Acta Mechanica Slovaca **27 (2): 18 - 25,** June **2023**
https://doi.org/10.21496/ams.2023.007

Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Face Shield Frame Material Planning Using Quality Function Deployment

Kristína Lengyelová [1,*], Renáta Turisová [1]

[1] Technical University of Košice, Faculty of Mechanical Engineering, Letná 9, 04200 Košice, Slovak Republic

Abstract: The inspiration for the research was a customer request for 3D printing of face shield frames during the COVID-19 pandemic. In this context, but also due to the possibilities of relatively cheap 3D printing of various products, a large amount of waste started to be generated that needed to be disposed of. The overall aim of the research was to contribute to the development of new products printed using the 3D Fused Filament Fabrication (FFF) technology from thermoplastic materials, with a view to maximizing the quality level and minimizing the environmental footprint and cost of production. A modified Quality Function Development (QFD) methodology was applied, supplemented by a material planning matrix and a 3D model planning matrix which is the scientific contribution of the research. According to an extended QFD methodology taking into account the particular characteristics of 3D printing quality control and material selection decisions in terms of minimizing environmental impact, frames were printed from biodegradable PHA Biowood 3D Rosa filament. Waste management improvement is proposed by using filaments from biologically degradable materials or recycled filaments.

Keywords: Quality Function Deployment; 3D printing; environmental footprint; thermoplastic filament; biodegradable filament; waste disposal

1. Introduction

Satisfying consumers with respect to all expected quality features and functions is a major challenge in product design. Designing a new product, or improving an existing one, requires an integrated set of activities, with creativity being considered an essential prerequisite. Selecting the best material to meet future customers' requirements involves many trade-offs, depending on the material's structure and mechanical and physical properties [1]. Therefore, designers must be involved in the design and selection of the material, mainly because of the huge number of problems to consider when selecting the best material for a particular design.

Decisions on material selection affect not only the safety of the product but also the consumption of raw materials and energy, the contamination of water and the atmosphere, and the consumer's ability to recycle or dispose of used products. Therefore, finding the optimum combination of material and its processing cannot be achieved in only a single stage of the project but must evolve progressively during the different development phases, as it is essential to select the optimum combination for the final product design the first time.

The starting point of the research was a literary survey of the history of 3D printing and related topics in the area of accuracy, safety, environmental and economic efficiency of printing using specific technology and materials, which is presented in more detail in the dissertation [2]. The main reason for the research was the creation of a large amount of plastic waste during the SARS-CoV-2 (COVID-19) pandemic

*** Corresponding author:** Kristína Lengyelová, ***E-mail address:*** *kristina.lengyelova@tuke.sk*

when the demand for 3D printing of protective face shields by Fused Filament Fabrication (FFF) technology increased enormously. The presented part of the research aims to select the most suitable filament material for the 3D printing of face shield frames from three types of thermoplastics: Polylactic acid (PLA), Polyethylene terephthalate (PETG) and Polyhydroxyalkanoate (PHA) from the aspects mentioned above. The practical part of the research concerned the application of the Quality Function Deployment (QFD) method for designing face shield frames concerning the material properties of the filaments.

2. Theoretical Framework

The theoretical analysis of the topic can be characterized as applied research with a predominantly quantitative approach. The research process is in line with the recommendations for the research of this nature according to [3], [4], [5].

Papers from scientific journals and conference proceedings from 2005 to 2022 regarding the life cycle of 3D printing and the QFD method were studied. More than 300 related resources were collected during the initial search. After an initial screening by reading titles, keywords and abstracts, 153 sources (part of the dissertation thesis Lengyelová, 2022) were used, which, in addition to published articles, contain manufacturers' recommendations in the form of manuals or websites as references for filament properties or recommended printing conditions.

