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LIFE CYCLE ASSESSMENT OF A PULLEY MANUFACTURED FROM VARIOUS POLYMER MATERIALS USING 3D PRINTING TECHNOLOGY

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Purpose: The reason for taking up the subject was many inadequate decisions in the scope of material choice for the production process. The main aim of the carried-out analyses was comparing environmental influence of materials used for designing and manufacturing machine elements.
Design/methodology/approach: The objectives achieved using literature review and special CAD/CAM software – SOLIDWORKS 2024 with integrated sustainability module. The software was used to obtain environmental impact results. The results of analyses were presented in the form of tables and charts with wide descriptions.
Findings: In the conclusions presented and discussed the influence of the harmful factors on the environment. Additionally, authors recommended the best selection method of material in the technological process.
Research limitations/implications: The limitation of research was material base not including bio-materials – for example popular in 3D printing polylactic acid (PLA) or others.
Practical implications: The prepared analyses help in the materials selection, products assessment and prevent harmful effects on the environment. The indicators presented in the form of charts and tables help make thoughtful decisions to prepare the manufacturing process.
Social implications: The presented results pay attention on the environmental problems in the form of carbon footprint, total energy consumption, air acidification and water eutrophication.
Originality/value: The novelty is LCA analyses of specific machine elements. In the study presented pulley wheel analyses of environmental factors as material, manufacturing, transport and end-of-life.
Keywords: Life cycle assessment (LCA), polymer materials, 3D printing, sustainable design.
Category of the paper: Research paper.

1. Introduction

The 3D printing technology, also known as the additive technology, is becoming increasingly important in modern industry, bringing significant changes to the way products are manufactured (Thakar et al., 2022). Due to its flexibility and versatility, 3D printing allows for the creation of complex forms, reduction of waste and decrease of raw material consumption (Jandyal et al., 2022). The use of additive technologies to manufacture machine parts and components, such as pulleys, creates new opportunities in process optimisation in terms of both cost and production time (Krawiec et al., 2021; Wygoda, Witko, 2024). Printing in 3D is increasingly used in sectors such as automotive and aviation industries, medicine, and electronics where precision, low weight and customisation of products are of key importance (Shahrubudin et al., 2019; Pavan Kalyan, Kumar, 2022).

Along with the growing popularity of 3D printing, there appears the need for in-depth analysis of its environmental impact (Khosravani, Reinicke, 2020; Shuaib et al., 2021). Modern engineering focuses on sustainability, which requires environmental aspects to be taken into account at every stage of the product life cycle (Jachimowski, 2021). An important tool in this regard is the Life Cycle Assessment (LCA) which allows a detailed analysis of the environmental impact of a product from the acquisition of raw materials, through the production and use, to the recycling and disposal (Hendrickson et al., 2006). In the case of components manufactured using 3D printing, such as pulleys, LCA becomes a key tool to assess the benefits and challenges of using different materials, both ecologically and economically (Da Silva Barros, Zwolinski, 2016).

It should be emphasised that in the face of the global challenges of climate change and increasingly stringent environmental regulations, life cycle assessment becomes an indispensable tool for engineers and designers (Hauschild et al., 2020). Through the application of LCA, it is not only possible to improve production processes in terms of energy savings and waste reduction, but also to develop strategies to minimise negative environmental impacts (Rödger et al., 2021; Croes, Vermeulen, 2021). Therefore, research into the use of LCA for products manufactured using 3D printing is of particular importance in the context of the search for greener materials and component manufacturing technologies (Saade et al., 2020; Ulkir, 2023).

This paper focuses on the life cycle assessment of a pulley made from four different materials, i.e. Acrylonitrile Butadiene Styrene (ABS), Polypropylene Copolymer (PP-c), Polyethylene Terephthalate (PET) and Polyamide PA6. Each of these materials is characterised by different mechanical and chemical properties, which bears upon the production process and the entire product life cycle (Al-Zaidi, Al-Gawhari, 2023). The purpose of the investigation is to compare the environmental impact of the different materials taking into account factors such as greenhouse gas emissions, energy consumption and potential risks in terms of air acidification and water eutrophication. The analysis is intended to help select the most environmentally friendly materials, which is crucial for sustainable design.

2. Literature review

In The 3D printing technology is becoming increasingly significant in the context of industrial sustainability (Gebler et al., 2014; Kim, 2018; de Mattos Nascimento et al., 2022; Dey et al., 2022; Prashar et al., 2023). Its growing importance is due to its unique properties that bring fundamental changes to manufacturing processes (Ćwikła et al., 2017; Herzberger et al., 2019). In engineering practice, there has always been a demand for low-volume production for various industries (Salobir et al., 2019). This is typically associated with the manufacture of prototypes, unavailable machine spare parts or modifications to a given design. The necessity of modification may be related to incorrect design assumptions, calculation errors, and the intention to increase the load on an object or to increase the durability of a particular component. The most common areas requiring intervention are those weakened by material discontinuities in the cross-section – known as notches. In addition to weakening the cross-section, the notch effect causes a local increase of stress – which contributes into fatigue life of the components (Romanowicz et al., 2024). In such cases it is necessary to reinforce the affected zone. One possible form of structural reinforcement is the use of an appropriately designed reinforcement – typically with a complex geometry directly related to the shape of the hole (Romanowicz et al., 2022). The problem of how to precisely form the shape of the reinforcement can be solved by additive technologies which are gaining in popularity and practicality (Gao et al., 2015).

Thus, with accurate dispensing of materials and the ability to create complex geometries without generating excess waste, 3D printing is becoming a key tool in the quest to minimise the environmental impact of industry (Ngo et al., 2018; Vanaei, Zirak, 2024). Unlike traditional manufacturing methods, which often involve large amounts of waste and high energy consumption, 3D printing allows for a more efficient use of raw materials resulting in lower resource consumption and lower emissions (De-la-Cruz-Diaz et al., 2022; Embia et al., 2023).

One of the most important aspects of the sustainability of 3D printing is the possibility to precisely adjust the manufacturing processes according to the actual demand (Xu et al., 2021). Traditional manufacturing often leads to mass production, resulting in overproduction and waste of materials. An example of this might be machining as part of the process of turning or drilling where the waste is the chips of the material being machined. Therefore, analyses should take into account the wear and tear of expensive cutting tools and their relatively short lifespan relative to the parts that are manufactured (Paprocki et al., 2021). With its ability to produce on demand, 3D printing allows for the production of only those components that are actually needed, which significantly reduces excess waste (Driouach et al., 2023; Lakshmanan et al., 2023). This technology also reduces the energy consumption associated with the storage of redundant products helping to further reduce the environmental impact (Javaid et al., 2021).

