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EFFECTIVE MANAGEMENT OF KEY VARIABLES IN THE 3D PRINTING PROCESS OF PULLEY-WHEEL

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Purpose: The aim of the study is to systematically compile information on 3D printing and provide an overview of how various parameters and factors in the technological process interrelate, particularly focusing on their impact on the final manufacturing time and filament consumption. This research seeks to enhance efficiency and optimize resource utilization in the realm of 3D printing technology.
Design/methodology/approach: The objectives are attained through a comprehensive review of the literature aimed at systematizing, describing, and highlighting important parameters within 3D printing technology. The management of the process is facilitated by specialized software capable of capturing process parameter values and analyzing their impact on both the manufacturing time and filament consumption during 3D printing. This approach leverages software tools to effectively control and optimize the 3D printing process, enabling a detailed examination of how specific parameters influence key out comes such as production time and material usage.
Key findings: In the scope of paper is analysis the influence of 3D printing parameters on the final time in the technological process. The parameters are juxtaposed in the form of tables and charts – it allows find significant parameters which mainly decide about manufacturing time of printing elements and material consumption.
Research limitations/implications: The limitation of the study is information about the mechanical properties of manufactured elements depends on the parameters of the 3D printing process. Future investigations should be based on the durability of the final 3D-printed object depending on loading conditions.
Practical implications: The presented study show the dependency between parameters of 3D printing process, final time manufacturing and consumption of filaments. In practice the consumption of material and correctly select of parameters to 3D printing is economical important due to costs.
Originality/value: The paper introduces a novel description of 3D printing factors and provides insightful considerations regarding the final manufacturing time of elements produced through additive technologies. By delving into the intricate relationship between various factors influencing 3D printing processes, this research offers a fresh perspective on optimizing manufacturing time and efficiency.

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Keywords: 3D Printing, process, influence, parameters, final-time, material consumption, analysis, management, pulley-wheel.
Category of the paper: Research paper.

1. Introduction

Additive technologies, also known as additive manufacturing or 3D printing, encompass a group of innovative processes that build objects layer by layer using digital 3D models (Jared et al., 2017; Prakash et al., 2018; Zhang et al., 2018). Unlike traditional subtractive manufacturing methods that involve cutting away material from a solid block, additive technologies add material sequentially to create complex shapes and structures with precision and efficiency. This approach offers several advantages, including reduced material waste, increased design flexibility, and the ability to produce customized or intricate parts (Mellor et al., 2014; Zhai et al., 2014).

In terms of individual case management, additive technologies present an excellent choice due to their adaptability and versatility. They enable the rapid prototyping of concepts, allowing individuals to iterate designs quickly and efficiently. This is particularly advantageous for entrepreneurs or innovators seeking to develop and test new products or concepts before committing to full-scale production. Additionally, additive technologies support decentralized manufacturing, enabling localized production and reducing the need for extensive supply chains. This can be highly beneficial for individuals or small businesses looking to reduce logistical complexities and lead times associated with traditional manufacturing processes. For individuals seeking customized solutions or one-off production runs, additive technologies offer a cost-effective and viable alternative. The ability to produce unique, personalized items on demand opens up new opportunities for small-scale production and customization in various industries, from healthcare to consumer goods (Jared et al., 2017; Li et al., 2017).

The research presents a novel and systematic analysis of the key variables in the 3D printing process of pulley-wheels, focusing specifically on how these variables impact final manufacturing time and filament consumption. The interrelationships among various parameters such as temperature, accuracy and resolution, and infill pattern and density were precisely examined. The identified critical factors that influence production efficiency and material usage, providing valuable insights that can enhance decision-making and optimize resource utilization in 3D printing.

Previous studies in the field of 3D printing have generally explored the impact of individual parameters on specific aspects of the printing process (Mao et al., 2017; Tetsuka, Shin, 2020; Wang et al., 2020). Researchers have identified that factors like layer height, infill density, and print speed significantly affect print quality, strength, and time. However, these studies often lack a comprehensive approach to understanding the combined effects of these parameters on both time and material consumption (Ansari, Kamil, 2021; Loflin et al., 2019; Rismalia et al., 2019; H. Zhang et al., 2022).

Research presented in this paper builds on this existing knowledge by offering a holistic view of how these variables interact. The new findings by specifically quantifying the impact of each parameter on the overall efficiency of the 3D printing process, providing a more integrated understanding that can directly inform practical applications and optimization strategies.

Overall, the adoption of additive technologies for individual case management represents a forward-thinking approach that aligns with the principles of sustainability, innovation, and agility in manufacturing and product development. As these technologies continue to evolve and become more accessible, their impact on individual creators and entrepreneurs is expected to grow, empowering individuals to bring their ideas to life in a more efficient and impactful manner. The examples of applications additive technologies in practice can be automotive parts reproduction (Dalpadulo et al., 2022), regeneration components of machines (Sawczuk et al., 2023) or as a helpful technology that can be used for individual cases in the scope of the irregular and complex shapes overlays fit to reinforcing structural elements with the notches and open-holes (Romanowicz et al., 2022, 2024).

2. Types of 3D printing technologies – description different techniques

The realm of 3D printing technologies is in a constant state of evolution, spurred by advancements in materials, hardware, and software. Each printing technique presents unique advantages and specialized capabilities, tailored to meet the diverse demands of industries spanning aerospace, healthcare, fashion, and art. As accessibility and versatility of these technologies expand, they unlock boundless possibilities for crafting intricate, customized, and functional objects. This transformative potential holds the promise of fundamentally reshaping the landscape of design, manufacturing, and innovation. The types of 3D printing technologies are presented in the figure (Figure 1).

