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ScienceDirect

Procedia Computer Science 253 (2025) 425–434

Procedia Computer Science

www.elsevier.com/locate/procedia

6th International Conference on Industry 4.0 and Smart Manufacturing

Experimentation on the sustainability of 3D printing with recycled filaments using Lean Six Sigma methodology

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Abstract

The integration of Lean Six Sigma (LSS) – a methodology focused on process improvement and waste reduction – with the technological advances of Industry 4.0 offers a powerful synergy capable of reshaping modern industrial paradigms. One of the most significant technologies within Industry 4.0 is additive manufacturing, which is closely linked to key factors such as quality, flexibility and the cost of manufactured products. However, its widespread application faces several challenges, particularly in process optimisation, including controlling set-up parameters and using new raw materials. This research was initially inspired by the demand for 3D-printed face shield frames during the Covid-19 pandemic. The ability to produce various products relatively cheaply through 3D printing has led to an increase in plastic waste, requiring effective solutions. Therefore, the objective of this research is to contribute to the development of 3D-printed products using polylactic acid (PLA), balancing quality and cost while minimising their environmental footprint. This project presents a methodology for experimentally assessing the use of recycled PLA (rPLA) filament for producing face shield frames using fused filament fabrication (FFF) technology and the LSS methodology. Using 100% rPLA filament, the critical-to-quality (CTQ) characteristics of the final product were defined according to the voice of the customer (VoC). Based on these requirements, the 3D printer settings were optimised for rPLA filament recycled by the Technical University of Košice and the results were compared with those using Prusa virgin PLA (vPLA).

Keywords: Fused filament fabrication; recycled PLA; environmental sustainability; Lean Six Sigma

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10.1016/j.procs.2025.01.104

1. Introduction

With the rapid increase in digitalisation and the adoption of advanced technologies in Industry 4.0 (I4.0), three-dimensional (3D) printing methods are now widely used in manufacturing processes across different industries. Indeed, 3D printing is considered the future of the manufacturing world [1]. Among these technologies, fused filament fabrication (FFF) process is considered the simplest, most affordable and readily available 3D printing technique for polymer-based materials, and it has been widely used in various industries [2]. It stands out due to its laser-free application and low use and maintenance costs. However, FFF has significant limitations, particularly in terms of production times, costs and its environmental impact, making mass production difficult [3]. The rise of this technology was evident on March 11, 2020, when the World Health Organisation declared Coronavirus Disease 2019 (Covid-19) a global pandemic. Preventing the spread of the virus largely depended on the effective use of personal protective equipment, such as gloves, masks, respirators, glasses and face shields [4]. The unprecedented demand for these products, along with supply chain disruptions caused by practical and political barriers, forced communities to seek alternative short-term manufacturing solutions [5]. Prusa Research rapidly developed and began mass-producing face shields using FFF technology, donating nearly 200,000 shields to doctors and other professionals in the Czech Republic. Although petroleum-based plastics fulfil many performance requirements, they contribute significantly to ecological and environmental challenges. The global production of plastics is estimated to be about 400 million tons annually, with nearly 87% becoming waste plastic [6]. Only 9–10% is recycled and reused, 12% is incinerated while 78–79% accumulates in oceans, lakes, rivers and landfills, contaminating ecosystems and impacting human health. Additionally, the polymer industry faces critical issues regarding carbon dioxide (CO2) emissions and the depletion of fossil resources[7]. In response to these concerns, the integration of Lean Six Sigma (LSS), a methodology focused on process improvement and waste reduction, with the technological advances of Industry 4.0 offers a powerful synergy that can redefine modern industrial paradigms [8] [9]. Since the onset of the Covid-19 pandemic, researchers have increasingly focused on addressing the growing problem of plastic waste. For example, Prusa Research began developing recycled filaments, and around the same time, the Technical University of Košice (TUKE) and Mondragon University (MU) explored recycling waste from face-shield frames and student experiments. This article presents the findings of a study conducted through collaboration between TUKE and MU professors, within the framework of the Erasmus+ training programme. The main objective, using the LSS methodology, is to contribute to the development of 3D-printed products using FFF and recycled polylactic acid (rPLA), seeking to find an appropriate balance between quality, cost and environmental footprint. This article is structured as follows. Section 2 describes the application of the proposed methodology in additive manufacturing (AM). Subsequently, section 3 presents an overview of the 3D printing processes, the characteristics of the PLA used in the study and an analysis of the availability of recycled PLA. Section 4 describes the development of the work carried out, and section 5 concludes the paper.