Furthermore, the 3D printing technology also opens up new opportunities with regard to designing products with the entire life cycle in mind (Subramoniam et al., 2021). Engineers and designers can now more easily choose materials with a lower environmental impact, such as biopolymers and other green substances that can replace traditional plastics (Ncube et al., 2020). Such materials not only reduce the environmental impact, but also facilitate recycling. 3D printing also allows for flexible design modifications during the manufacturing process, which supports iterative design and allows for further product improvements towards greater material and energy efficiency (Jandyal et al., 2022; Prashar et al., 2023).

A key tool in analysing the environmental impact of 3D printing is life cycle assessment (Cerdas et al., 2017; Kumar et al., 2022; Roux et al., 2023; Tay, Tan, 2023). In the context of 3D printing, LCA is particularly useful as it allows the comparison of different materials in terms of greenhouse gas emissions, energy consumption and impacts on air acidification and water eutrophication (Caceres-Mendoza et al., 2023; Kokare et al., 2023). This type of analysis allows for more informed choices of materials and production methods that are most environmentally efficient (Pollini, Rognoli, 2021; Lunetto et al., 2021).

Another aspect of sustainability in 3D printing is the possibility of local production (Longhitano et al., 2021; Rayna, Striukova, 2021). Due to the flexibility of this technology, the manufacturing of components can take place closer to their end use, reducing the need for long-distance transport and thereby reducing the gas emissions associated with the transport of goods (Javaid et al., 2021). Locating production close to the consumers not only reduces logistics costs, but also reduces the environmental impact of the global supply chains (Attaran, 2017).

Taking this into account, a diagram (Fig. 1) was proposed to show the key aspects of sustainability in the 3D printing technology. In particular, the various factors that contribute to a green and efficient production process are shown.

It should be emphasised that when viewed in this way, the 3D printing technology has great potential to promote sustainability in many industries. By reducing the use of materials, energy and waste as well as promoting local, flexible production, additive technologies contribute to minimising negative environmental impacts (Peng et al., 2018; Godina et al., 2020; Javaid et al., 2021; Gopal et al., 2022; Nyika et al., 2022; Hegab et al., 2023). Combined with the search for even greener materials and improvements in manufacturing processes, 3D printing can play a key role in the future of industrial production, fostering a more responsible and resource-efficient response to the global environmental challenges.

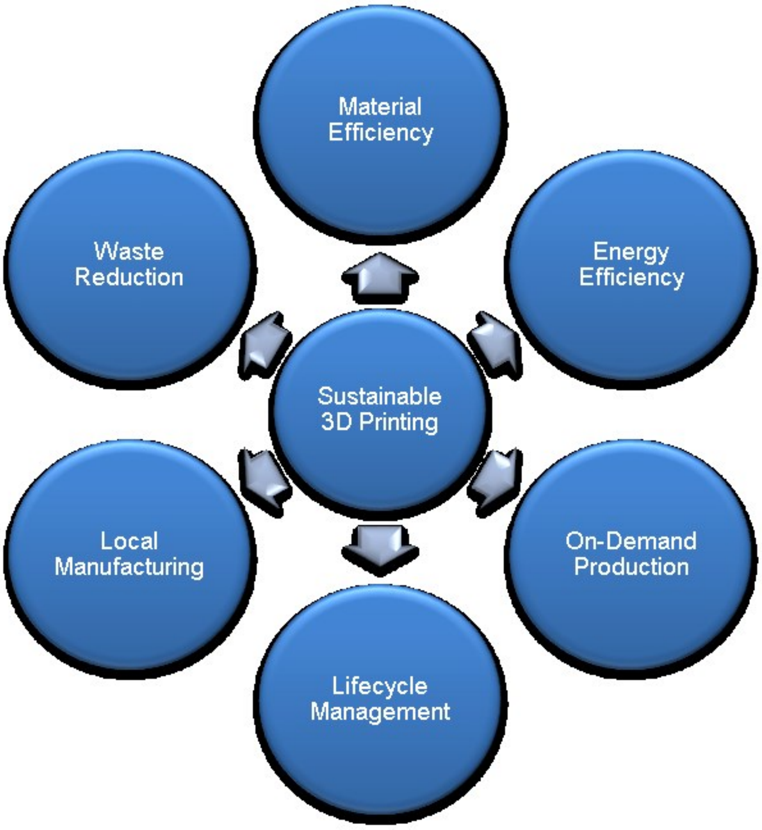

Figure 1. Aspects of the sustainability of 3D printing.
Source: author's work.

3. Methods

The present investigation uses a model of a pulley made using the SOLIDWORKS 3D CAD software. Figure 2 presents the spatial model of the object under investigation; the exact geometry together with the technical drawing was presented in the previous paper on 3D printing parameters (Wygoda, Witko, 2024).

The environmental analyses made use of the specialised SOLIDWORKS Sustainability module which allows the assessment of the environmental impact of a product by combining life cycle assessment (LCA) with engineering design (Casamayor, Su, 2021; Dudkowiak et al., 2024). The Sustainability module was implemented in 2009 and is integrated into the SOLIDWORKS CAD software. It allows the assessment of carbon dioxide emissions (in kg CO2 eq), energy consumption (in MJ), air acidification (in kg SO2 eq) and water eutrophication (in kg PO4 eq) throughout the life cycle of the product under investigation (Bałdowska-Witos et al., 2022).

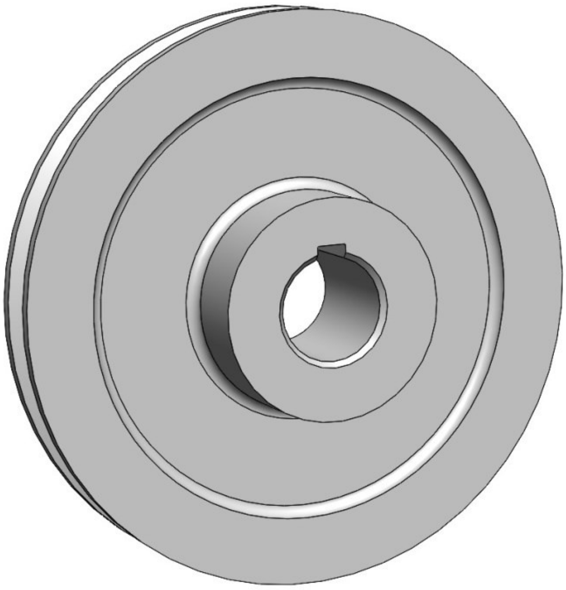

Figure 2. The 3D model of the pulley wheel.

Source: author's work.

Four types of polymeric materials were used for the environmental analyses, i.e. acrylonitrile-butadiene-styrene terpolymer (ABS), polyethylene terephthalate (PET), polypropylene block copolymer (PP-c) and PA6 (Polyamide 6). Table 1 presents a comparison of unit prices and selected physical and mechanical properties (SOLIDWORKS Software, 2024). The materials selected for the analyses are available in both the SOLIDWORKS Sustainability software and the BCN3D Stratos software used to prepare 3D prints.