2.1 3D prined product life cycle

In Slovakia, Act No. 79/2015 Coll. on Waste, amended by Act No. 230/2022 Coll. (in force since 30 June 2022), applies to the life cycle of products in Slovakia, and defining the methods of waste recovery, recycling and disposal, where waste recovery is a set of activities leading to the use of physical, chemical or biological properties of waste and waste disposal is waste management that does not cause environmental damage or endanger human health [6]. Slovakia has an approved environmental policy strategy [7] but still lags behind more developed countries, especially in waste management and air quality. Municipal waste recycling rates are among the lowest in the EU, and landfilling is still the dominant form of waste management.

The environmental strategy known as Cradle-to-Cradle [8] is part of the European Union (EU) policy and drives the European economy towards a circular economy [9]. Slovakia's approved environmental circle of a 3D printing product life cycle can be described according to Fig. 1.

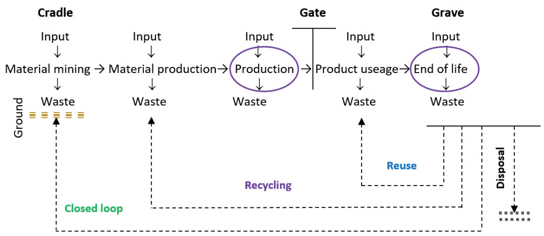

Figure 1: Cradle-to-cradle environmental cycle according to [2].

Legend: ◯ – life cycle phases studied in this research.

The ability to produce environmentally suitable and biodegradable 3D printing products is a major challenge for environmental conservation; however, production cost and environmental sustainability are often conflicting requirements. This is why our research is dedicated to finding the most suitable material in terms of disposability or reusability. The environmental impact of 3D technologies has not been examined in scholarly sources in sufficient detail, although this research has grown substantially in recent years, and in 2022, filament manufacturers even provide information on reusability, recyclability or final disposability. Traditional subtractive manufacturing technologies often require a combination of milling, turning, grinding processes, etc., where these processes' environmental impact varies and depends on the component being manufactured. However, in additive manufacturing of a 3D-printed part, such a combination is usually unnecessary.

When studying 3D printing processes, the main problems related to environmental impact can be thought to result from the product's entire life cycle, i.e. energy consumption, waste materials, water footprint, global warming potential, and air pollution. In addition, the environmental impact of 3D printing depends on various parameters, such as the 3D printer setup and the chosen material [10].

The quality and strength of the FFF structural part depend mainly on the process parameters. In order to understand the performance and capability of the printer and the behaviour of products created using this technology, it was necessary also to study the impact of process parameters on the quality of the final product. Several studies have been conducted in this field, analysing the most important factors of 3D printing and their impact on the different product quality characteristics. The results of this part of the research are presented in [2] and [11].

Knowing the impact of a product or service on the environment, already at the stage of its design, is a fundamental manifestation of a company's culture and maturity [12].

A literature survey in [2] suggests that metrics and standards for assessing the environmental impact of additive manufacturing processes are insufficient. Currently, Life Cycle Assessment (LCA) and Design for Environment (DFE) are the two most commonly used methods for assessing environmental impact [13] and [14], with LCA being a standardized methodology according to ISO 14040:2006 [15] and ISO 14044:2006 [16] representing the most commonly used tool for measuring the environmental impact associated with all life cycle phases of a product, process or service. A detailed life cycle assessment covers all impacts of a product, process or activity, including its transport and distribution, use, maintenance, recycling and final disposal [17] (EPA, 1994).

2.2 Quality Function Deployment

The research presented in this article uses the Quality Function Deployment (QFD) method. This method already shows the development of "What" and "How" to be solved, what technologies can be used and what limitations can occur. Quality Function Deployment is a structured approach to defining customer needs or requirements and translating them into specific plans for producing products that meet those needs. The Voice of the Customer (VoC) is captured in various ways: direct discussions or interviews, surveys, focus groups, customer specifications, observations, warranty details, field reports, etc. Customer needs are then summarized in a product planning matrix called the "House of Quality" (HOQ) [18]. The QFD methodology was developed in the late 1960s by Joji Akao in Japan and applied at Mitsubishi Heavy Industries. The QFD algorithm consists of four basic stages (1. product planning, 2. product design, 3. process design and 3. quality control design), which are represented by houses of quality [19]. A more detailed presentation of the matrices that make up the houses of quality is shown in Fig. 2.