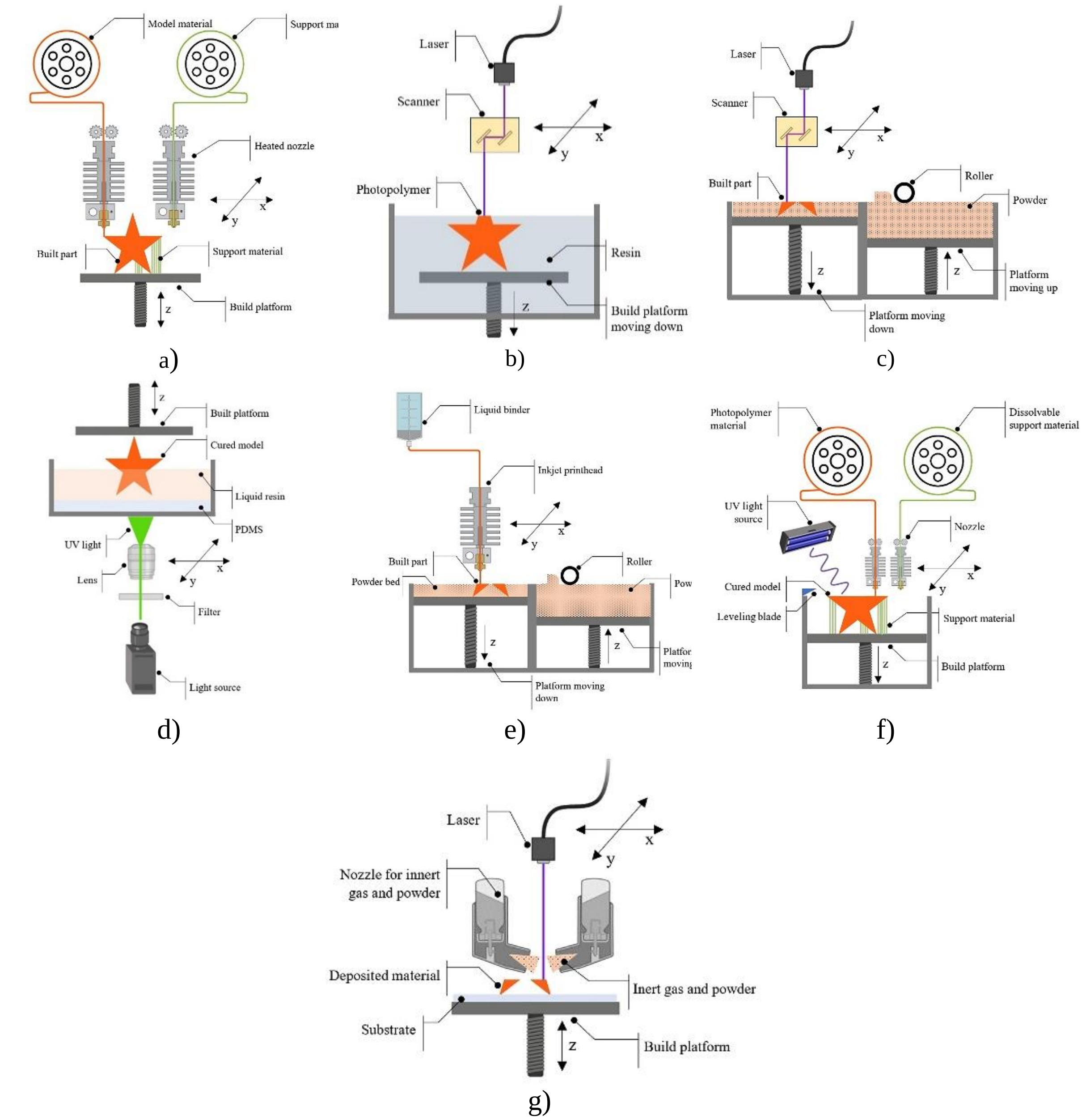


Figure 1. Schematic drawings illustrating the principle of operation of individual 3D printing techniques: a) FDM/FFF, b) SLA, c) SLS, d) DLP, e) BJT, f) MJ3D, g) DED.

Sources: Own work.

Currently, there are several 3D printing techniques in widespread use, each differing in principle of operation and application area.

2.1. Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) printing technology is also known as Fused Filament Fabrication (FFF) (Szmidt, Rębosz-Kurdek, 2017). This is one of the most common and accessible 3D printing techniques. In FDM, a thermoplastic filament is heated and extruded through a nozzle that moves along predefined paths to create layers. These layers quickly solidify upon deposition, gradually building up the desired object (Figure 1a). FDM printers are widely used for rapid prototyping, functional part production, and educational purposes due to their affordability and ease of use (Dudek, 2013; Jared et al., 2017; Kristiawan et al., 2021; Li et al., 2017). Key advantages of FDM include low material waste, support for a wide range of thermoplastics, and the ability to produce functional prototypes and end-use parts with decent strength and durability. However, FDM parts may exhibit visible layer lines, and intricate geometries can be challenging to achieve due to nozzle size limitations (Ćwikła et al., 2017).

2.2. Stereolithography (SLA)

Stereolithography (SLA) utilizes a process called photopolymerization to create objects layer by layer. A UV laser selectively cures liquid photopolymer resin according to the cross-sectional shape of the object, which is dictated by a digital model sliced into layers (Figure 1b). SLA produces highly detailed and smooth parts with excellent surface finish, making it ideal for applications requiring intricate details and fine features (Ćwikła et al., 2017; Deshmane et al., 2021; Manapat et al., 2017). The SLA is commonly used in industries such as jewelry, dentistry, and product design where aesthetics and precision are paramount. However, SLA resins can be relatively expensive, and post-processing steps such as curing and resin removal are required (Maines et al., 2021).

2.3. Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) involves using a high-powered laser to selectively fuse powdered material (typically nylon, polyamide, or metal) into solid layers based on a digital model. Unlike FDM and SLA, SLS does not require support structures as the unsintered powder acts as self-supporting material during printing (Awad et al., 2020; Charoo et al., 2020) (Figure 1c).

SLS is renowned for its ability to produce robust and functional parts with complex geometries, making it a preferred choice for manufacturing end-use components, tooling, and parts for aerospace and automotive applications. The versatility of materials available for SLS, including engineering-grade thermoplastics and metal powders, contributes to its wide-ranging utility.

2.4. Digital Light Processing (DLP)

Digital Light Processing (DLP) is similar to SLA but uses a different light source and projection method to cure photopolymer resin (Figure 1d). DLP printers utilize a digital micromirror device (DMD) or liquid crystal display (LCD) to project an entire layer of the object simultaneously, offering faster print speeds compared to traditional SLA (Chaudhary et al., 2023).

DLP is favored for its speed and efficiency in producing high-resolution parts, making it suitable for applications in dentistry, jewelry, and consumer electronics prototyping. However, DLP may exhibit a lower surface quality compared to SLA due to the pixelated nature of the light projection (Zhao et al., 2020).

2.5. Binder Jetting (BJT)

In binder jetting, a print head selectively deposits a liquid binding agent onto a thin layer of powder material (such as gypsum, metal, or ceramic), solidifying it to form the desired shape. After each layer is printed, a new layer of powder is spread over the previous one, and the process repeats until the object is complete (Gibson et al., 2021a; Ziaee, Crane, 2019) (Figure 1e).

Binder jetting is generally faster compared to some other 3D printing techniques, such as selective laser sintering (SLS) or stereolithography (SLA). This is because it does not require a laser to selectively sinter or cure each layer, but rather uses inkjet printheads to quickly deposit binding agents onto powder layers. This technique is s well-suited for printing large objects or multiple parts simultaneously due to its ability to spread a new layer of powder over a wide build area after each layer is printed. This makes it an efficient option for producing large-scale prototypes or parts especially complex geometries with intricate internal structures without the need for support structures. This is because the surrounding powder acts as a natural support during the printing process, enabling the fabrication of intricate designs with minimal post-processing (M. Li et al., 2020).

2.6. Material Jetting (MJ3D)

Material jetting, also known as PolyJet or MultiJet, operates similarly to traditional inkjet printing. It uses multiple print heads to jet layers of photopolymer materials onto a build platform. These materials are then cured with UV light to solidify them (Figure 1f). Material jetting can produce highly detailed and multi-material objects with varying properties, making it useful for creating prototypes with realistic textures and colors (Gibson et al., 2021b).

Material jetting supports a variety of materials, including photopolymers with different mechanical, optical, and thermal properties. This versatility allows for the production of prototypes with specific material requirements, such as flexibility, transparency, or heat resistance. Material jetting systems are capable of achieving high dimensional accuracy and repeatability, ensuring that printed parts match the intended design specifications. This reliability is important for applications where precision is critical, such as in the aerospace or medical industries (Elkaseer et al., 2022).