Table 1.
The unit-prices, physical and mechanical properties of selected materials

Material	Unit Price	Density	Young's Modulus	Poisson's Ratio	Tensile Strength
[-]	[USD/kg]	[g/cm^3]	[GPa]	[-]	[MPa]
ABS	2.90	1.02	2.00	0.39	30.0
PET	2.20	1.42	2.96	0.37	57.3
PA-6	4.90	1.12	2.62	0.34	90.0
PP-c	2.80	0.89	0.90	0.41	27.6

Source: author's work based on (SOLIDWORKS Software, 2024).

The first step was to prepare the geometry of the pulley model in line with the engineering approach to designing structural components. The pulley was designed in accordance with the relevant standards, and a detailed description is presented in the paper (Wygoda, Witko, 2024). It should be noted that within the scope of the environmental studies carried out, the changes to the materials that were needed for the analyses can significantly affect the durability of the target component. The choice of a particular material will change the stresses acting on the pulley under operating conditions. In engineering practice to accuracy assessment of the loaded machine elements is possible by the Finite Element Method – advanced numerical computations. The obtained results in the form of stress and strains allow for the selection of reliable material.

The second step was to import the model into the BCN3D Stratos software in which manufacturing simulations were performed. The materials that were selected from the available material databases had the designation of the manufacturer BCN3D. For the purpose of the simulation, it was assumed that the constant parameters would be the pattern design (PD), the printing accuracy / layer height (LH), the printing speed (v), and the type of build plate adhesion (BPA). For further calculations, it was assumed that the power consumption (P3D) of the 3D printer available in the laboratory, i.e. BCN3D Epsilon W27, is 840W. The main and only variable was the infill density expressed as a percentage (I_D) that ranged from 10 to 100%. The input data provided information on print time (t) and print weight (w). This made it possible to determine the total energy consumption [kWh] needed to produce the model (P_C), according to formula (1):

$$P_c = (P_{3D} \cdot t)/1000 \tag{1}$$

where:
P3D – power consumption of the 3D printer [W],
t – time [h].

In order to calculate the electricity required per gram of print (EC) formula (2) was used:

$$E_c = P_c \div w \tag{2}$$

where:
P_C – power consumption of the process,
w – weight.

The simulation results, together with the calculated energy consumption parameters, are presented in Table 2.

The results obtained from the analyses (Table 2) also include an averaged value of electricity consumption (AVG. E_C) per gram of print produced. The authors decided to average the value of electricity consumption per unit mass due to the small differences in the individual results and the limitations of the environmental assessment module (SOLIDWORKS Sustainability) in terms of rounding the values entered. Therefore, further work on determining the environmental impact of the selected pulley material will be carried out for the solid component.

For the environmental analyses carried out, Europe was assumed as the region of production and use of the product. It was specified that the product was designed with a service life of 5 years and would then be decommissioned after 5 years. For each of the materials used, it was assumed that production was carried out from new raw material. In addition, with regard to the end of life, a 100 percent recyclability was assumed for all material variants. For the production process, average energy consumption per gram (AVG. E_C) of print was assumed for the selected materials as shown in Table 2. In the next step, it was assumed that transport would take place by road, with an input value of 149 km. Available analyses (Raport Transport drogowy, 2021) show that in Poland, more than 60% of goods (by weight) are transported by land over the above-stated distance (Tseng et al., 2021; Miranda et al., 2023).

Table 2.
The results of 3D printing simulations

Material	Infill Density	Time	Weight	Power consumption of 3D Printing Process	Manufacturing Process – Electricity consumption	Average Value of Electricity Consumption
-	I_D [%]	t [h]	w [g]	P_c [kWh]	E_c [kWh/g]	AVG. Ec [kWh/g]
ABS	10	8.80	119	7.392	0.062	0.056
	25	11.07	163	9.296	0.057	
	50	14.75	237	12.390	0.052	
	75	18.42	311	15.470	0.050	
	100	26.25	385	22.050	0.057	
PET	10	11.87	178	9.968	0.056	0.051
	25	14.62	224	12.278	0.055	
	50	18.43	301	15.484	0.051	
	75	20.77	376	17.444	0.046	
	100	24.12	452	20.258	0.045	
PP-c	10	7.45	87	6.258	0.072	0.065
	25	9.70	124	8.148	0.066	
	50	13.40	186	11.256	0.061	
	75	17.07	247	14.336	0.058	
	100	24.90	309	20.916	0.068	
PA6	10	7.45	107	6.258	0.058	0.052
	25	9.70	153	8.148	0.053	
	50	13.40	230	11.256	0.049	
	75	17.07	307	14.336	0.047	
	100	24.90	383	20.916	0.055	

* The analyses are presented for constant values: Pattern design, PD: grid; Layer height, LH: 0.3 [mm]; Speed of printing, v: 45 [mm/min]; Build plate adhesion, BPA: raft; Power consumption of the 3D printer, P3D: 840 [W].

Source: author’s work.

4. Results

Based on the available research results with regard to the environmental impact, a division was made into four categories, i.e. carbon footprint, energy consumption, air acidification and water eutrophication (Kruszelnicka et al., 2020). The analyses used the CML method through which it is possible to estimate environmental pollution in terms of material, manufacturing process, transport and end-of-life (Dong et al., 2021; Zegardło, 2021). Furthermore, the CML methodology is based on European regional conditions and is the most commonly used set of environmental indicators in LCA studies.

Taking the above into account, four test scenarios were carried out to analyse the life cycle of a product made from different filaments, such as ABS, PP-c, PET and PA6, in three stages: material, manufacturing and transport. The results as well as the environmental indicators are presented in Tables 3 and 4.

Table 3.
The results of Carbon Footprint and Total Energy Consumption

		Carbon Footprint [kg CO_2e]				Total Energy Consumption [MJ]			
		ABS	PET	PA-6	PP-c	ABS	PET	PA-6	PP-c
Influence	Material	1.2	1.4	3.8	0.599	30	39	70	23
	Manufacturing	12	14	11	12	230	270	220	230
	Transport	0.0024	0.0034	0.0027	0.0021	0.036	0.05	0.04	0.032
	End-Of-Life*	0	0	0	0	0	0	0	0
	SUMMARY	13	15	15	13	260	309	290	253

* End-Of-Life - the obtained results caused by the assumption of 100% recycling of materials.

Source: author's work.