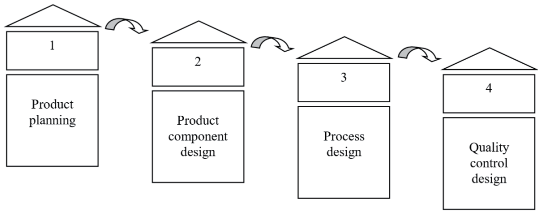

Figure 2: Visualization of the original four-matrix QFD approach.

Several mathematical procedures have already been proposed for selecting the most suitable materials for different engineering applications. These procedures are usually used to calculate the importance of individual criteria, which are based on the subjective judgement of the designer. "Multi-Criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design" is an original publication in the field of QFD application in material selection decisions [1].

The approach to material selection using QFD is divided at the second stage of a QFD project into (a) HOQ construction for designing product components; (b) HOQ construction for variant materials that should be considered for designing product components. Tab. 1, adapted according to [20], presents the concept of the two-stage model of the second QFD stage used for material selection decisions.

This material selection model can be used for each product component or for its systems or subsystems [21]. It connects the design or technical requirements for each product with the material properties and then selects the most suitable material based on a prioritization matrix and correlation links. A more detailed representation of matrices and relationships in the first house of quality is shown in Fig. 3.

Table 1: Conceptual model for material selection.

	Material properties	
Technical requirements	**Importance**	Correlation matrix
List of materials	Material property values	Order of materials

Our research extends this conceptual model to investigate the impact of material on the life cycle of a 3D printed product and adds a material planning matrix and a 3D model planning matrix to classical QFD. The article presents only the material planning matrix.

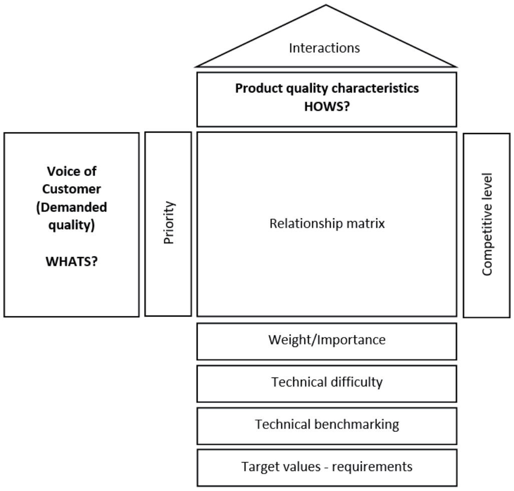

Figure 3: More detailed presentation of the matrices and relations in the first house of quality.

3. Results and Discussion

The research results are presented on the example of 3D printing of face shield frames during the Covid-19 Pandemic using FFF technology. The possibilities of relatively fast and relatively cheap 3D printing by previously unspecialized workplaces made it possible to print this protective equipment and thus helped medical facilities and ordinary citizens protect themselves from the previously unexplored virus. The negative result was a large amount of waste that had to be disposed of.

The result of this part of the research is the basic quality and performance indicators and the analysis of variant designs of materials that were necessary for the solution of the extended QFD methodology.

3.1 Measuring of basic quality and performance indicators

Metrics and methods of measuring quality and performance indicators necessary for making decisions about material selection are presented in four steps:

1. Understanding customer desires and requirements: Understanding the desires and needs of future users of face shields (summarised in Tab. 2) was crucial for creating a new product that takes into account safety and minimizes the environmental footprint, with an acceptable amount of material consumed, i.e., acceptable cost of the filament consumed.