2.7. Directed Energy Deposition (DED)

DED is an additive manufacturing technique that involves melting metal powder or wire using a high-energy source, such as a laser or an electron beam, and depositing it onto a substrate (Figure 1g). This process is often used for repairing or adding material to existing components, as well as for creating large, complex metal parts directly from CAD models (Gibson et al., 2015).

DED can be a rapid manufacturing process, especially for larger parts, due to its ability to deposit material quickly using high-energy sources like lasers or electron beams. This 3D printing technique is capable of working with a wide range of materials, including metals, polymers, ceramics, and composites. This versatility allows for the production of parts with diverse properties and functionalities, it is often used for repairing or adding material to existing components, making it valuable for industries such as aerospace, automotive, and tooling where part repair and remanufacturing are common (Elkaseer et al., 2022; Saboori et al., 2019).

3. Comparison of 3D Printing Technologies − review

By examining factors such as printing speed, resolution, material compatibility, and cost-effectiveness, we seek to guide readers in making informed decisions when selecting the most suitable method for their specific needs. Through this exploration, we aim to shed light on the ever-expanding landscape of additive manufacturing and its profound impact on modern industry and innovation. Below, in the Table 1 the key parameters of selected 3D printing techniques are presented.

Table 1.
Comparison of selected 3D printing techniques

3D printing technique	Speed [mm/h]	Material Flexibility	Resolution [µm]	Complex geometries	Material waste	Surface finish	Post proce ssing	Equipmen t cost [x1000$]
FDM	40-150	Thermoplastics (PLA, ABS, etc.)	100-400	Limited	10-30%	++	++	0,2-10
SLA	20-100	Photopolymer resins	25-100	Yes	5-15%	+++	+	3-100
SLS	10-100	Plastics, metals, and ceramics	50-200	Yes	5-15%	++	++	100-1000
DLP	50-200	Photopolymer resins	25-100	Yes	5-15%	+++	+	5-250
BJT	100-1000	Gypsum, metals, and ceramics	50-150	Moderate	20-40%	+	+++	10-500
MJ3D	20-1000	Photopolymer resins	16-30	Yes	5-15%	+++	+	20-500
DED	100-1000	Metals, polymers, and composites	100-500	Yes	5-15%	++	++	100-2000

Source: Own elaboration on the basis (Kuang et al., 2018; Low et al., 2017; Mao et al., 2017; Tan et al., 2017; Tetsuka, Shin, 2020; Wang et al., 2020).

Energy consumption is a critical consideration in selecting the appropriate 3D printing method due to its direct impact on operational costs and environmental sustainability. High energy consumption can significantly increase production expenses, especially for large-scale manufacturing operations. Additionally, minimizing energy usage aligns with broader sustainability goals, making it imperative to choose printing techniques that strike a balance between energy efficiency and production requirements. By opting for 3D printing technologies with lower energy consumption, businesses can reduce their carbon footprint and contribute to a more sustainable manufacturing ecosystem. Estimated energy consumption values for individual types of 3D printing are presented in Table 2.

3D printing technique	Power consumption [W/h]
FDM	50-250
SLA	100-500
SLS	500-2000
DLP	100-600
BJT	100-500
MJ3D	500-1500
DED	1000-5000

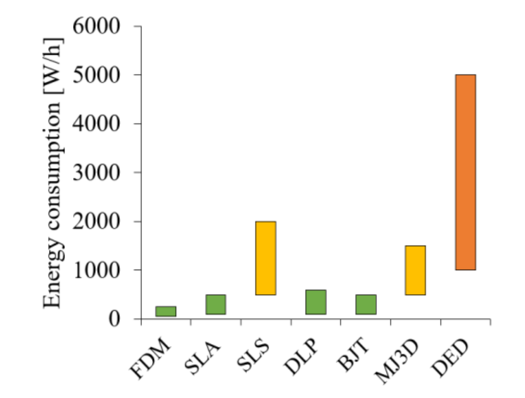


Figure 2. Estimated energy consumption of operation for individual types of 3D printing technologies.

Source: Own elaboration base on the (Annibaldi, Rotilio, 2019; Hopkins et al., 2021; Kreiger, Pearce, 2013; Nyika et al., 2022).

4. Technology of 3D printing – significant economical, ecological and management issues

In recent years, 3D printing technology has emerged as a transformative force in manufacturing, offering unique advantages and posing distinct challenges across economic, ecological, and management spheres (Liu et al., 2016).

One significant economic parameter in 3D printing is production speed. The speed of printing directly affects production throughput and operational efficiency (Oropallo, Piegl, 2016). Faster printing speeds reduce manufacturing lead times, enabling businesses to meet customer demands more effectively. However, it's important to balance speed with print quality to ensure that accelerated printing does not compromise the structural integrity or accuracy of the printed objects. Cost effectiveness is a critical consideration in 3D printing. While the technology offers the potential for localized and on-demand production, the initial costs of acquiring 3D printers and materials can be substantial. Additionally, ongoing operational costs, including maintenance, material consumption, and energy usage, must be carefully managed to optimize cost efficiency. Businesses must evaluate the total cost of ownership against traditional manufacturing methods to determine the economic viability of 3D printing for their specific applications.

The main ecological issue associated with 3D printing is material waste. Traditional subtractive manufacturing processes often generate significant waste through machining and cutting. In contrast, 3D printing can significantly reduce material waste by only using the necessary amount of raw material to build the object (Cendrero et al., 2021; Unruh, 2018). However, challenges remain in optimizing material efficiency and recycling or reusing post-production waste to minimize environmental impact. The ecological impact of 3D printing also extends to energy consumption. The energy requirements of 3D printers vary depending on the technology used (e.g., FDM, SLA, SLS) and the size and complexity of the printed objects. Sustainable practices involve optimizing print settings to minimize energy consumption without compromising print quality. Furthermore, advancements in energy-efficient 3D printing technologies, such as using renewable energy sources, can further reduce the ecological footprint of this manufacturing process (Zhu et al., 2021).

Effective management of 3D printing encompasses design complexity and optimization. Leveraging the design freedom offered by additive manufacturing requires expertise in CAD (Computer-Aided Design) software and an understanding of material properties. Design optimization for 3D printing involves considerations such as minimizing support structures, reducing material usage, and optimizing part orientation to enhance print quality and efficiency (Liu et al., 2016).

The economic, ecological, and management parameters discussed highlight the multifaceted considerations associated with the adoption and implementation of 3D printing technology. By strategically addressing these parameters, businesses can maximize the potential of 3D printing to drive innovation, reduce costs, and minimize environmental impact across diverse industries. Ongoing advancements in technology and sustainable practices will continue to shape the future landscape of additive manufacturing and its role in modern manufacturing ecosystems.