Table 4.
The results of Air Acidification and Water Eutrophication

		Air Acidification [kg SO_2e]				Water Eutrophication [kg PO_4e]			
		ABS	PET	PA-6	PP-c	ABS	PET	PA-6	PP-c
Influence	Material	0.0027	0.0025	0.0057	0.0013	0.00047	0.00024	0.00067	0.00012
	Manufacturing	0.081	0.093	0.077	0.082	0.0029	0.0034	0.0028	0.003
	Transport	1.1E-05	1.6E-05	1.3E-05	9.9E-06	2.6E-06	3.6E-06	2.8E-06	2.3E-06
	End-Of-Life*	0	0	0	0	0	0	0	0
	SUMMARY	0.084	0.096	0.083	0.083	0.0034	0.0036	0.0035	0.0031

* End-Of-Life - the obtained results caused by the assumption of 100% recycling of materials.

Source: author's work.

In addition, Table 3 and Table 4 indicate the most negative (red) and the lowest (green) environmental impacts for the four stages, i.e. material, manufacturing, transport and end-of-life. Based on these results, a percentage comparison was prepared in the form of pie charts (Figs. 3-6). Due to the zero values of the end-of-life results, no further presentation was made for them.

Figure 3 shows the percentage impact on CO_2 emissions for the various plastics. It follows from the analyses that PA-6 (54%) has the largest share in material footprint while PP-c has the smallest share at only 9%. PET had the largest impact at the manufacturing stage with a result of 29% and PA-6 the smallest with 22%. In terms of transport, on the other hand, PET again has the highest result (32%) and PP-c the lowest at 20%.

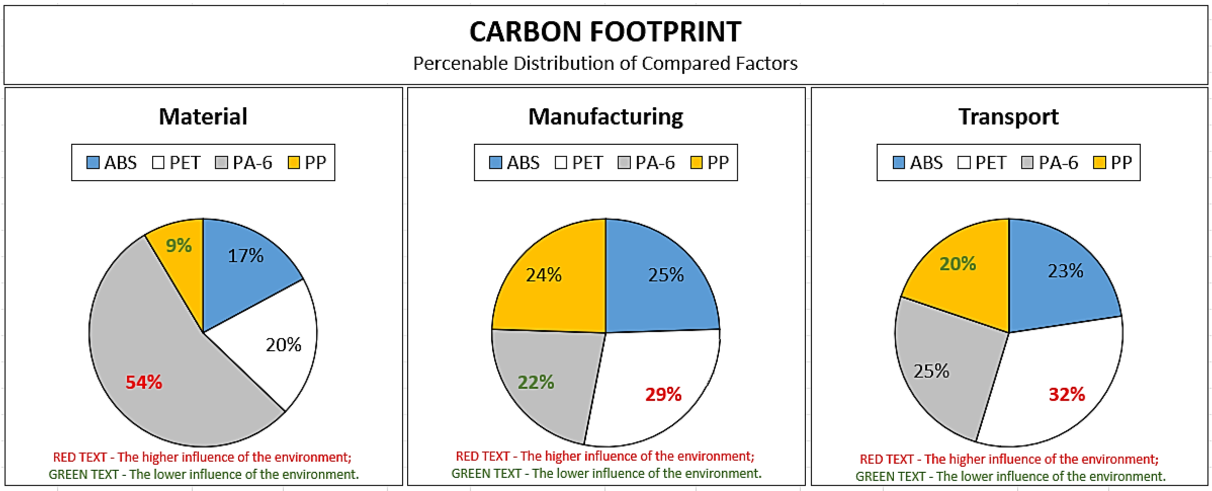

Figure 3. The results of the Carbon Footprint.

Source: author's work.

In the Figure 4 presented the analysis of the total energy consumption for the different materials. The analyses show that PA-6 has the highest contribution to energy consumption in terms of material (43%) and PP-c the lowest at 14%. PET had the highest impact at the manufacturing stage with a score of 29% and PA-6 the lowest with 23%. In terms of transport, on the other hand, PET has the highest result with 32% and PP-c the lowest with 20%.

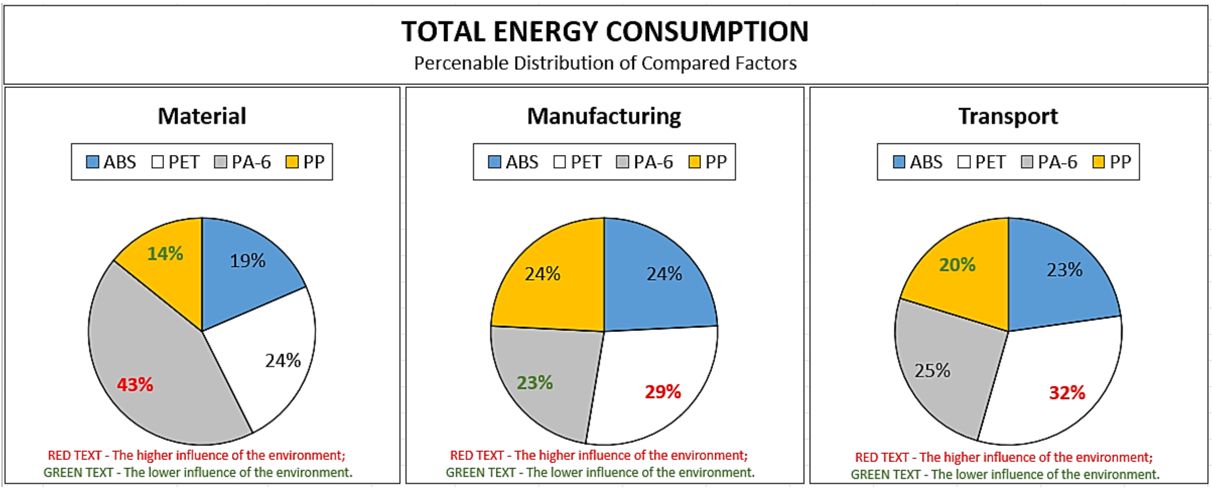

Figure 4. The results of the Total Energy Consumption.

Source: author's work.

Figure 5 shows how different materials affect air acidification at each stage of the product life cycle. The analyses show that PA-6 has the highest contribution in terms of material (43%) and PP-c the lowest at 11%. PET had the highest impact at the manufacturing stage with a score of 28%, and PA-6 the lowest with 23%. In terms of transport, on the other hand, PET has the highest score with 32% and PP-c the lowest with 20%.