2. Methodology

In modern industrial contexts, continuous improvement and the adoption of advanced manufacturing technologies are no longer optional but essential. The combination of LSS and I4.0 offers a robust framework for addressing these challenges. LSS allows for designing efficient production systems that generate less waste and deliver high-quality products while optimising resource use. One of LSS's core components is the Six Sigma (SS) methodology, a powerful approach for achieving continuous improvement by identifying and eliminating process errors. SS uses both statistical and non-statistical tools to address process variability and deviations, enabling manufacturers to improve customer satisfaction while maximising economic gains. SS is a well-established problem-solving approach, which employs qualitative and analytical tools to develop core processes based on the DMAIC (define–measure–analyse–implement–control) [10] [11]. As shown in Table 1, this study adopts a modified SS DMAIC methodology, referred to as DMAIC – 7P (Phases), which defines the arguments and routines used in each phase and integrates them into the case study. This approach aims to build knowledge in the field of quality engineering (QE) [8]. A project team was assembled for the research, comprising eight people – three from TUKE, with expertise in production facilities, testing laboratories and green belt-level knowledge of the LSS methodology. In addition, the MU team consisted of members of the industrial organisation and processes department, possessing master black belt- and black belt-level knowledge of LSS methodology and advance expertise in 3D printing techniques. The research was structured around the DMAIC-

7P process, using previously prepared support materials, with tasks planned according to each phase and weekly monitoring to track progress.

Table 1. Six Sigma methodology roadmap [12]

PHASE	OBJECTIVE
D: Define: P1: Identify the problem	Strictly validated project: The project should have measurable impacts on key strategic areas of the company or end users, who are identified as the main customer(s). These impacts must be relevant to the customer's needs, expectations and Critical-to-quality (CTQ). The project must also have a dedicated, motivated team with the necessary resources, along with clear objectives agreed upon by everyone involved.
M: Measure: P2: Collect and analyse data	Deep initial diagnosis: The project should start with a detailed diagnosis based on validated metrics and rigorously defined problems/opportunities.
A: Analyse: P3: Analyse the causes	Identification of key variables (X's). The root cause of the problem should be identified through experimental tests. Different types of variables (X's) will affect the process, including permanent X's, which cause issues due to their variation. Non-optimal X's are stable but not optimised, while degradable X's occasionally degrade and negatively impact the process. The goal is to process data, identity these variables and determine how they impact the process.
I: Implement: P4: Plan and implement solutions	Potential improvements should be tested in controlled pilot tests, and the results should be monitored for side effects. These tests will help refine the ideas and determine if they work as intended.
C: Control: P5: Check the results	It is important to determine whether the improvement is sustained over time (working as in the pilot test). Key performance indicators (KPIs) should be established and agreed upon by all affected parties, including the process owner and customer.
C: Control: P6: Standardise the results	The new way of working should be validated, ensuring the process is repeatable and that everyone responsible for monitoring is fully on board. The process is repeated until full acceptance is achieved.
C: Control: P7: Reflection on the process and problems encountered	Project closure: The project team will conclude its involvement by evaluating the results and getting formal approval from management, which will recognise and accept the work that has been completed.