5. Materials and methods

In this paper, the printing optimization process was conducted for FDM technology using the software of BCN3D Stratos dedicated for Epsilon W27 3D printer. The Epsilon W27 is manufactured by BCN3D Technologies (Barcelona, Spain), renowned for its reliability and precision in industrial-grade printing (Migliore, 2023). Polylactic Acid (PLA) filament (BCN3D) with a diameter of 2.85mm was selected as the printing material due to its wide availability, affordability, and ease of use. PLA is known for its biodegradability and low tendency to warp, making it suitable for printing large and complex objects taking into account ecological aspects (Witko, 2019; Witko et al., 2020). The printer offers a workspace with dimensions of 420x300x220mm and the best printing resolution equal 150μm (*Epsilon W27*, 2023).

The slicing and preparation of the 3D model for printing were performed using Stratos software (BCN3D Technologies, Barcelona, Spain). This software allows precise control over printing parameters such as layer height, infill density, and print speed, essential for optimizing the printing process (*BCN3D Stratos*, 2023). The 3D model of the pulley was created using computer-aided design (CAD) software – Inventor (Autodesk CA, USA). The printing process environment was controlled to minimize factors such as temperature fluctuations, drafts, and dust accumulation, which could adversely affect print quality. The printer was operated in a well-ventilated, airconditioned clean, and stable environment conducive to optimal printing conditions.

In the first phase of investigations is attempting pulley wheel 3D printing in the two variants – with and without supports of printing element. The aim of the this step is verification of possibility printing the diagonal surfaces of the pulley wheel. In the next phase the series of simulations were conducted by using Stratos Software to optimize the printing parameters for the Epsilon W27 printer. Parameters including layer height, infill density, printing temperature, and print speed were systematically varied to determine their impact on print quality and structural integrity. Prior to printing the pulley, the printer was calibrated to ensure accurate extrusion, bed leveling, and nozzle alignment. Before the process of 3D printing of elements, the important activity is device calibration. This step ensures the dimensional accuracy and adhesion of successive layers during the printing process. The printing temperature of the nozzle and build plate in Stratos Software for the PLA filament was set as per the filament manufacturer's recommendations.

Data obtained from the Stratos Software, including printing time and material consumption, were analyzed statistically to assess the effectiveness of the optimization efforts and identify areas for further improvement.

6. The Pulley-Wheel – Engineering Object of the Study

In the scope of the study is an engineering case in the form of the pulley wheel. The common method of transmitting power and torque from one shaft to another is using gear in the form of driving belt. Generally, in engineering practice, the pulley-wheel is one of the power and torque transmission possibilities. To get a simple transmission mechanism usually needs two pulley-wheels with shafts and a connection them by the driving belt. The pulley wheels are distanced away from each other and keyed to the shafts. To transmit power between two pulleys there must be a difference in tension of the belt on either side of the driving and driven pulleys. In the Figure 3 presented the kinds of belt and chain transmissions (Bird, Chivers, 1993).

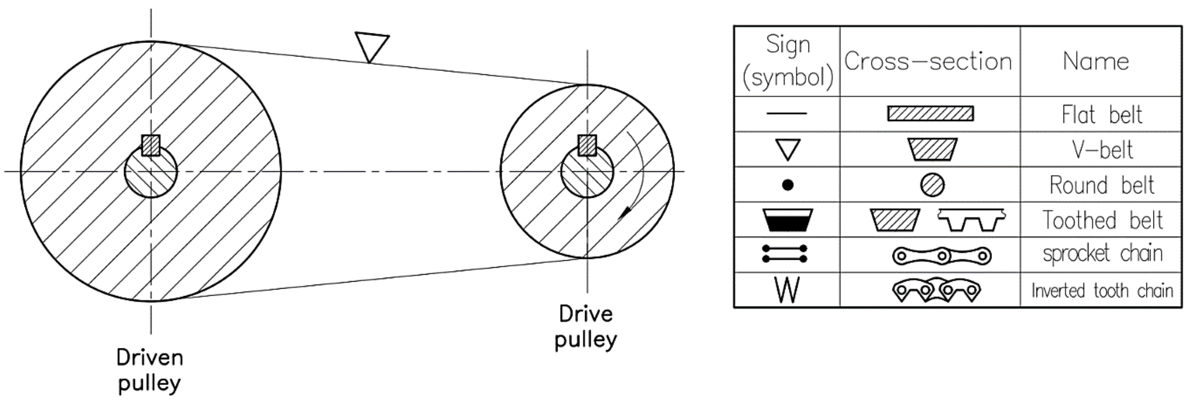


Figure 3. The scheme of the various types of transmissions.

Source: Own elaboration based on the (Grzelak et al., 2023).

The belt drive systems are an effective mean for power transmission which offer the advantages of easy installation, low maintenance, high reliability, adaptability to nonparallel drive, and high transmission speeds. Unfortunately, belt-drives also have disadvantages in the form power transmission capacity and limited speed ratio capability. Additionally, belt drives are less compact than either gear or chain drives and are susceptible to changes in environmental conditions such as contamination with lubricants. The important issue is impact of vibration and shock loading can damage belts (Childs, 2021).

The typical application of this type of mechanism includes several branches of industry as mechanical, electric, hydraulic and pneumatic. Examples can be an electric motor driving a line of shafting and an engine driving a rotating saw. In this paper, authors try to attempt to renewable the simple one groove-row pulley with belt drive for the AC generator set. The drive of the transmission is intended for use with a single V-belt type according to DIN 2215 – profile A. The pulley-wheel groove belt is designed according to DIN 2211 and the hub-groove is designed according to DIN 6885 and PN-70/M-85005.

The study's scope includes the process parameters of 3D printing influencing the final time and material consumption. Application additive technology in the form of 3D printing makes possible the creation of complex geometries with minimal material waste. The series of investigations are carried out based on the pulley-wheel presented in the Figure 4. The original technical draw with dimensions and geometric tolerances and descriptions is attached in the appendix in the form of Figure 10.