2. Market segment definition: The customers will be ordinary citizens, but health professionals were also involved in the research. Note: In the case of the final product intended for medical staff, it will be necessary to follow the Decree of the Ministry of Environment of the Slovak Republic 371/2015 Coll. dated 13 November 2015, implementing certain provisions of the Waste Act) [22] and all three examined materials: PLA and PETG from Prusament Research ($PLA_{PRUSA-ORIG}$) and ($PETG_{PRUSA-ORIG}$) and PHA Biowood from Rosa 3D ($PHA_{BW-ORIG}$) of the frames are to be disposed of as hazardous waste. Quality management systems in healthcare organizations apply (ISO 13485: 2016 [23].

3. CTQ design for the market segment: In designing CTQ, it was necessary to consider and understand the different, often conflicting, customer requirements. The aim of identifying feasible solutions was to balance these requirements and to design critical to quality (CTQ) parameters.

An effective way to balance customer voices was to use the voice of customers (VOC) method, described in more detail in [11].

4. Creation of Metrics and How to Measure Them:

The team discussed the problems and examined the metrics in detail, identified the effect on the customer, and specified the expected benefits of the project. The following metrics were arrived at:

– *Flexibility [MPa]: Young's modulus*
– *Precision [mm]: Dimensions*
– *Printing time [s]: To calculate environmental sustainability*
– *Price of material [€]: To calculate the price of consumed material*
– *Weight [kg]: To calculate the price of consumed material for printing the sample*
– *Environmental sustainability [CO2-eq]: measured at the 3D printing stage and at the end of the product life and dependent on (a) printing duration [s]; (b) calculated and dependent on the possibility of recovery (reusability, recyclability) or disposal (Fig. 4).*

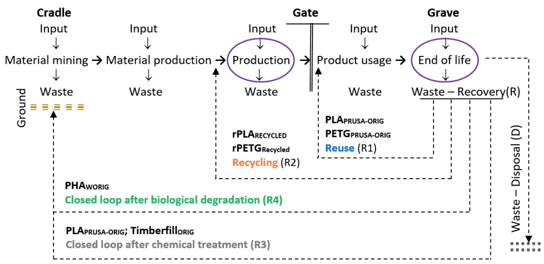

Figure 4: Cradle-to-cradle environmental cycle for the examined plastics (adapted according to [2] and [6]).

3.2 Analyzing variant designs of materials

When analyzing variant designs, we proceeded in four consecutive steps according to Fig. 5, which was the result of research published in [2].

1. Generation of variant designs: In our case, a modified QFD method, adapted to the 3D printing process, is used for design generation. The starting point of the research was to decide on the choice of material for 3D printing, and the procedure involves planning the 3D model and printer setup parameters (dealt with in more detail in the dissertation thesis [2]). This modified QFD method is a formalized procedure to support decision-making about the properties, functions and materials of the future product, i.e., the face shield frame, but can be *used in the design of any 3D-printed product (Fig. 5).*

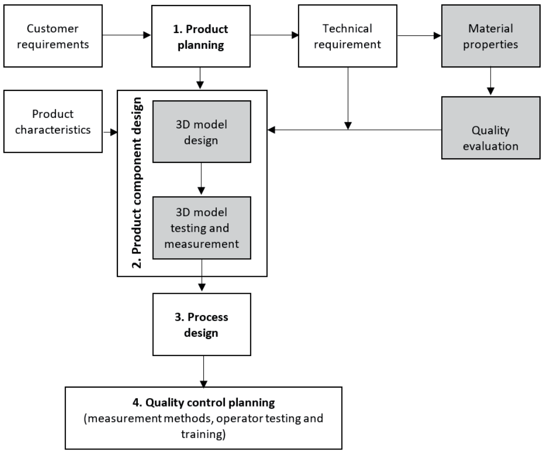

Figure 5: Modified QFD procedure for a new 3D printed product with respect to material properties.

Note: The addition to the standard QFD method is highlighted in grey.