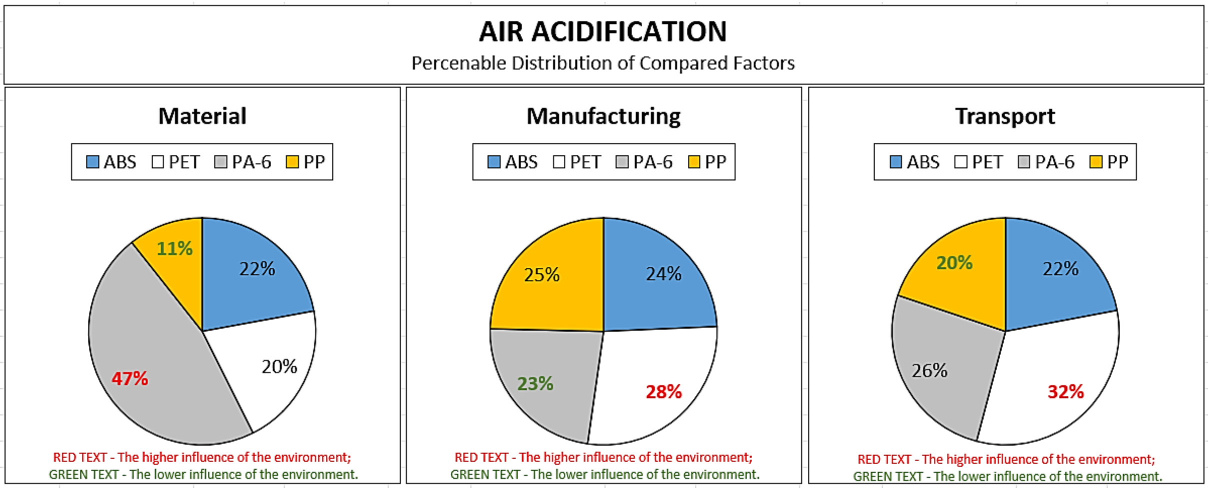

Figure 5. The results of the Air Acidification.

Source: author's work.

In the Figure 6 presented the analysis of water eutrophication in the context of different filaments. The analyses show that PA-6 has the highest impact on water eutrophication in terms of material (45%) while PP-c has the lowest impact of only 8%. PET had the highest impact at the manufacturing stage with a score of 28% while PA-6 had the lowest impact of 23%. In terms of transport, on the other hand, PET has the highest result with 32% and PP-c the lowest with 20%.

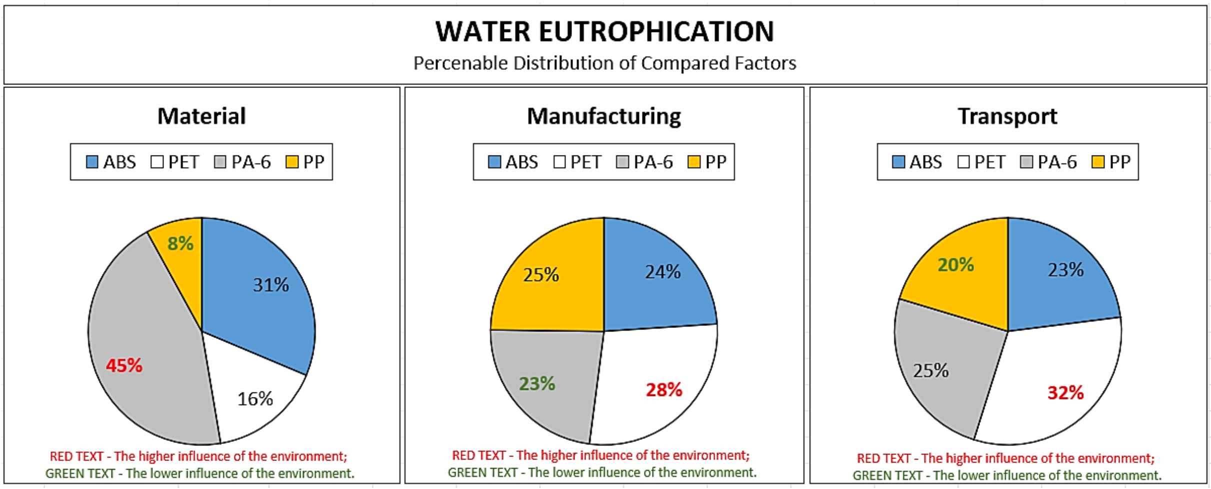

Figure 6. The results of the Water Eutrophication.

Source: author's work.

5. Discussion

When comparing the results with similar studies, it is evident that much of the literature focuses on the life cycle assessment (LCA) of polymer materials, particularly in the context of 3D printing (Faludi et al., 2015; Ma et al., 2018; Výtisk et al., 2019; Kumar et al., 2022; Ulkir 2023; Al Rashid, 2024). However, some studies explore a wider range of materials or other manufacturing technologies (Garcia et al., 2021; Chatzipanagiotou et al., 2023; Kokare et al., 2023). The results presented in this paper, which show that PP-C has the lowest environmental impact, align with trends highlighting the benefits of using low-density materials that require less energy for transportation (Fan, Njuguna, 2016; Czerwiński, 2021). At the same time, the significant impact of PA6 and PET in terms of emissions and transport confirms the need for optimization of production and transportation processes for materials with a higher environmental footprint.

The limitations of the study include focusing solely on 3D printing technology and four polymer materials, which may not fully represent the entire range of manufacturing possibilities. The results are based on data from the SOLIDWORKS Sustainability software, which may not be entirely accurate in some cases as it is limited to four environmental categories. Additionally, the material library does not contain bio-type of materials, for example (polylactic acid) PLA.

Future research should include an analysis of other materials, such as biopolymers, and consider different manufacturing methods, such as injection molding. Additionally, further studies on recycling and the end-of-life phase of products should be conducted to develop more sustainable solutions. Another important direction is the analysis of the impact of transport and production location on the product's life cycle.

6. Summary

In the analysis of the environmental impact of ABS, PP-c, PET and PA-6 filaments, covering categories such as carbon footprint, energy consumption, air acidification and water eutrophication, provides important information about their life-cycle environmental impact. The investigation carried out using the CML method allowed the assessment of the impacts at the material, manufacturing and transport stages. The main conclusions of the analysis are presented below:

- In terms of carbon footprint, PA-6 shows the highest contribution to CO_2 emissions (54%) while PP-c has the lowest emissions (9%). In transport, PET generates the most emissions (32%) while PP-c is the greenest (20%).
- With regard to energy consumption, PA-6 stands out as having the highest energy requirement at the material stage (43%) while PP-c has the lowest consumption (14%). PET requires the most energy in the manufacturing process (29%) while PA-6 requires the least (23%).
- In respect of air acidification, PA-6 has the greatest negative impact (43%) while PP-c has the least (11%). In transport, PET generates the greatest impact (32%) and PP-c the least (20%).
- As far as water eutrophication is concerned, PA-6 has the highest impact at the material stage (45%) while PP-c is again the most environmentally friendly (8%). In transport, PET has the highest impact (32%) and PP-c the lowest (20%).