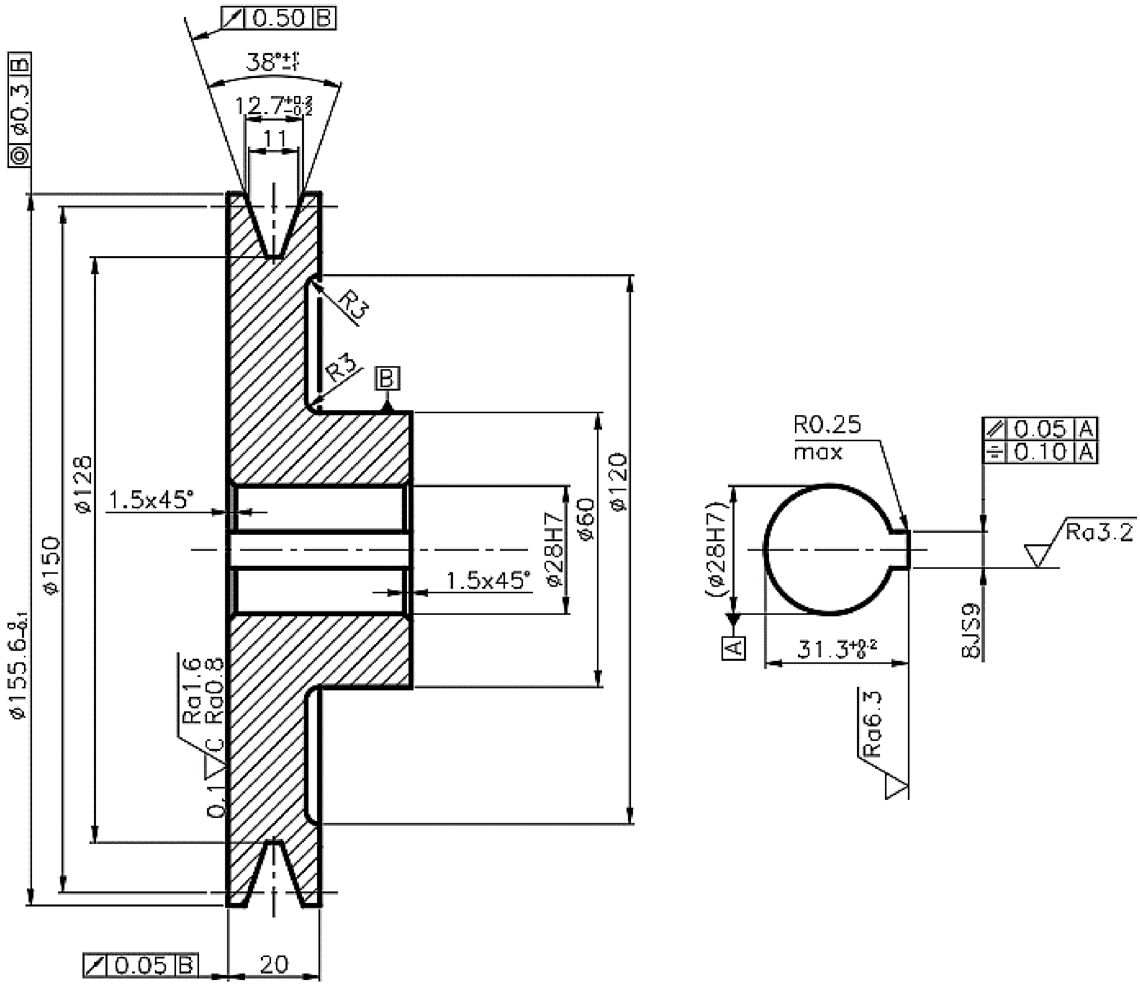


Figure 4. The technical draw of pulley-wheel and section of hub-groove.

Source: Own elaboration.

7. Influence of 3D printing parameters on the element manufacturing final time

Before the perform analysis parameters of 3D printing process verified possibility of manufacture the two prototypes of pulley-wheel. The first prototype was printed without additional and optional supports and the second one with water-soluble supports (BVOH filament). The first process was conducted only for PLA filament with constant parameters as speed v = 45mm/min, infill pattern in the form of I_P = grid with density I_D = 20%, resolution of printing in the form of layer height equal L_H = 0.3, temperature of extruder (T_E) for PLA 215°C, and bed-plate temperature T_B = 40°C for PLA. In the second case the support parameters of BVOH filament set as speed v = 20mm/min, temperature T_E = 210°C, heated-bed T_B = 60°C. Both of the models were printed without any problems in the form of polymer overhang on inclined surfaces. The examples of pulley-wheels are presented in the Figure 5.

a) b) c)

Figure 5. The pulley wheel (A) manufactured in the 3d printing process (additive technology): without supports (B) with water-soluble supports(C).

Source: Own elaboration.

In the first stage of investigations take extruder (T_E) and heated-bed (T_B) temperature and their influence on the final time (T) of process and material consumption. The material consumption is divided into two sections – weight material consumption (C_W) and length material consumption (C_L). The range of the PLA filament temperatures fit from 210°C to 225°C. The results of analyses are presented in the Table 3. In the cause of the use support material (BVOH) the build plate model is also printed from support material.

Table 3.
Influence temperatures of extruder (PLA filament) and bed-plate on the final time and material consumption in variants with and without supports

	TEMPERATURES		WITHOUT SUPPORTS			WITH SUPPORTS*		
	Extruder temperature	Heated-bed temperature	Time	Material consumption		Time	Material consumption	
No	T_E	T_B	T	C_W	C_L	T	C_W	C_L
	[°C]	[°C]	[min]	[g]	[m]	[min]	[g]	[m]
1	210	40	722	202	25,37	-	-	-
2		60	722	202	25,37	1009	247	30,87
3	215	40	722	202	25,37	-	-	-
4		60	722	202	25,37	1009	247	30,87
5	220	40	722	202	25,37	-	-	-
6		60	722	202	25,37	1009	247	30,87
7	225	40	722	202	25,37	-	-	-
8		60	722	202	25,37	1009	247	30,87

Other parameters with the constant value: resolution (layer height) L_H = 0.3; infill pattern I_P = grid, infill density I_D = 20%; build model plate: raft; PLA filament speed v = 45 mm/min; *supports (BVOH filament) printed with speed v = 20mm/min.

Source: Own elaboration.

The second stage is directed on the influence of 3D printing resolution. In the software the resolution is possible to set in the 3 base parameters described as layer height (L_H). The obtained results of simulations are presented in the Table 4.

Table 4.
Influence the resolution (level of accuracy) 3D printing on the final time and material consumption in variants with and without supports

No	RESOLUTION – LAYER HEIGHT	WITHOUT SUPPORTS			WITH SUPPORTS*		
		Time	Material consumption		Time	Material consumption	
	L_H	T	C_W	C_L	T	C_W	C_L
	[-]	[min]	[g]	[m]	[min]	[g]	[m]
1	0,15 (high accuracy)	1 186	152	19,06	1 813	183	22,66
2	0,20 (medium accuracy)	971	162	20,34	1 594	202	25,03
3	0,30 (low accuracy)	722	202	25,73	1 145	249	30,87

Other parameters with the constant value: infill pattern I_P = grid, infill density I_D = 20%; build model plate: raft; PLA filament speed v = 45 mm/min; PLA filament: extruder temperature T_E = 215°C, heated-bed temperature T_B = 40°C; *supports (BVOH filament) printed with speed v = 20mm/min; BVOH filament: extruder temperature T_E = 210°C, heated-bed temperature T_B = 60°C.

Source: Own elaboration.

In the terms of the infill the space of model it should be mentioned about different possibilities of the pattern choose. The pattern of infill space decide about strength of model in depending on the loading conditions but also of course from process final time and material consumption. The possible infill patterns using in additive technologies are presented in the Figure 6 and example of the percentage infill is presented in the Figure 7.