2. <u>Evaluation of alternative solutions</u>: In our case, in the first year of the solution, the selection was made from three filament materials: PLAORIG, PETGORIG, PHABW-ORIG, and the final product was face shield frames for ordinary users. For deciding on the properties and functions of the materials, a quality assessment methodology was applied according to [24]. The decision-making aspect was primarily the environmental impact of the 3D product while maintaining its functionality and safety.

3. <u>Combining best practices and solutions</u>: The traditional procedure according to [25] was extended to include the "Materials Quality Assessment Methodology" and the "3D Model Design House" (Fig. 6).

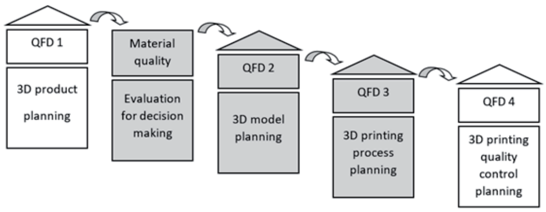

Figure 6: QFD procedure for 3D printing with FFF technology taking into account the material properties of the final product.

4. <u>Creation of the final design</u>: In the design of the final frame of the face shield for ordinary users, we used the houses of quality, which were developed in the template [26]. In the first QFD house Product Planning of 3D Printing (Fig. 7), the most important quality

Table 2: Inputs for assessing the quality level of filaments.

Customer requirements	***PLA_{ORIG}***		***$PETG_{ORIG}$***		***$PHA_{BW\text{-}ORIG}$***	
	Qi	***w_i***	***Q_i***	***w_i***	***Q_i***	***w_i***
DQ1: Pleasant to touch *Roughness – rated*	1.0	5.49	1.0	5.49	1.0	5.49
DQ2: Adaptable to different faces *Flexibility: Young's modulus [GPa] – measured*	0.6	9.89	1.0	9.89	1.0	9.89
DQ3: Light *Weight [g]*	0.4	5.49	0.6	5.49	1.0	5.49
DQ4: Long life *Reuse – rated*	1.0	7.69	0.8	7.69	0.6	7.69
DQ5: Disinfectable *Resistance to disinfectants*	1.0	12.09	1.0	12.09	1.0	12.09
DQ6: Environmentally friendly *[CO2-eq – rated]*	0.2	13.19	0.4	13.19	1.0	13.19
DQ7: Safe *Resistance to viruses [rated]*	0.8	14.29	0.8	14.29	1.0	14.29
Q 8: Replaceable plexi visor *Dimension precision [mm]*	1.0	7.69	1.0	7.69	1.0	7.69
DQ9: Water- and acid-resistant *Moisture absorption**	1.0	10.99	1.0	10.99	0.8	10.99
DQ10: Cheap *Price of material [€/ kg]*	0.6	13.19	1.0	13.19	0.4	13.19
Q_{SUM}	74.06		85.49		86.81	

Note: $Q_{SUM}=\sum_{i}^{n} w_i \cdot q_i$, where wi represents the importance of individual quality characteristics according to customer requirements, Q_i is an indicator of the quality level of the i-th characteristic, and Q_{SUM} is a summary showing the quality levels of the examined filament material where i=1 and n=10.