3. Background

3.1. Fused filament fabrication (FFF)

The FFF Original PRUSA I3 MK3S+ printer is highly regarded in the maker community. With the rise of FFF technology in manufacturing, research into the behaviour of printed materials has also expanded. The properties of the materials processed through this technology can vary significantly depending on the parameters set during manufacturing. Therefore, process parameters play a significant role in determining the mechanical properties of FFF-produced parts FFF [13].

Regarding the polymer used in testing, thermoplastics such as acrylonitrile butadiene styrene (ABS), polycarbonate (PC), nylon and PLA are the most common materials in 3D printing. PLA is derived from plant materials, whereas the others are produced using petroleum. PLA, a rigid thermoplastic polymer classified as an aliphatic polyester, is compostable and sourced from renewable materials. Compared to traditional polymers, PLA production offers several benefits: it uses 65% less energy and produces 68% fewer greenhouse gases. Furthermore, it is a highly recyclable and contains no toxins [7]. Although PLA is biodegradable, it requires specific conditions, such as an industrial composting environment with high oxygen levels, temperatures, humidity and microorganisms [14]. Under these conditions, PLA can degrade by more than 90% within 30–150 days, breaking down into CO2, H2O and compost [15]. In terms of emissions from FFF manufacturing, researchers have quantified the release of particles and volatile organic compounds (VOCs) from five different FFF 3D printers using nine common materials, including PLA. The results show no significant evidence of inhalation toxicity from lactide, the primary VOC emitted by PLA filaments [16].

According to Anderson (2017), recycling is the best solution for minimising the environmental impact of PLA waste. Several companies produce recycled filaments from consumer waste. While mechanical recycling offers clear environmental benefits, the process is not without drawbacks. Studies [17] have shown that mechanical recycling reduces the molecular weight of PLA, as indicated by the decrease in intrinsic viscosity and key properties. Research has focused on the mechanical performance of 3D-printed samples made from both virgin (v) and recycled (r) PLA. The findings of these studies indicate that 3D printing with recycled PLA is viable, as the recycling process does not significantly alter mechanical properties, and the tensile elastic modulus remains stable [18] [22]. In another study using the Prusa I3 MK3S+ printer, short-beam resistance tests were performed on specimens printed with vPLA and rPLA filaments. The results showed that once- and twice-recycled PLA exhibited short-beam resistance comparable to vPLA, demonstrating minimal differences [18]. Additionally, researchers have evaluated the technical feasibility of distributed mechanical recycling of PLA 3D printing waste [19] [20]. Their results suggest that a distributed recycling scheme for vPLA could produce mechanically recycled materials with good performance, which remain compostable at the end of their useful life.

4. Results

The results described in this section are the outcome of applying the SS7P methodology [8], following the DMAIC steps and phases (P) detailed in Table 1.

D: Define – P1: Identify the problem. In this phase, teams must delineate the environment in which the project will take place and identify the inputs and outputs involved in the process.
To analyse the process and its environment, a high-level process map was created. This process map, structured as a SIPOC diagram, identified the suppliers (S), inputs (I), process (P), outputs (O) and customers (C). Fig. 1 provides an overview of the process to be analysed through the SIPOC framework. As shown in the SIPOC diagram Prusa PLA material is the input, which is then processed in a 3D printer. The parts produced were analysed to optimise the manufacturing process of face shields for healthcare workers or ordinary citizens. The FFF 3D printer used for this study was the Original Prusa I3 MK3S+. The 3D designs of the specimens were created with PrusaSlicer software, which is compatible with the Original Prusa I3 MK3S+ printer. The 3D models were created following the dimensions specified in the EN ISO 527-2:2012 standard, which is used to conduct tensile tests on composite materials.