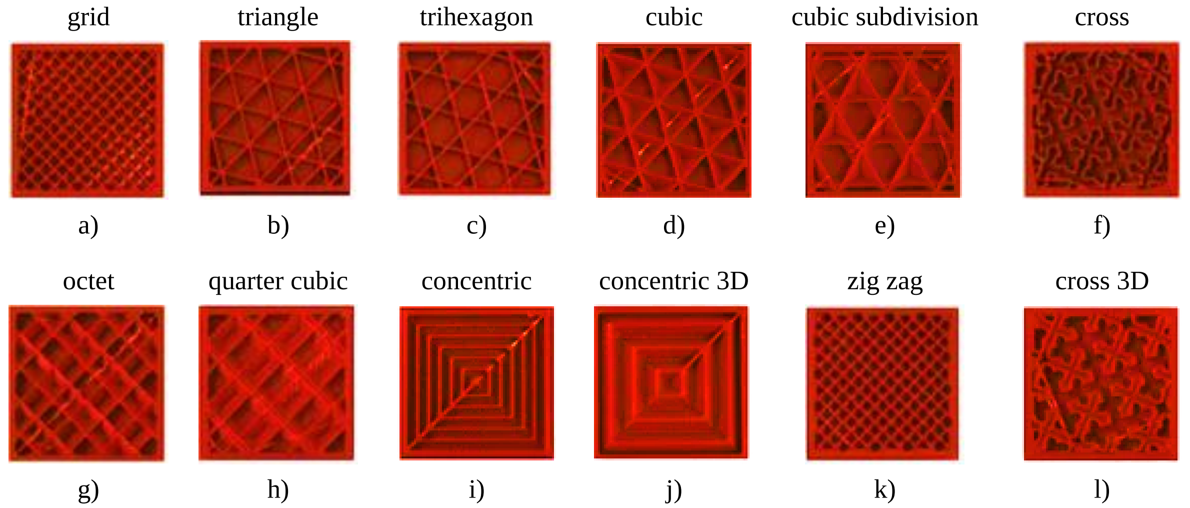
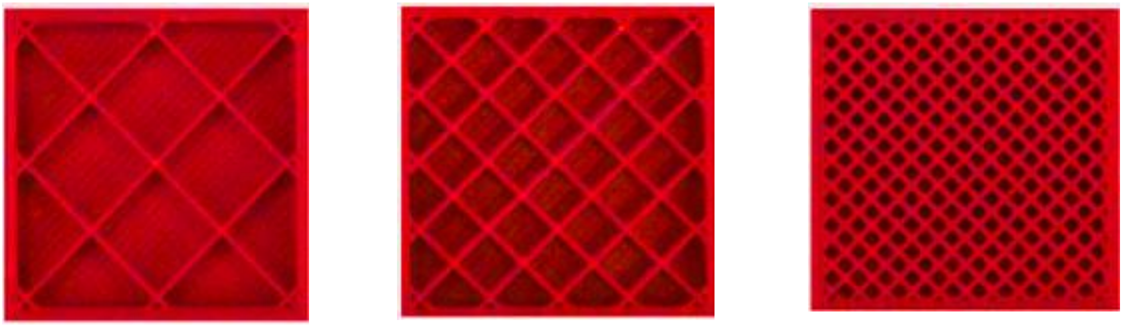


Figure 6. Various types of infill pattern.

Source: Own elaboration based on the (*BCN3D Stratos: 3D Printing Slicing Software - BCN3D Technologies*, 2024).



a) 10% infill b) 25% infill c) 50% infill

Figure 7. Examples density of infill grid pattern.

Source: Own elaboration based on the (*BCN3D Stratos: 3D Printing Slicing Software - BCN3D Technologies,* 2024).

To the analysis of 3D printing process of pulley wheel selected the most used patterns in the form of grid (Figure 6a), triangle (Figure 6b), trihexagon (Figure 6c) and concentric (Figure 6i) (Gonabadi et al., 2020; Kattel et al., 2023; Ma et al., 2021). The obtained results are presented in the Table 5.

Table 5.
Influence the infill pattern and percentage of fillings on the final time and material consumption in variants with and without supports

	INFILL		WITHOUT SUPPORTS			WITH SUPPORTS*		
	Infill Pattern	**Infill Density**	**Time**	**Material consumption**		**Time**	**Material consumption**	
No	**I_P**	**I_D**	**T**	**C_W**	**C_L**	**T**	**C_W**	**C_L**
	[-]	**[%]**	**[min]**	**[g]**	**[m]**	**[min]**	**[g]**	**[m]**
1	Without	0	556	143	17,93	979	190	23,44
2	Grid	10	643	173	21,69	1 066	219	27,19
3	Grid	25	759	217	27,22	1 183	264	32,72
4	Grid	50	952	291	36,49	1 375	338	41,99
5	Grid	75	1 142	365	45,76	1 565	411	51,27
6	Grid	100	1 328	438	54,88	1 751	484	60,39
7	Triangles	10	643	173	21,66	1 067	219	27,17
8	Triangles	25	761	217	27,20	1 184	263	32,70
9	Triangles	50	953	291	36,49	1 376	338	41,99
10	Triangles	75	1 143	365	45,78	1 566	412	51,28
11	Triangles	100	1 328	438	54,88	1 752	484	60,38
12	Trihexagon	10	639	173	21,65	1 063	219	27,15
13	Trihexagon	25	754	217	27,21	1 177	264	32,71
14	Trihexagon	50	944	291	36,48	1 368	337	41,98
15	Trihexagon	75	1 131	365	45,76	1 555	411	51,26
16	Trihexagon	100	1 315	438	54,88	1 739	484	60,38
17	Concentric	10	623	169	21,14	1 046	215	26,64
18	Concentric	25	738	213	26,69	1 162	259	32,20
19	Concentric	50	930	288	36,14	1 354	335	41,64
20	Concentric	75	1 121	364	45,64	1 544	410	51,14
21	Concentric	100	1 306	438	54,90	1 730	484	60,40

Other parameters with the constant value: resolution (layer height) $L_H = 0.3$; build model plate: raft; PLA filament speed v = 45 mm/min; PLA filament: extruder temperature T_E = 215°C, heated-bed temperature T_B = 40°C; *supports (BVOH filament) printed with speed v = 20mm/min; BVOH filament: extruder temperature T_E = 210°C, heated-bed temperature T_B = 60°C.

Source: Own elaboration.

In the third stage analyzed the influence and importance of build plate adhesion in the printing process (Lv et al., 2022; Jyothish Kumar et al., 2018). In the Figure 8 presented the examples of types of model build plates and in the Table 6 presented the obtained results. Every types of model build plates ensure the preliminary cleaning of the nozzle and adaptation to the printing conditions of the model. The skirt is the line printed around the model as the first layer – without connection. This type of build model plate purpose is help prime your extruder, obtain work temperature and establish a smooth flow of filament. The brim is the sequential of printed lines around the model with hold down the edges of the model. This type of model build plate prevent warping and displacements of model. It is faster and more saving material type of build plate than raft, but the weak point is possibility of separating from the model. The raft is horizontal latticework – the model will be printed on top of this raft, instead of directly on the build platform surface. This type build plate is recommended to stabilize model creating a stabilize foundation for the upper layers of model. The obtained results for different types of build plates of models are presented in the Table 6.

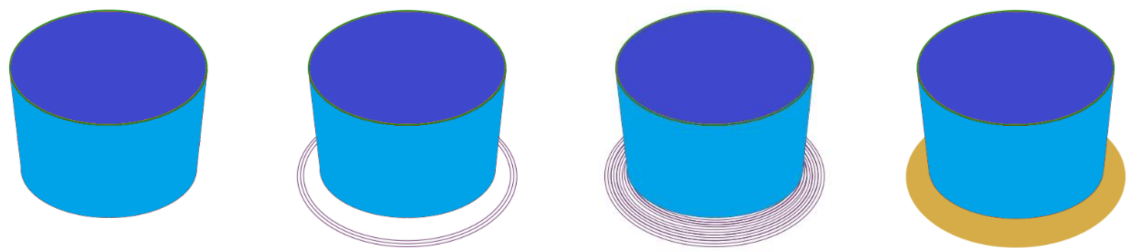


Figure 8. Examples of build model plate.