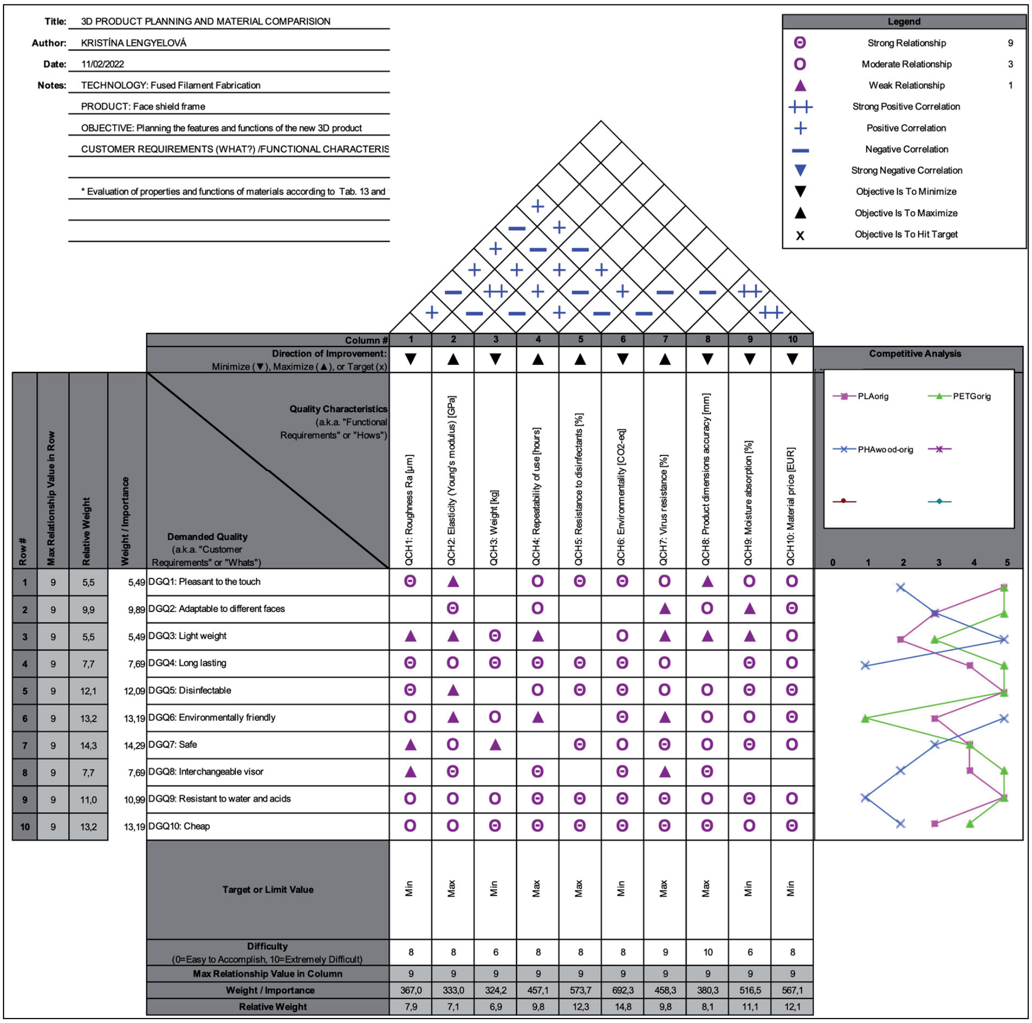

Figure 7: First house of quality: Planning the face shield frame.

Explanation: DQ – Demanded quality; QCH – Quality characteristics.

properties and functions of the face shield frame were investigated. To identify customer requirements, the project team had a detailed brainstorming session with 40 customers (33 from Spain and 7 from Slovakia), of whom 36% were ordinary users, and 64% were medical staff, who identified ten critical requirements (What do they want?). Based on these requirements, the team translated the requirements into functional characteristics (How can this be technically provided?). These data were added to the first house of quality, in which correlation relations between rows and columns (⊙ - strong, ○ - medium, ▲ - moderate) and their effect between columns (++ strong positive, + - positive, - negative, ▼ strong negative) were then added.

The importance of customer requirements for the 1st house of quality was found using the pairwise comparison method [21] taking into account detailed the detailed optimization goals (the higher the value is better ↑, or the lower the value, is better ↓).

Then, based on the previous experiments, the quality level of those partial properties that were not measurable with instruments was rated (from 5 – highest) to (1 – lowest), and the most suitable material was selected, which at that point in the work was the $PHA_{BW\text{-}ORIG}$ filament.