SUPPLIERS (S)	INPUTS (I)	PROCESS (P)	OUTPUTS (O)	CUSTOMERS (C)
Prusa Research	• recycled PLA (rPLA) 	• 3D printing • Original Prusa I3 MK3S+ 	• EN ISO 527-2 mechanical test specimen  • Face shield frame  • Dimensions and propertiers	• Heathcare workers • Ordinari citizens

Fig. 1. SIPOC of the analysed process

Critical-to-quality (CTQ) characteristics also had be identified, with metrics defined for each to determine both the initial values and the target values to be achieved. To accomplish this, the Quality Function Development (QFD) and

Voice of Customer (VoC) tools were used, identifying the CTQ characteristics as the Young's modulus, tensile stress at break, total elongation, weight, length and thickness accuracy, as outlined previously [21].

M: Measure – P2: Collect and analyse data: In this phase, the focus was on conducting a thorough initial diagnosis based on validated metrics and rigorously defined defects or opportunities.

Process variable identification: The quality and strength of 3D-printed construction parts largely depend on the process parameters used during manufacturing. To fully understand the performance and behaviour of these parts, the influence of specific process parameters must be studied. In this study, prior research findings [21] were utilised, and a brainstorming session was conducted to identify the factors that could affect the process. These factors were then classified and represented in a cause-and-effect diagram (Fig. 2).

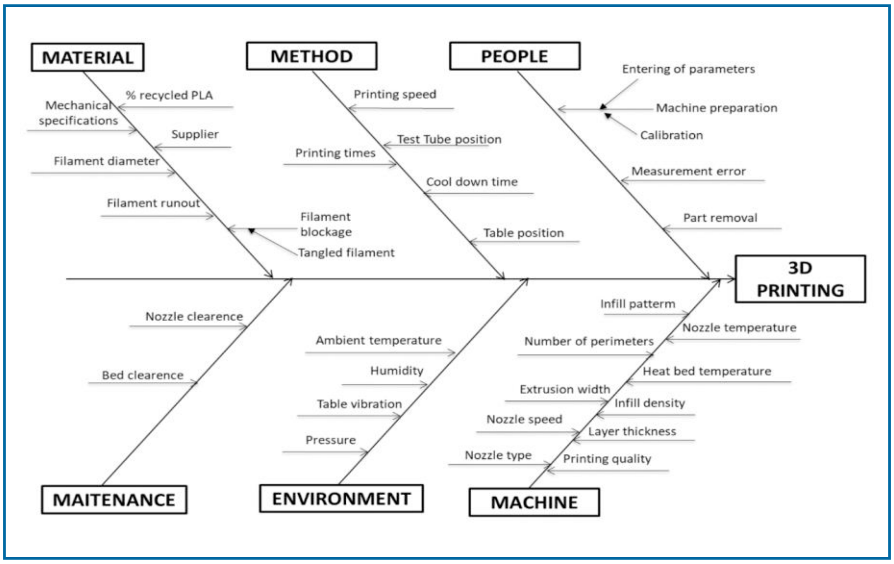

Fig. 2. 3D printing process cause and effect diagram

Definition of the metrics and measurement systems: If measurements are not accurate or precise, the data gathered may be misleading, resulting in incorrect decision. Depending on the reliability of the system, a defective item may be misjudged as good, or a good item may be misjudged as defective. Therefore, validating the accuracy and precision of the measurement system is a crucial activity within the SS process. Table 2 presents the CTQ characteristics, measurement units, instruments used and the laboratory where the experiment was conducted.

Table 2. CTQ characteristics, measurement units, instruments and laboratory.

CTQ characteristics	Units	Measurement instrument	Laboratory
Young's modulus	Gpa	Tinius Olsen H10KS testing machine	Neksten laboratory
Tensile stress at break	Mpa		
Total elongation	%		
Weight	g	T-scale weight	
Width accuracy	mm	Mitutoyo CD-500-151-30 electronic calliper	Technical University of Košice
Length accuracy	mm		
Thickness accuracy	mm		
Price	€	Filament price/weigh	

As shown in Fig. 3, the tensile tests were conducted using a Tinius Olsen H10KS machine following the ISO 13485:2016, 2020 standardised procedures. The weight of the specimens was measured on a T-scale at the Neksten laboratory. Dimensions and precision were manually verified using an electronic calliper. The cost of each piece was determined based on the amount of material used for production.