In summary, the presented study with the use SOLIDWORKS Sustainability module shows that PP-c stands out as the most environmentally friendly filament, especially in terms of material and transport factors. However, the presented advantages should be treated with some caution, due the lowest tensile strength (27.6 MPa) of all studied materials. For this reason, it may be a limit of its functional applicability for some cases, from the point of view of the loading conditions of elements and their capacity. Therefore, a more responsible approach to the environmental and sustainability balance in relation to mechanical performance is required. On the other hand, it should be noted that the PA-6 - despite the highest tensile strength equals 90 MPa - has the greatest negative impact on the environment, mainly in terms of CO_2 emissions and air acidification at the material stage, while PET (tensile strength 57.3 MPa) shows the greatest negative environmental impact in the manufacturing process and transport.

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References

1. Al Rashid, A., Khan, S.A., Koç, M. (2024). Life cycle assessment on fabrication and characterization techniques for additively manufactured polymers and polymer composites. *Cleaner Environmental Systems*, *12*, 100159. https://doi.org/10.1016/j.cesys.2023.100159
2. Al-Zaidi, A.A. M.A., Al-Gawhari, F.J.J. (2023). Types of Polymers Using in 3D Printing and Their Applications: A Brief Review. *European Journal of Theoretical and Applied Sciences*, *1(6),* 978-985. https://doi.org/10.59324/ejtas.2023.1(6).94
3. Attaran, M. (2017). Additive manufacturing: the most promising technology to alter the supply chain and logistics. *Journal of Service Science and Management*, *10(03),* 189. https://doi.org/10.4236/jssm.2017.103017
4. Bałdowska-Witos, P., Macko, M., Łączny, D., Kruszelnicka, W., Lewandowski, J. (2022). Computer-aided Eco-design Grinding Machines using Software SolidWorks Sustainability. *MATEC Web of Conferences, Vol. 357*, p. 02022. EDP Sciences. https://doi.org/10.1051/matecconf/202235702022
5. Caceres-Mendoza, C., Santander-Tapia, P., Sanchez, F. A. C., Troussier, N., Camargo, M., Boudaoud, H. (2023). Life cycle assessment of filament production in distributed plastic recycling via additive manufacturing. *Cleaner Waste Systems*, *5*, 100100. https://doi.org/10.1016/j.clwas.2023.100100
6. Casamayor, J.L., Su, D. (2021). Investigation of a process to eco-design led lighting products to enhance the adoption of eco-design methods and tools by industry. *Sustainability*, *13(8),* 4512. https://doi.org/10.3390/su13084512
7. Cerdas, F., Juraschek, M., Thiede, S., Herrmann, C. (2017). Life cycle assessment of 3D printed products in a distributed manufacturing system. *Journal of Industrial Ecology*, *21(S1),* S80-S93. https://doi.org/10.1111/jiec.12618
8. Chatzipanagiotou, K.R., Antypa, D., Petrakli, F., Karatza, A., Pikoń, K., Bogacka, M., ..., Koumoulos, E.P. (2023). Life Cycle Assessment of Composites Additive Manufacturing Using Recycled Materials. *Sustainability*, *15(17),* 12843. https://doi.org/10.3390/su151712843
9. Croes, P.R., Vermeulen, W.J. (2021). The assessment of positive impacts in LCA of products. *The International Journal of Life Cycle Assessment*, *26*, 143-156. https://doi.org/10.1007/s11367-020-01820-x
10. Ćwikła, G., Grabowik, C., Kalinowski, K., Paprocka, I., Ociepka, P. (2017). The influence of printing parameters on selected mechanical properties of FDM/FFF 3D-printed parts. *IOP conference series: materials science and engineering, Vol. 227, No. 1*, p. 012033. IOP Publishing. https://doi.org/10.1088/1757-899X/227/1/012033
11. Czerwinski, F. (2021). Current trends in automotive lightweighting strategies and materials. *Materials*, *14(21),* 6631. https://doi.org/10.3390/ma14216631

12. Da Silva Barros, K., Zwolinski, P. (2016). Influence of the use/user profile in the LCA of 3d printed products. *Procedia CIRP*, *50*, 318-323. https://doi.org/10.1016/j.procir.2016.05.005
13. de Mattos Nascimento, D.L., Mury Nepomuceno, R., Caiado, R.G.G., Maqueira, J.M., Moyano-Fuentes, J., Garza-Reyes, J.A. (2022). A sustainable circular 3D printing model for recycling metal scrap in the automotive industry. *Journal of Manufacturing Technology Management*, *33(5),* 876-892. https://doi.org/10.1108/JMTM-10-2021-0391
14. De-la-Cruz-Diaz, M., Alvarez-Risco, A., Jaramillo-Arévalo, M., de las Mercedes Anderson-Seminario, M., Del-Aguila-Arcentales, S. (2022). 3D print, circularity, and footprints. In: A. Alvarez-Risco, S.S. Muthu, S. Del-Aguila-Arcentales (Eds.), *Circular Economy: Impact on Carbon and Water Footprint* (pp. 93-112). Singapore: Springer Singapore.
15. Dey, D., Srinivas, D., Panda, B., Suraneni, P., Sitharam, T.G. (2022). Use of industrial waste materials for 3D printing of sustainable concrete: A review. *Journal of cleaner production*, *340*, 130749. https://doi.org/10.1016/j.jclepro.2022.130749
16. Dong, Y., Hossain, M.U., Li, H., Liu, P. (2021). Developing conversion factors of LCIA methods for comparison of LCA results in the construction sector. *Sustainability*, *13(16),* 9016. https://doi.org/10.3390/su13169016
17. Driouach, L., Zarbane, K., Beidouri, Z. (2023). The impacts of additive manufacturing technology on lean manufacturing. *Journal of Achievements in Materials and Manufacturing Engineering*, *120(1),* 22-32. doi: 10.5604/01.3001.0053.9641
18. Dudkowiak, A., Dostatni, E., Czerw, A. (2024). Comparison of Environmental Analysis Results from Two IT Tools Based on an Additive Manufactured Prosthesis. *International Scientific-Technical Conference Manufacturing* (pp. 193-205). Cham: Springer Nature Switzerland.
19. Embia, G., Moharana, B.R., Mohamed, A., Muduli, K., Muhammad, N.B. (2023). 3D printing pathways for sustainable manufacturing. In: A. Nayyar, M. Naved, R. Rameshwar (Eds.), *New horizons for industry 4.0 in modern business* (pp. 253-272). Cham: Springer International Publishing.
20. Faludi, J., Bayley, C., Bhogal, S., Iribarne, M. (2015). Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal*, *21(1),* 14-33. https://doi.org/10.1108/RPJ-07-2013-0067
21. Fan, J., Njuguna, J. (2016). An introduction to lightweight composite materials and their use in transport structures. In: J. Njuguna (Ed.), *Lightweight Composite Structures in Transport* (pp. 3-34). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-325-6.00001-3
22. Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C.B., Wang, Ch.C. L., Shin, Y.C., Zhang, S., Zavattieri, P.D. (2015). The status, challenges, and future of

additive manufacturing in engineering. *Computer-aided design*, *69*, 65-89. https://doi.org/10.1016/j.cad.2015.04.001