To decide on the choice of material as part of the extension of the QFD methodology, measured values were added to the 1st quality house and points proposed by a team of experts were assigned, which established the importance of individual properties according to customer requirements. Tab. 2 shows the background and the resulting evaluation of the quality level of the three filaments included in the decision-making process in the first QFD matrix.

PHA filament achieved the highest level of quality in terms of properties required by customers, according to Tab. 2, while PHABW-ORIG is the material with the lowest impact on the environment, with a mean of 0.029 kg CO2-eq. CO2-eq is the standardised measure for calculating the amount of greenhouse gases emitted into the atmosphere due to a process or material use. The electricity mix of Slovakia has been used to calculate the electricity use of the 3D printer and ReCiPe LCA methodology for environmental impacts [27].

Final experiments were performed by printing a test set of face shield frames from biodegradable PHABW-ORIG filament on a 3D Original Prusa i3 MK3S+ printer (Fig. 8).

Figure 8: Face shield frames made of biodegradable filament PHABW-ORIG.

4. Conclusions

The overall aim of the research was to find a suitable filament material for printing new products that do not burden the environment and yet meet customer requirements in terms of quality. The experimental research focused on face shield frames, chosen due to the increased demand for them during the Covid-19 pandemic and the limited possibilities to experiment with 3D printing of other products. An extended Quality Function Deployment (QFD) methodology was applied, supplemented by a material planning matrix and a 3D model planning matrix. From the literature survey as well as from our own observations, it was found that environmental performance is a quality indicator and its examination in the development of new products and related materials is justified. Metrics and methods of measuring quality and performance indicators necessary for material selection decisions were proposed and proposals for three types of filaments were analyzed.

The resulting knowledge from the research is a recommendation for improving waste management through the use of filaments from biologically degradable materials marked in Fig. 4 as R4 or R3 – biodegradable material or at least the use of the recycled filaments R2 – recycled material.

The knowledge gained can also be generalized to other 3D printing technologies, which create an increased amount of waste. Further possibilities for research:

- *Examination of Copper 3D PLActive setup parameters and optimization according to safety and sustainability criteria and development of a new product according to a modified QFD methodology.*
- *Investigation of Felfil Plastic Shredder setup parameters and recycling of PLA and PETG waste material at TUKE for new filament production.*

Acknowledgments

The research was conducted as part of the project VEGA 1-0633-20 project "Research on the variability of properties of products manufactured from composite materials using additive technologies", the project APVV-19-0367 Framework of the Integrated Process Safety Management Approach for the Intelligent Enterprise and the project KEGA 019TUKE-4/2020 Application-oriented education in the field of implementation of the requirements of the ISO 9001:2015 standard.

References and Notes

1. Jahan, A., Edwards, K.L. and Bahraminasab, M. (2016). Materials selection in the context of design problem-solving. Multi-Criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design. Amsterdam: Elsevier Ltd., 25-40. http://doi.org/10.1016/B978-0-08-100536-1.00002-3.
2. Lengyelová, K. (2022). Výskum materiálových a geometrických vlastností produktov vyrábaných aditívnymi technológiami. Košice: Technická univerzita v Košiciach.
3. Kothari, C. R., Garg, G. (2019). Research methodology methods and techniques. New Delhi: New Age International.
4. Espuny, M., Neto, A. F., Da Motta Reis, J. S., Santos, S. (2021). Building New Paths for Responsible Solid Waste Management. Environmental Monitoring and Assessment. 193, 7, 442. https://doi.org/10.1007/s10661-021-09173-0.