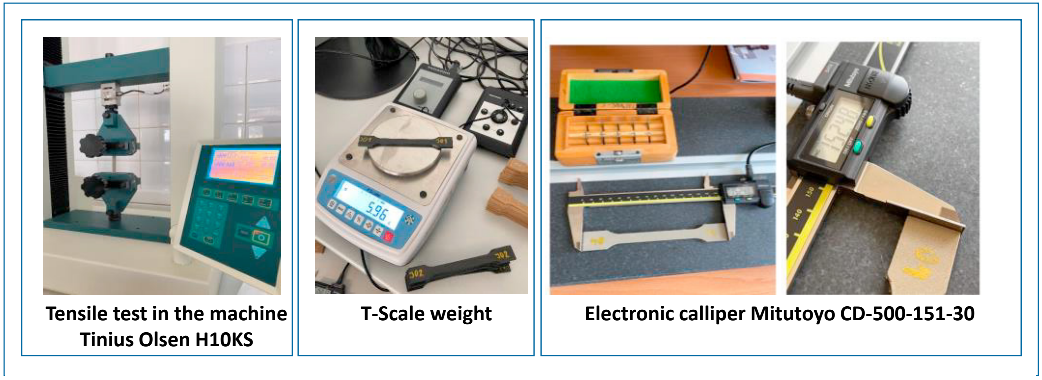
Tensile test in the machine Tinius Olsen H10KS
T-Scale weight
Electronic calliper Mitutoyo CD-500-151-30

Fig. 3. Measurement Systems

A: Analyse – P3: Analyse the causes: The fourth phase of the project involved designing, testing and optimising the process to align with customer needs, using the design of experiments (DOE) methodology [22] [23]. By the end of this phase, prototypes were created and assessed to ensure they align with the optimal design. The process consisted of the following steps:

Identification of factors to analyse: In this phase, a deeper understanding of the process was cultivated, and the best design concepts were developed to respond to the customer's requirements. The purpose was to generate variations in input variables for each CTQ parameter, assess these variations and combine the best attributes of these variables to create the final design. This stage was focused on the 3D printing machine, as the critical characteristics of the product stem from it. The integrity and strength of FFF construction parts hinge on the process parameters. To comprehend how these parameters affect the performance and quality of parts produced by FFF, their influence must be studied. Numerous studies [20]have investigated this issue, analysing the critical parameters of FFF for different quality characteristics of the parts. Table 3 outlines the most crucial controllable input variables and selected levels for testing.

Table 3. Most relevant controllable input variables and their testing levels [24]

N.º	Variable	Levels to be tested	
A	Layer thickness [mm]	0.1	0.3
B	Number of perimeters [n. º]	1	4
C	Extrusion width [mm]	0.4	0.8
D	Infill density [%]	15	45
E	Nozzle temperature [ºC]	205	217

Experimentation: In this phase, the DOE [22] method was utilised to define the experimental approach and determine the number of replicas necessary to calculate experimental error and analyse the significance of effects and interactions. The selection of this method was based on the number of controllable factors and the constraints inherent in the process. Typically, factorial design is the most efficient approach for experiments involving the effects of two or more factors. This design allows all possible combinations of factors levels to be investigated in each complete replicate of the experiment. The effect of a factor is defined as the change in response produced by a change in its level. A factorial design helps to identify interactions, thereby avoiding misleading conclusions. It also allows the effects of a factor to be estimated at several levels of the other factors, yielding conclusions that apply across a range of experimental conditions [22].