23. Garcia, F.L., Nunes, A.O., Martins, M.G., Belli, M.C., Saavedra, Y.M., Silva, D.A.L., Moris, V.A.D.S. (2021). Comparative LCA of conventional manufacturing vs. additive manufacturing: the case of injection moulding for recycled polymers. *International Journal of Sustainable Engineering*, *14(6),* 1604-1622, https://doi.org/10.1080/19397038.2021.1990435
24. Gebler, M., Uiterkamp, A.J.S., Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, *74*, 158-167. https://doi.org/10.1016/j.enpol.2014.08.033
25. Godina, R., Ribeiro, I., Matos, F.T., Ferreira, B., Carvalho, H., Peças, P. (2020). Impact assessment of additive manufacturing on sustainable business models in industry 4.0 context. *Sustainability*, *12(17),* 7066. https://doi.org/10.3390/su12177066
26. Gopal, M., Lemu, H.G., Gutema, E.M. (2022). Sustainable additive manufacturing and environmental implications: literature review. *Sustainability*, *15(1),* 504. https://doi.org/10.3390/su15010504
27. Hauschild, M.Z., Kara, S., Røpke, I. (2020). Absolute sustainability: Challenges to life cycle engineering. *CIRP annals*, *69(2),* 533-553. https://doi.org/10.1016/j.cirp.2020.05.004
28. Hegab, H., Khanna, N., Monib, N., Salem, A. (2023). Design for sustainable additive manufacturing: A review. *Sustainable Materials and Technologies*, *35*, e00576. https://doi.org/10.1016/j.susmat.2023.e00576
29. Hendrickson, C.T., Lave, L.B., Matthews, H.S. (2006). *Environmental life cycle assessment of goods and services: an input-output approach*. New York: Routledge.
30. Herzberger, J., Sirrine, J.M., Williams, C.B., Long, T.E. (2019). Polymer design for 3D printing elastomers: recent advances in structure, properties, and printing. *Progress in Polymer Science*, *97*, 101144. https://doi.org/10.1016/j.progpolymsci.2019.101144
31. https://tlp.org.pl/wp-content/uploads/2022/04/raport.pdf (in Polish).
32. Jachimowski, A. (2021). *Zarządzanie procesami logistycznymi w przedsiębiorstwach przetwarzających odpady komunalne*. Kraków: Wydawnictwo Uniwersytetu Ekonomicznego w Krakowie (In Polish).
33. Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., Haq, M.I.U. (2022). 3D printing–A review of processes, materials and applications in industry 4.0. *Sustainable Operations and Computers, 3,* 33-42. https://doi.org/10.1016/j.susoc.2021.09.004
34. Javaid, M., Haleem, A., Singh, R.P., Suman, R., Rab, S. (2021). Role of additive manufacturing applications towards environmental sustainability. *Advanced Industrial and Engineering Polymer Research*, *4(4),* 312-322. https://doi.org/10.1016/j.aiepr.2021.07.005

35. 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
36. Kim, H. (2018). Market analysis and the future of sustainable design using 3D printing technology. *Archives of Design Research*, *31(1),* 23-35. http://dx.doi.org/10.15187/adr.2018.02.31.1.23
37. Kokare, S., Oliveira, J.P., Godina, R. (2023). Life cycle assessment of additive manufacturing processes: A review. *Journal of Manufacturing Systems*, *68*, 536-559. https://doi.org/10.1016/j.jmsy.2023.05.007
38. Krawiec, P., Czarnecka-Komorowska, D., Warguła, Ł., Wojciechowski, S. (2021). Geometric Specification of Non-Circular Pulleys Made with Various Additive Manufacturing Techniques. *Materials*, *14(7),* 1682. https://doi.org/10.3390/ma14071682
39. Kruszelnicka, W., Kasner, R., Bałdowska-Witos, P., Flizikowski, J., Tomporowski, A. (2020). The integrated energy consumption index for energy biomass grinding technology assessment. *Energies*, *13(6),* 1417. https://doi.org/10.3390/en13061417
40. Kumar, R., Sharma, H., Saran, C., Tripathy, T.S., Sangwan, K.S., Herrmann, C. (2022). A comparative study on the life cycle assessment of a 3D printed product with PLA, ABS & PETG materials. *Procedia CIRP*, *107*, 15-20. https://doi.org/10.1016/j.procir.2022.04.003
41. Kumar, R., Vilochani, P.P., Kahnthinisha, S., Patil, O., Cerdas, F., Sangwan, K.S., Herrmann, C. (2022). Live life cycle assessment implementation using cyber physical production system framework for 3D printed products. *Procedia CIRP*, *105*, 284-289. https://doi.org/10.1016/j.procir.2022.02.047
42. Lakshmanan, R., Nyamekye, P., Virolainen, V.M., Piili, H. (2023). The convergence of lean management and additive manufacturing: Case of manufacturing industries. *Cleaner Engineering and Technology*, *13*, 100620. https://doi.org/10.1016/j.clet.2023.100620
43. Longhitano, G.A., Nunes, G.B., Candido, G., da Silva, J.V.L. (2021). The role of 3D printing during COVID-19 pandemic: a review. *Progress in additive manufacturing*, *6*, 19-37. https://doi.org/10.1007/s40964-020-00159-x
44. Lunetto, V., Priarone, P.C., Kara, S., Settineri, L. (2021). A comparative LCA method for environmentally friendly manufacturing: Additive manufacturing versus Machining case. *Procedia CIRP, 98*, 406-411. https://doi.org/10.1016/j.procir.2021.01.125
45. Ma, J., Harstvedt, J.D., Dunaway, D., Bian, L., Jaradat, R. (2018). An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment. *Journal of Cleaner Production*, *192*, 55-70. https://doi.org/10.1016/j.jclepro.2018.04.249
46. Miranda, S.A.S., dos Santos Almeidaa, E., Brito, J.M. (2023). *LCA applied to eco design: a comparison between results from a rigorous cradle-to-grave assessment and solidworks sustainability tool*. IX International Symposium on Innovation and Technology. Engineering and the Future of the Industry.

