteristics (13.9%).

**Table 2.** Level 1 QFD for 3D FDM printer.

| Requirements                                                                 | Generalized characteristics |
|-------------------------------------------------------------------------------|-----------------------------|
| Significance to the consumer abs / rel                                       | Weight | Dimensions of the working table | Type and characteristics of the working table | Type and characteristics of control system | Types of data transfer | Maintenance time | Material change time | Required competence for assembly and maintenance | Availability of accessories | Material included |
| Quality (accuracy and roughness) of printing                                 | 1      | 9                             | 3                                             | 9                                              | 5                       | 3                | 3                  | 3                   | 3                  | 3                  |
| Structural reliability                                                      | 0      | 7                             | 5                                             | 3                                             | 3                       | 3                | 5                  | 5                   | 5                  | 5                  |
| Ability to print with various materials                                      | 9      | 14.                           | 7                                             | 4                                             | 4                       | 3                | 3                  | 4                   | 4                  | 4                  |
| Ease of use and maintenance                                                 | 11.    | 8                             | 4                                             | 4                                             | 3                       | 2                | 5                  | 3                   | 5                  | 5                  |
| High print speed                                                             | 8      | 14.                           | 10.                                           | 3                                             | 3                       | 4                | 3                  | 3                   | 5                  | 5                  |
| Safety (including noise and vibration)                                      | 9      | 14.                           | 2                                             | 4                                             | 4                       | 3                | 3                  | 4                   | 4                  | 5                  |
| Low purchase and operating cost                                             | 7      | 14.                           | 10.                                           | 3                                             | 4                       | 5                | 3                  | 1                   | 2                   | 5                  |
| Abs. Importance                                                             | 378    | 399                           | 33                                            | 28                                            | 35                      | 372              | 500                | 500                 | 500                | 500                |
| Rel. Importance                                                             | 75.6   | 79.7                          | 66.                                           | 57.                                           | 70.                     | 74.              | 74                 | 74                  | 74                 | 74                 |

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| Quality (accuracy and roughness) of printing                                 | 1      | 9                             | 3                                             | 9                                              | 5                       | 3                | 3                  | 3                   | 3                  | 3                  |
| Structural reliability                                                      | 0      | 7                             | 5                                             | 3                                             | 3                       | 3                | 5                  | 5                   | 5                  | 5                  |
| Ability to print with various materials                                      | 9      | 14.                           | 7                                             | 4                                             | 4                       | 3                | 3                  | 4                   | 4                  | 4                  |
| Ease of use and maintenance                                                 | 11.    | 8                             | 4                                             | 4                                             | 3                       | 2                | 5                  | 3                   | 5                  | 5                  |
| High print speed                                                             | 8      | 14.                           | 10.                                           | 3                                             | 3                       | 4                | 3                  | 3                   | 5                  | 5                  |
| Safety (including noise and vibration)                                      | 9      | 14.                           | 2                                             | 4                                             | 4                       | 3                | 3                  | 4                   | 4                  | 5                  |
| Low purchase and operating cost                                             | 7      | 14.                           | 10.                                           | 3                                             | 4                       | 5                | 3                  | 1                   | 2                   | 5                  |
| Abs. Importance                                                             | 378    | 399                           | 33                                            | 28                                            | 35                      | 372              | 500                | 500                 | 500                | 500                |
| Rel. Importance                                                             | 75.6   | 79.7                          | 66.                                           | 57.                                           | 70.                     | 74.              | 74                 | 74                  | 74                 | 74                 |
In general, the extruder and movement elements and guides make the greatest contribution to meeting customer requirements (Table 3). The control system, which includes the control unit and software, etc., is of no small importance. The quality of the products obtained and the satisfaction of consumers depend on their capabilities.

Table 3. Assessment of the importance of improving the elements of a 3D printer.

| Requirements                                                                 | Main assemblies and details   |
|------------------------------------------------------------------------------|------------------------------|
|                                                                              | Extruder | Desktop (platform) | Moving mechanisms and guides | Control system | Power supply | Frame |
| Significance to the consumer abs / rel                                       |          |                    |                               |                |             |       |
| Dimensions of the working chamber                                           | 9        | 13.1               | 9                               | 1               |             |       |
| Quality (accuracy and roughness) of printing                                | 1        | 14                 | 3                               | 3               | 9           | 9     |
| Structural reliability                                                       | 9        | 13                 | 9                               | 9               | 9           | 9     |
| Ability to print with various materials                                      | 8        | 11                 | 9                               | 9               | 9           | 9     |
| Ease of use and maintenance                                                  | 7        | 10                 | 9                               | 9               | 9           | 9     |
| High print speed                                                             | 8        | 11                 | 9                               | 9               | 9           | 9     |
| Safety (including noise and vibration)                                       | 1        | 10                 | 9                               | 9               | 9           | 9     |
| Low purchase and operating cost                                              | 7        | 10                 | 9                               | 9               | 9           | 9     |
Taking into account the obtained assessments of importance, first of all, the risks of inconsistencies are considered: inconsistency of the characteristics of the kinematics: the movement error is greater than the established one; mismatch of the extruder characteristics: plugging of the print head, instability of the extruder temperature.

The consequences of these inconsistencies are: Insufficient print quality (defects); Inability to print with some materials; Insufficient print quality (defects); Slow print speed. Taking into account the assessment of the significance of customer requirements and the FMEA method for these nonconformities, a significance score of S = 10 was established.

Within the framework of this work, with regard to first-time users in prototyping and using an FDM 3D printer, possible reasons are considered: Insufficient structural rigidity; Incorrectly configured software; Incorrect material or extruder design.

Highest priority risk score (RPN = 500 points) for causes Insufficient structural rigidity and Incorrectly selected material or extruder design and Incorrectly configured software. These potential causes are difficult to manage in the early stages of using an FDM 3D printer. Many newcomers rely on the manufacturer's recommendations, but cannot clearly assess and articulate their needs.

The actions to reduce these risks can be: Making changes to the FDM 3D printer software; analysis and calculation of the required design and material of the extruder, purchase and use of several extruders for different materials.

These actions will affect purchase and maintenance costs, but will improve quality and reduce assembly and maintenance time for the printer.

### 5. Conclusion

The analysis of the types of kinematics of 3D printers and further study of the design of the FDM 3D printer of the Cartesian type by the QFD and FMEA methods are carried out. The most important elements and generalized characteristics of a 3D printer for prototyping and manufacturing of UAV parts have been determined. Actions have been developed to reduce risks and improve the most important aspects.

In the future, research will be continued using quality tools and robust design [3, 4, 8, 9, 10] to improve the quality of the technological process design and production of UAV parts on an FDM 3D printer.
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