The choice of DOE depends on the experimental objective, resource limitations, costs or practical constraints [23]. In this case, a factorial design with k factors, each at two levels (i.e., a 2^k factorial design), was considered most suitable. With five controllable factors at two levels, one complete replicate of the 2^5 factorial design requires 32 runs. Another option would be to use a half fraction of the 2^5 design, where main effects and low-order interactions are explored by conducting only a fraction of the full factorial experiment. Fractional factorial designs are among the most widely used for process design, product improvement and industrial/business experimentation [22]. Previous research on vPLA used this design [24], which shares characteristics with the present study, allowing for comparisons of experimental outcomes. Hence, the $2^{(5-1)}$ fractional design of resolution V with two replicates was selected for the experiments, totalling 32 runs. Resolution V designs are powerful in that they allow for the unique estimation of all main effects and two-factor interactions, assuming all interactions involving three or more factors are negligible. The fractional factorial design was developed using Minitab 22 software, and at this stage, the samples were printed on the Prusa i3 MK3S printer and finally measured, weighed and tested in the Neksten laboratory.

Analysis: Once the measurements of the experimental parts were completed, the data were fitted to a model, and the effects of the main factors and interaction terms were estimated. For each response, the Pareto chart of the standardised effects, the normal plot of the standardised effects, main effects and interaction plots were analysed. This analysis provided insights into the influence of each variable on the results. The models and graphs for each analysed response were generated using Minitab 22 software. Figure 4 (a, b and c) illustrates the influence of each variable and its trends for output factors including width precision (Figure 4a), thickness precision (Figure 4b) and length precision (Figure 4c). The results indicate that the factors that had the greatest influence on width precision were the number of perimeters (B) and extrusion width (C). The number of perimeters (B) suggests greater precision at the lowest values, with extrusion width (C) at the highest level. Specifically, greater width precision is achieved with fewer perimeters and a higher extrusion width. For thickness precision, the key factors included layer thickness (A), extrusion width (C) and the number of perimeters (B), all of which had a positive effect in this study. In terms of length precision, the significant parameters were extrusion width (C) and layer thickness (A). As with thickness and width accuracy, the main effects plot demonstrates that length accuracy improved when both inputs were at the lowest levels.

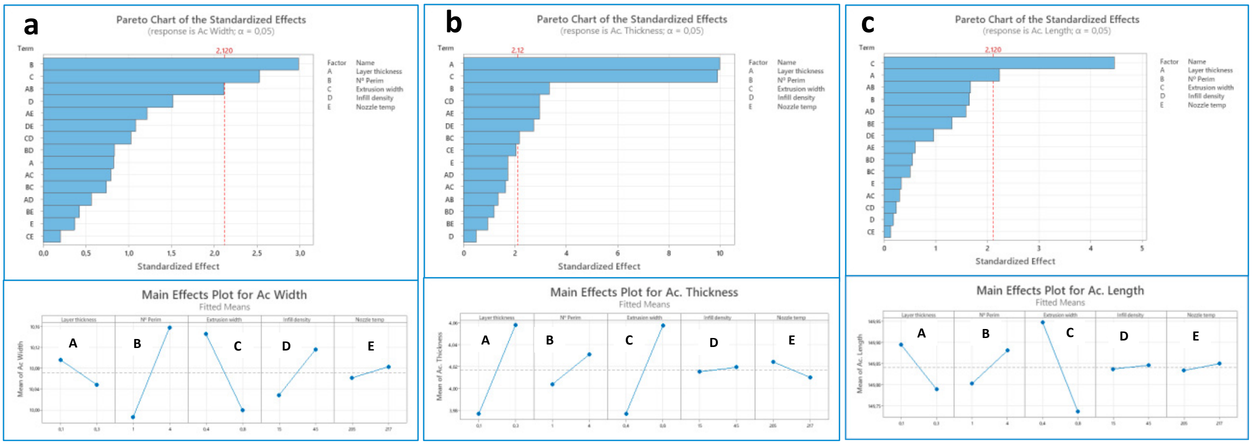

Figure 4: The influence of each variable and its trends for the output factors of width precision (Fig. 4a), thickness precision (Fig. 4b) and length precision (Fig. 4c)

In Figure 5 (a, b and c), the influence of mechanical characteristics and variables on the output factors are analysed, focusing on Young's modulus (Figure 5a), tensile stress at break (Figure 4b) and total elongation (Figure 5c). For Young's modulus, the number of perimeters (B), extrusion width (C), the interaction between B and C and infill density (D) all had significant effects. In the case of tensile stress at break, similar variables exerted a significant influence. The number of perimeters (B) and extrusion width (C) were primary factors affecting tensile stress.