47. Ncube, L.K., Ude, A.U., Ogunmuyiwa, E.N., Zulkifli, R., Beas, I.N. (2020). Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid based materials. *Materials*, *13(21),* 4994. https://doi.org/10.3390/ma13214994
48. Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T., Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*, 172-196. https://doi.org/10.1016/j.compositesb.2018.02.012
49. Nyika, J., Mwema, F.M., Mahamood, R.M., Akinlabi, E.T., Jen, T.C. (2022). Advances in 3D printing materials processing-environmental impacts and alleviation measures. *Advances in Materials and Processing Technologies*, *8(sup. 3),* 1275-1285. https://doi.org/10.1080/2374068X.2021.1945311
50. Paprocki, M., Wygoda, M., Wyczesany, P., Bazan, P. (2021). Symptoms of wear HSS cutting tools in different wear stages. *Manufacturing Technology*, *21(3).* http://dx.doi.org/10.21062/mft.2021.047
51. Pavan Kalyan, B.G., Kumar, L. (2022). 3D printing: applications in tissue engineering, medical devices, and drug delivery. *Aaps Pharmscitech*, *23(4),* 92. https://doi.org/10.1208/s12249-022-02242-8
52. Peng, T., Kellens, K., Tang, R., Chen, C., Chen, G. (2018). Sustainability of additive manufacturing: An overview on its energy demand and environmental impact. *Additive manufacturing*, *21*, 694-704. https://doi.org/10.1016/j.addma.2018.04.022
53. Pollini, B., Rognoli, V. (2021). Early-stage material selection based on life cycle approach: tools, obstacles and opportunities for design. *Sustainable Production and Consumption*, *28*, 1130-1139. https://doi.org/10.1016/j.spc.2021.07.014
54. Prashar, G., Vasudev, H., Bhuddhi, D. (2023). Additive manufacturing: expanding 3D printing horizon in industry 4.0. *International Journal on Interactive Design and Manufacturing*, *17(5),* 2221-2235. https://doi.org/10.1007/s12008-022-00956-4
55. Raport Transport drogowy w Polsce 2021+.
56. Rayna, T., Striukova, L. (2021). Assessing the effect of 3D printing technologies on entrepreneurship: An exploratory study. *Technological Forecasting and Social Change*, *164*, 120483. https://doi.org/10.1016/j.techfore.2020.120483
57. Rödger, J.M., Beier, J., Schönemann, M., Schulze, C., Thiede, S., Bey, N., Herrmann, Ch., Hauschild, M. Z. (2021). Combining life cycle assessment and manufacturing system simulation: evaluating dynamic impacts from renewable energy supply on product-specific environmental footprints. *International Journal of Precision Engineering and Manufacturing-Green Technology, 8*, 1007-1026. https://doi.org/10.1007/s40684-020-00229-z

58. Romanowicz, P.J., Szybiński, B., Wygoda, M. (2022). Static and fatigue behaviour of double-lap adhesive joints and notched metal samples reinforced by composite overlays. *Materials*, *15(9),* 3233. https://doi.org/10.3390/ma15093233
59. Romanowicz, P.J., Szybiński, B., Wygoda, M. (2024). Fatigue performance of open-hole structural elements reinforced by CFRP overlays. *International Journal of Adhesion and Adhesives*, *130*, 103606. https://doi.org/10.1016/j.ijadhadh.2023.103606
60. Roux, C., Kuzmenko, K., Roussel, N., Mesnil, R., Feraille, A. (2023). Life cycle assessment of a concrete 3D printing process. *The International Journal of Life Cycle Assessment, 28(1),* 1-15. https://doi.org/10.1007/s11367-022-02111-3
61. Saade, M.R.M., Yahia, A., Amor, B. (2020). How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. *Journal of Cleaner Production, 244*, 118803. https://doi.org/10.1016/j.jclepro.2019.118803
62. Salobir, J., Duhovnik, J., Tavčar, J. (2019). Methods and principles of product design for small-scale production based on 3D printing. *Proceedings of the Design Society: International Conference on Engineering Design, Vol. 1, No. 1*, pp. 789-798. Cambridge University Press. https://doi.org/10.1017/dsi.2019.83
63. Shahrubudin, N., Lee, T.C., Ramlan, R.J.P.M. (2019). An overview on 3D printing technology: Technological, materials, and applications. *Procedia manufacturing*, *35*, 1286-1296. https://doi.org/10.1016/j.promfg.2019.06.089
64. Shuaib, M., Haleem, A., Kumar, S., Javaid, M. (2021). Impact of 3D Printing on the environment: A literature-based study. *Sustainable Operations and Computers*, *2*, 57-63. https://doi.org/10.1016/j.susoc.2021.04.001
65. SOLIDWORKS Software, Dassault Systèmes, version: 2024, SP 3.1.
66. Subramoniam, R., Sundin, E., Subramoniam, S., Huisingh, D. (2021). Riding the digital product life cycle waves towards a circular economy. *Sustainability*, *13(16),* 8960. https://doi.org/10.3390/su13168960
67. Tay, Y.W.D., Tan, M.J. (2023). Sustainability and life cycle analysis of 3D printing industries. *Key Engineering Materials*, *968*, 161-166. https://doi.org/10.4028/p-ZBzEz1
68. Thakar, C.M., Parkhe, S.S., Jain, A., Phasinam, K., Murugesan, G., Ventayen, R.J.M. (2022). *3d Printing: Basic principles and applications. Materials Today: Proceedings, 51*, 842-849. https://doi.org/10.1016/j.matpr.2021.06.272
69. Tseng, T.L.B., Rahman, M.F., Chiou, R., Ho, J.C. (2021). *Sustainable green design and life cycle assessment for engineering education*. 2021 ASEE Virtual Annual Conference Content Access.
70. Ulkir O. (2023). Energy-consumption-based life cycle assessment of additive-manufactured product with different types of materials. *Polymers*, *15(6),* 1466. https://doi.org/10.3390/polym15061466

71. Vanaei, S., Zirak, N. (2024). *Diverse Application of 3D Printing Process*. In: H.R. Vanaei H.R.S. Khelladi, A. Tcharkhtchi (Eds.), Industrial Strategies and Solutions for 3D Printing: Applications and Optimization, 59-80.
72. Výtisk, J., Kočí, V., Honus, S., Vrtek, M. (2019). Aktualne możliwości w ocenie cyklu życia produktów wytwarzania przyrostowego. *Otwarta inżynieria*, *9(1),* 674-682. https://doi.org/10.1515/eng-2019-0073
73. Wygoda, M., Witko, T. (2024). Effective management of key variables in the 3d printing process of pulley-wheel. *Scientific Papers of Silesian University of Technology. Organization & Management [Zeszyty Naukowe Politechniki Slaskiej. Seria Organizacji i Zarzadzanie]*, *197*, 641-666.
74. Xu, X., Rodgers, M.D., Guo, W.G. (2021). Hybrid simulation models for spare parts supply chain considering 3D printing capabilities. *Journal of Manufacturing Systems*, *59*, 272-282. https://doi.org/10.1016/j.jmsy.2021.02.018
75. Zegardło, B. (2021). Evaluation of Environmental Effects by LCA Method of Recycling of Depleted Electrical Insulators by Their Reuse for Cementitious Composites. *Rocznik Ochrona Środowiska*, *23*, 672-683. https://doi.org/10.54740/ros.2021.047