Source: Own elaboration based on the (*IdeaMaker Library: Find the Best IdeaMaker Profile for Your 3D Printer*, 2024).

Table 6.
Influence the build plate of model on the final time and material consumption in variants with and without supports

	BUILD PLATE ADHESION	WITHOUT SUPPORTS			WITH SUPPORTS*		
		Time	Material consumption		Time	Material consumption	
No	Type	T	C_W	C_L	T	C_W	C_L
	[-]	[min]	[g]	[m]	[min]	[g]	[m]
1	None	618	180	22,55	899	224	27,91
2	Skirt	619	180	22,58	902	225	27,97
3	Brim	624	181	22,68	905	225	28,03
4	Raft	722	202	25,37	1 145	249	30,87

Other parameters with the constant value: infill pattern I_P=grid, infill density I_D = 20%; resolution (layer height) L_H = 0.3; PLA filament speed v = 45 mm/min; PLA filament: extruder temperature T_E = 215°C, heated-bed temperature T_B = 40°C; *supports (BVOH filament) printed with speed v = 20mm/min; BVOH filament: extruder temperature T_E = 210°C, heated-bed temperature T_B = 60°C.

Source: Own elaboration.

8. Discussion

The final time and material consumption of pulley-wheel 3D printing process were the main aim of the performed analyses. The analyses included the four different variants for the selected parameters. In analyses one of the process the one parameter was the variable and the other parameters were constant values.

In the study of influence temperature there was no effect on final parameters (Table 3). The one important is that the bed-plate temperature of 40°C is dedicated for the PLA filament for the additive process without the supports. In the case of the printing supports the requirement is bed-plate temperature equal 60°C. It is caused by the use BVOH filament (water-soluble) dedicated for supports and build-plate type of model. The studies of various temperatures do not show changes of final parameters. The main differences concern 3D printing without and with supports. The final time is extended to ΔT = 287 [min] for the printing process with model supports. The material consumption in the case of use model supports is higher for the weight ΔC_W = 45 [g] and for the length ΔC_L = 5,50 [m].

The next issue of analysis is accuracy and resolution of the additive process (Table 4). The resolution can be defined as the single layer high. For the model with and without supports it should be noticed that the increase the accuracy influence on the longer time of process but it allows decrease material consumption. The difference of the final time of process between high and low resolution for model without supports equal ΔT = 464 [min] and with supports ΔT = 668 [min]. At the same time, higher resolution decreases the material consumption – for the high accuracy is possible saving weight equal ΔC_W = 50 [g], in resulting it saving length of filament equal ΔC_L = 6,67 [m]. For the 3D printing process of model with supports the differences are higher and amount to longer time ΔT = 668 [min] and saving material weight ΔC_W = 66 [g], and length of filament ΔC_L = 8,21 [m]. The differences between resolutions can be explained that, the excess of material on the edges of model which is caused by the effect of low accuracy. The high resolution (lower layer height) provides less material on the walls in the form of excess (lower imprecision). To sum up, increasing the resolution of 3D printing increases the final process time, but allows material savings.

The results of the influence infill pattern and infill density on the final investigated parameters of process are presented in the Table 5. The examples of the analysis data in the form of charts are presented in the Figure 9. The infill density growth is the main factor deciding about the final time and material consumption increase. The changes of the infill pattern are symbolic and do not constitute a significant variable for final time and material consumption. Additionally, it has to be noticed that, the strength of the selected infill patterns are not within the scope of consideration in the pulley-wheel case.

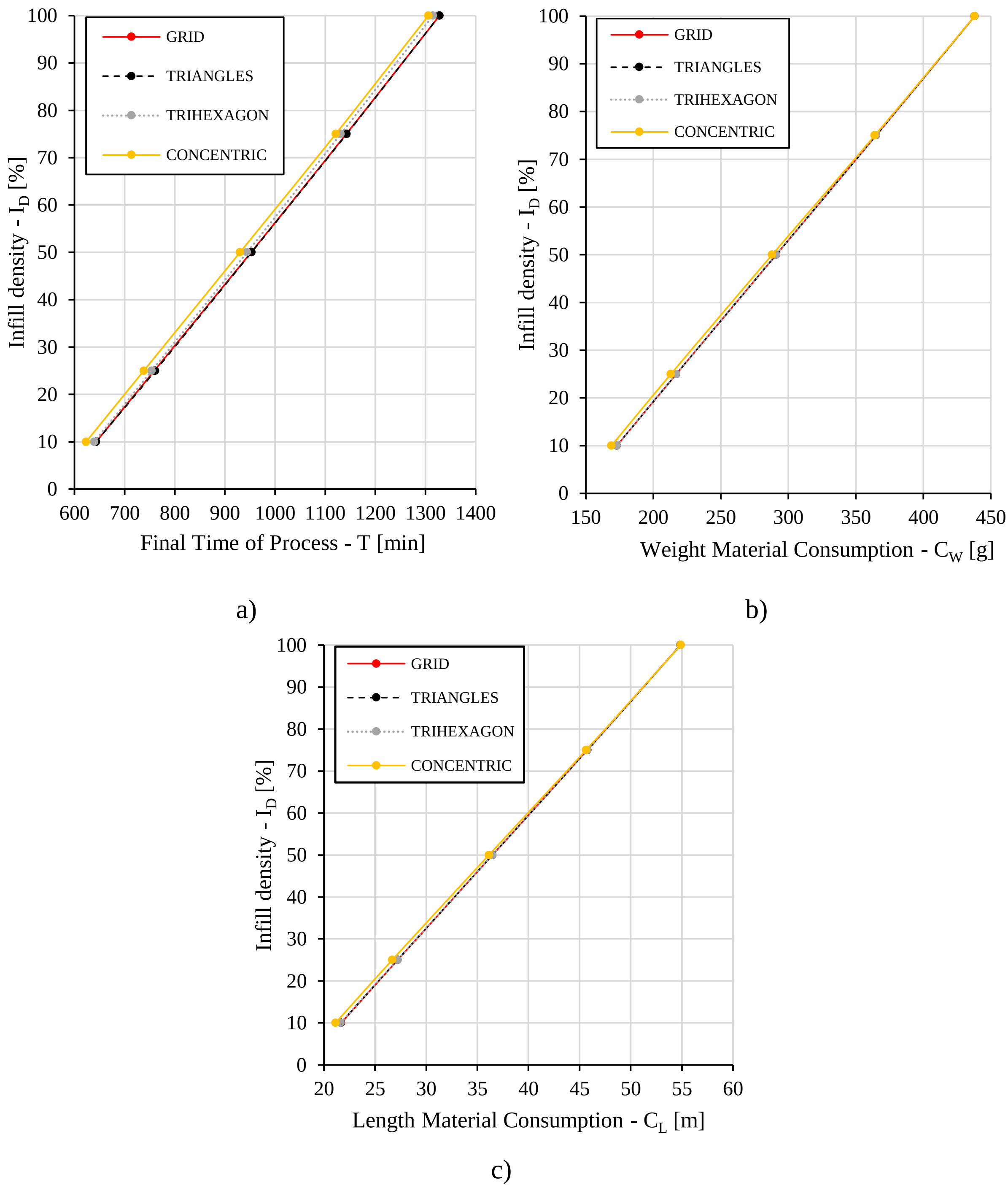


Figure 9. The influence of the infill pattern and infill density on the: final time of process – T (a); weight material consumption – C_W (b) and Length material consumption – C_L (c).