Additionally, infill density (D) and nozzle temperature (E) had significant positive effects on tensile stress. Conversely, layer thickness (A) exhibited a significant negative effect, with increasing thickness resulting in reduced tensile stress at break. For total elongation, the response shows that layer thickness (A) interacting with nozzle temperature (E), along with infill density (D), the number of perimeters (B) and extrusion width (C) are important contributors. A higher number of perimeters (B) and infill density substantially increased elongation. In contrast, a higher extrusion width (B) tended to reduce elongation, indicating a trade-off between part rigidity and flexibility.

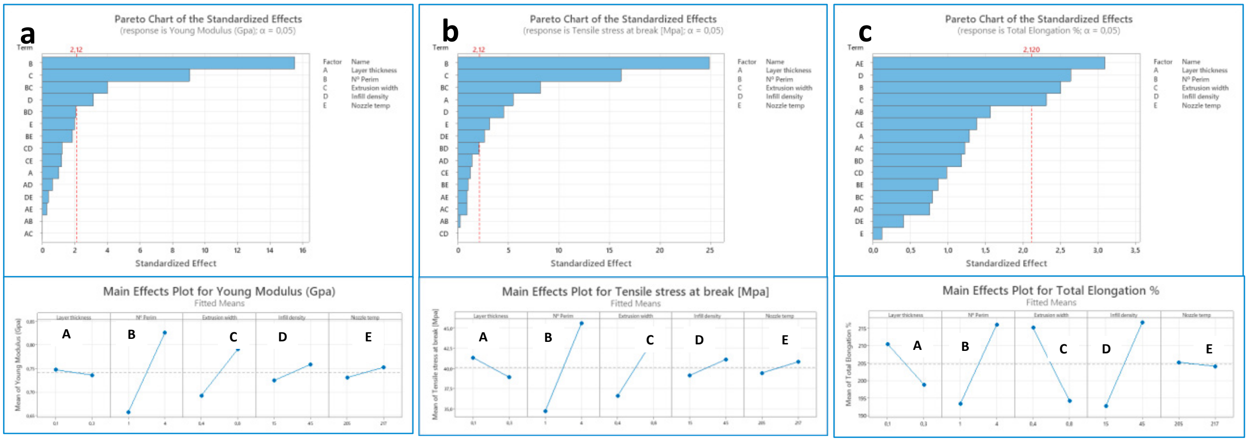

Fig. 5. The level of influence of each the mechanical characteristics, variable and its trends for the output factors of in the case of Young's modulus (Fig. 5a), tensile stress at break (Fig. 4b) and total elongation (Fig. 5c)

I: Implement – P4: Plan and implement solutions. The optimisation of the responses was achieved by minimising the significant negative effects identified during the analysis. Using Minitab 22 software, optimal levels for each parameter were defined, considering all the responses. Table 4 illustrates the proposed optimisation settings, showing the levels to be programmed for each variable to maximise performance. These optimisations were compared against the settings used for Prusa vPLA, ensuring the most efficient use of parameters for superior material and print quality.