5. de Souza Sampaio, N.L., et al. (2022). Contributions to the future of metaheuristics in the contours of scientific development. Gest. Prod. 29, https://doi.org/10.1590/1806-9649-2022v29e099.
6. Odpady Portal (2022). Zneškodňovanie odpadov, from https://www.odpady-portal.sk/Dokument/100386/zneskodnovanie-odpadov.aspx, date of access 15.1.2022.
7. Ministerstvo životného prostredia (2019). Zelenšie Slovensko. Stratégia environmentálnej politiky Slovenskej republiky do roku 2030, from https://www.minzp.sk/files/iep/03_vlastny_material_envirostrategia2030_def.pdf, date of access 10.11.2022.
8. Arvanitoyannis, I. S. (2008). Waste Management for the Food Industries. Food Industries. https://doi.org/10.1016/B978-0-12-373654-3.X5001-9.
9. European Commission. Real Economy – Cradle to cradle: powering Europe's circular economy from https://ec.europa.eu/regional_policy/en/newsroom/news/2016/01/28-01-2016-real-economy-cradle-to-cradle-powering-europe-s-circular-economy, date of access 28. 1. 2016.
10. Khosravani, M. R., Reinicke, T. (2020). On the environmental impacts of 3D printing technology. Applied Materials Today, 20, 100689. https://doi.org/10.1016/j.apmt.2020.100689.
11. Zgodavová, K., Lengyelová, K., Bober, P., Eguren, A., Moreno, A. (2021). 3D Printing Optimization for Environmental Sustainability: Experimenting with Materials of Protective Face Shield Frames. Materials 14, 21, 6595. http://doi.org/10.3390/ma14216595
12. Zgodavova, K., Petrik, J., Solc, M. (2014). Principles Concepts Standards of Management Systems: Quality, Metrology, Information Security. Chisinau: LAP LAMBERT Academic Publishing.
13. Jawaid, M., Thariq, M. and Saba, N. (2018). Durability and Life Prediction in Biocomposites. Fibre-Reinforced Composites and Hybrid Composites. Amsterdam: Elsevier.
14. Rao, R. V. (2016). Decision Making in the Manufacturing Environment. Using Graph Theory and Fuzzy Multiple Attribute Decision-Making Methods. Berlin: Springer.
15. ISO 14040 (2006). Environmental management – Life cycle assessment – Principles and framework. Geneva: ISO.
16. ISO 14044 (2006). Environmental management – Life cycle assessment – Requirements and guidelines. Geneva: ISO.
17. EPA (1994). Pollution prevention accomplishments. Policy lead to action. Washington: National Service Center for Environmental Publications (NSCEP).
18. Hauser, J. R., Don, C. (1988). The House of Quality. Harvard Business Review.
19. Turisová, R., Pačaiová, H. (2018). Inžinierstvo kvality produkcie. Košice: TU v Košiciach.
20. Isaac, O. T., Olumide, O. T., Rasaki, O. O. (2015). Application of House of Quality Matrix to Material Selection for Engineering Designs. British Journal of Applied Science & Technology, 10, 1-11. http://doi.org/10.9734/BJAST/2015/19105.
21. Lengyel, L., Zgodavová, K. (2018). Quality Function Deployment in an Open Innovation Project Team: Development of a Tool for Attribute Data Entering and Analyzing. Atlanta, GA: Scholars' Press.
22. Slovlex (2015). Vyhláška 371/2015 Z. z. ktorou sa vykonávajú niektoré ustanovenia zákona o odpadoch. Bratislava: Ministerstva životného prostredia Slovenskej republiky.
23. ISO 13485 (2016). Medical devices – Quality management systems – Requirements for regulatory purposes. Geneva: ISO.
24. Mlčoch, L., Slimák, I. (1897). Řízení kvality a strojírenská metrologie. Praha: SNTL.
25. Akao, Y. (1994). Development History of Quality Function Deployment. The Customer Driven Approach to Quality Planning and Deployment. Tokyo: Asian Productivity Organization.
26. QFD Online. QFD and House of Quality Templates: Traditional House of Quality ver. 2.0.346.0, from http://www.qfdonline.com/templates/qfd-and-house-of-quality-templates/ date of access 12. 8. 2022.
27. RIVM. LCIA: the ReCiPe model, from https://www.rivm.nl/en/life-cycle-assessment-lca/recipe date of access 31. 8. 2022.