Source: Own elaboration.

For the analyses of build-plate of model noticed that, the raft build-plate is the most time and material consumption possibility (Table 6). Between the none and raft build-plate of model the difference of time is ΔT = 104 [min] and material weight and filament length consumption is C_W = 22 [g] and C_L = 2,82 [m], respectively. For the skirt and brim build-plates the differences of time and material are negligible in the compare to none build-plate. The range of the time is T = 1-6 [min] and for the material consumption C_W = 1 [g] and C_L = 0,03-0,13 [m].

The differences in the case of supports model are similar, although maintaining the same tendency.

The obtained results of the investigations have similarities and differences towards other scientific studies in the scope of the 3D printing as the additive technology. The similarities can be found in the previous studies and confirm that higher resolution (lower layer height) leads to longer print times but improves print quality and reduces material usage (Loflin et al., 2019). Additionally, the influence of infill density on print time and material consumption aligns with existing research, showing that higher infill densities significantly increase both time and material usage (Rismalia et al., 2019). The obtained results also show discrepancies and differences from other research works. Unlike some studies that suggested temperature variations might affect print outcomes, our analysis found that bed-plate temperature variations (within the tested range) had no significant effect on final manufacturing parameters (Magri et al., 2020; Schiavone et al., 2020; Vanaei et al., 2020). In addition, the present study uniquely highlights the negligible impact of infill pattern on time and material consumption, a factor often overlooked or assumed to be significant in earlier studies.

In the reference to presented study, the future investigations should be directed to mechanical properties and conditions of the loaded object. The scope of the attention should contain considerations about infill density and infill patterns. The determine of the mechanical properties in the form of tensile strength and yield stress in the simple tensile test for the dog-bone samples is required to draw further conclusions.

9. Conclusions

To sum up, from the conducted study and discussion several key conclusions can be drawn:

- Temperature Stability: Within the tested ranges, bed-plate temperature does not significantly impact final manufacturing time or filament consumption. This suggests that once the optimal temperature for filament adhesion is reached, further adjustments do not enhance efficiency.
- Resolution vs. Material Consumption: Increasing the resolution of the print (reducing layer height) extends the printing time but reduces material wastage. This trade-off is crucial for applications where material cost is a significant concern, highlighting the importance of balancing resolution and efficiency based on specific project requirements.
- Infill Density Over Pattern: Infill density is a primary driver of both time and material consumption, whereas the infill pattern has a minimal effect. This insight allows for more focused optimization strategies, where adjusting density can be prioritized over pattern changes.

– Support Structures Impact: The use of support structures significantly increases both print time and material usage. This factor must be carefully managed, especially in complex designs requiring extensive supports, to optimize overall efficiency.

Research presented in this study enhances the understanding of the intricate dependencies in the 3D printing process, offering a comprehensive framework for optimizing both manufacturing time and material consumption. These findings are not only applicable to the production of pulley-wheels but can be extended to other components and industries utilizing additive manufacturing technologies. Providing a detailed analysis of the key variables sets a foundation for further research and innovation aimed at improving the efficiency and sustainability of 3D printing processes.

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Appendix

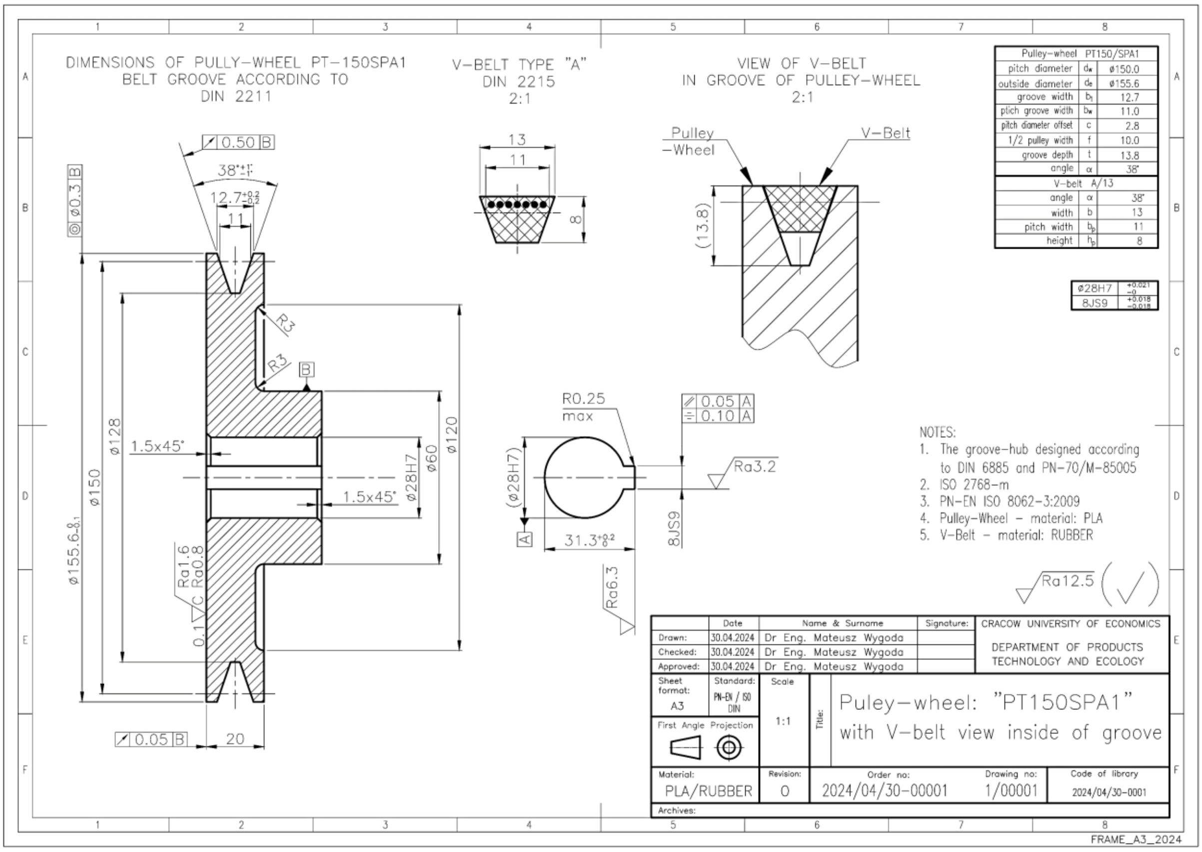

Figure 10. The original technical draw of pulley-wheel with descriptions of details.