Table 4. Most relevant controllable input variables and their testing levels [24]

N.º	Variable	vPLA (PRUSA)	Value proposed Minitab 22 rPLA (TUKE)	Valued used for tested rPLA (TUKE)
A	Layer thickness [mm]	0.2	0.28	0.3
B	Number of perimeters [n. º]	2	1.78	2
C	Extrusion width [mm]	0.45	0.4	0.4
D	Infill density [%]	15	15	15
E	Nozzle temperature [ºC]	215	205	205

C: Control – P5: Check results, P6: Standardise results and **P7: Reflection on the process and following problems.** Once the significant factors that affect the process were defined and the levels that improve response were identified, 10 final parts were printed to verify compliance with the CTQs.

Table 5. Comparison of CTQ results between vPLA (PRUSA) and rPLA (TUKE)

	Mean		Standard deviation		Difference		
	vPLA (PRUSA)	rPLA (TUKE)	vPLA (PRUSA)	rPLA(TUKE)	Trend	Quantity	Percentage
Young's modulus [Gpa]	0.6261	0.6774	0.01591	0.02007	↑	0.0513	8.2 %
Tensile stress at break [Mpa]	30.94	30.75	1.435	0.6972	↓	0.19	0.6 %
Elongation [%]	183.7	243.4	17.36	19.28	↑	59.7	32.5 %
Thickness	0.045	0.208	0.04565	0.03048	↑	0.163	362.2 %
Length	0.1	0.2	0.1311	0.07031	↑	0.1	100 %
Width	0.023	0.04	0.012	0.01958	↑	0.017	73.9 %
Price [€]	0.14	0.1611	0.0005	0.0008	↑	0.0211	15.1 %

Table 5 summarises the means and standard deviation for each result obtained with the optimal configuration from this DOE, rPLA (TUKE), compared with the configuration recommended by the producer of the analysed material, vPLA (PRUSA). In the case of Young's modulus, the average increased by 8%, compared with the vPLA (PRUSA) configuration, although the standard deviation was slightly larger with the rPLA (TUKE) configuration. For tensile stress at break, the mean value with rPLA (TUKE) decreased by 0.6%, but the results were more centralised than with the producer's configuration, indicating greater consistency. Regarding elongation, the positive trend was significant, with an increase of 32.5% compared with vPLA (PRUSA). However, for the three dimensions of precision – thickness, length and width – there was a visible negative impact of rPLA (TUKE) fit on accuracy. Despite this, in terms of weight and price, the rPLA (TUKE) solution is 15.1% more expensive than the vPLA (PRUSA) solution, but this deviation is considered acceptable. The team defined new work standards for the 3D printer and printed a batch of easy masks with these parameters, confirming that the work objectives were achieved and maintained. The following parameters were established for the new printing process using recycled material: nozzle temperature: 205 ºC; layer thickness: 0.28 mm; extrusion width: 0.4 mm; filling density: 15%; and number of perimeters: 2.

5. Conclusion

This research successfully designed and implemented a methodology to experimentally verify the use of environmentally sustainable rPLA filament for printing face-shield frames using FFF technology. By applying the QDF methodology, customer requirements were translated into CTQ characteristics, such as Young's modulus, tensile stress at break, total elongation, weight, width precision, length precision, thickness accuracy and price. Following the LSS methodology helped identify the process factors that most influence CTQ responses, including layer thickness, number of perimeters, extrusion width, infill density, nozzle temperature, ambient temperature and humidity. Using DOE, the optimal combination of input factors levels was determined to meet the desired CTQ characteristics, and they were tested with rPLA material provided by PRUSA. While the initial optimisation yielded highly precise results, maximised the modulus of elasticity, tensile stress at break, total elongation and minimised printing time and weight, this approach was found to be unprofitable due to increased weight and longer printing times. However, the verification of the PRUSA rPLA parts demonstrated improvements in Young's modulus (8.2%) and elongation (32.5%), two of the most important CTQ characteristics for the customer. Although some attributes, particularly accuracy, decreased with this new configuration, the results showed that recycled PLA (rPLA) filaments can achieve comparable or even superior characteristics to virgin PLA (vPLA) in certain areas, effectively closing the loop in the PLA life cycle.

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