Study regarding the influence of material type on economic objectives in MEX fabrication

Mihaela-Elena Ulmeanu[1,*], *Cristian-Vasile* Doicin[1], Liviu Roșca[2], *Allan EW* Rennie[3], *Tom* Abram[3] and *Andrei-Bogdan* Nuță[1]

[1]University POLITEHNICA of Bucharest, Splaiul Independentei 313, Bucharest, Romania
[2]"Lucian Blaga" University of Sibiu, Victoriei 10, Sibiu, Romania
[3]Lancaster University, Bailrigg, LA1 4YW, Lancaster, UK

Abstract. Material Extrusion has been used extensively as an additive manufacturing technology for a variety of applications like visual models, functional prototypes, tooling components, patterns for castings, and final parts. The current research paper proposes a study on the material type influence on economic objectives in material extrusion fabrication of complex assemblies. Three economic objectives have been analysed, namely, estimated fabrication time, material usage and material cost, whilst two commercial additive manufacturing machines have been considered for the simulation. Cura and ZSuite slicing software were used for the generation of Gcode and project files. Five filaments were selected from the same manufacturer and all components of the selected assembly were included in the analysis. Throughout the study, the additive manufacturing parameters were kept constant, as well as the component layout on the build platform of the two machines. Study results were analysed in correspondence with the manufacturing requirements and the optimum fabrication scenario was selected. Further research includes the analysis of multiple material manufacturers, in order to evaluate the influence of chemical composition on economic outputs.

1 Introduction

Developing a new product involves understanding the needs and desires of customers, the competitive environment and the market typology [1]. Cost, time and quality are the main variables that drive customer needs. Based on these three variables, companies are continually developing techniques and strategies to better meet customer requirements and to increase their market share by constantly developing new products [2]. The process of product development has undergone a huge evolution in recent years, at the same time with the increase of the rate of adoption of additive manufacturing (AM) technologies, themselves already having an age of maturity of more than 30 years. New AM equipment is small in size and can produce real objects in a relatively short period of time. The advantages of AM technologies have made the product development process include, almost invariably, a rapid prototyping step [3]. Many specialists consider AM technologies

* Corresponding author: mihaela.ulmeanu@upb.ro

to be the next disruptive step in technology, similar to the emergence of personal computers, offering everyone the opportunity to imagine, design and create custom products [4, 5, 6]. Others claim that these technologies will continue to be used primarily for prototyping applications [7]. This is driven by the current inability of AM technologies to effectively meet, in terms of costs, the global demand for production applications. Other opinions show that AM will revolutionize manufacturing processes and the economic and social environment [4, 7]. Regardless of the point of view, it is a certainty that in the last decade AM technologies have undergone a spectacular evolution in terms of the functionality of the manufacturing systems, the ease of use, the cost efficiency and the adoption rate in multiple industrial sectors [3]. There is also an obvious change in the applicability of AM technologies, from rapid modelling and prototyping to rapid manufacturing of finished products [8]. If the future evolution will follow the same upward trend, the role of AM technologies in the manufacturing value chain will be a key one in terms of purpose, scale and complexity. It is expected that these technologies will reach their full potential in the next 15-20 years [3, 8, 9]. During this period, it is preferable for most companies to analyse their potential benefits in the proposed performance, development and innovation targets.

Compared to traditional prototype manufacturing technologies, AM technologies significantly shortens the development process from concept to prototype or finished product. For specific applications and when using competent personnel, the process of developing prototypes and medical products can be shortened from weeks to days or even hours [10, 3].

The costs involved in developing prototypes with traditional methods are also significantly reduced when using the optimal AM technologies for the studied applications. Thus, it can be said that these technologies are easily adaptable and are more efficient in the case of prototypes and personalised medical products of small or unique series, especially in comparison with the traditional methods of injection moulding, casting or mechanical processing [11, 12]. One of the most affordable and readily available AM technologies is Material Extrusion (MEX), hence the plethora of research studies undertaken in this area. The selection of an AM technology is influenced by a variety of factors, such as: the functional role of the part, the work environment of the part, the characteristics of the technology, the experience of the company that makes the part, etc. In the report "The state of 3D printing 2018" [9], Sculpteo researchers state that Fused Deposition Modelling (a proprietary name for MEX by a leading international AM company) was the most used technology in 2017 (36%) and 2018 (46%) with an ascending general trend.

In this context, the current research paper proposes a study on the material type influence on three economic objectives in MEX fabrication. The importance of this research relies on the benefits which could be brought to companies in the early product development stages.

2 Materials and methods

Three economic objectives have been analysed, namely, estimated fabrication time, material usage and material cost. Their choice was directly corelated with the capabilities of the software to provide measurable outputs. To evaluate the influence of the material type on these three economic objectives, two commercial AM machines have been considered for the simulation. The first one is a low-cost Creality CR 20-Pro, chosen to represent the hobby and DIY market segment. A Zortrax M300+ AAM machine was chosen to represent the professional market segment with a capacity of a medium series production volume. Cura and ZSuite slicing software were used for the generation of Gcode and project files. Using Cura the files obtained were *.gcode and *.3mf files and using ZSuite the files obtained were *.zcodex and *.zprojx. Throughout the study, the optimised AM parameters were kept constant, as well as the component layout on the building platform of the two machines. Ten filaments were selected from the same two manufacturers and all components of the selected assembly were included in the analysis. For the Creality CR 20-Pro PLA, ABS, PETG, PC, NYLON filaments were used from Polymaker. The Zortrax M300+ equipment was simulated with Z-PLA, Z-ABS, Z-PETG, Z-PCABS, Z-NYLON from Zortrax. The diameter size is the same for all ten filaments, namely 1.75 mm. Table 1 shows the material characteristics used for all simulations.

Table 1. Material characteristics

Nr. Crt.	Brand	Material	Net Weight [g]	Extrusion temperature [^{0}C]	Cost [€]
1.	Polymaker	PLA	1000	210	29.95
2.		ABS	1000	260	29.95
3.		PETG	1000	240	29.95
4.		TPU95	750	235	49.95
5.		PC	1000	270	34.95
6.	Zortrax	Z-PLA	800	190	34.32
7.		Z-ABS	800	220	43.05
8.		Z-PETG	800	230	54.12
9.		Z-PCABS	800	260	54.12
10.		Z-NYLON	800	235	65.19

The assembly used for the study is a concept model (Figure 1) for an automatic wiping board [13]. The main mechanical components of the assembly are presented in Table 2. The electronics and software modules do not represent the target of the study, but their specific characteristics, functions and overall dimensions influenced the design of the concept model and its' assembly pattern.

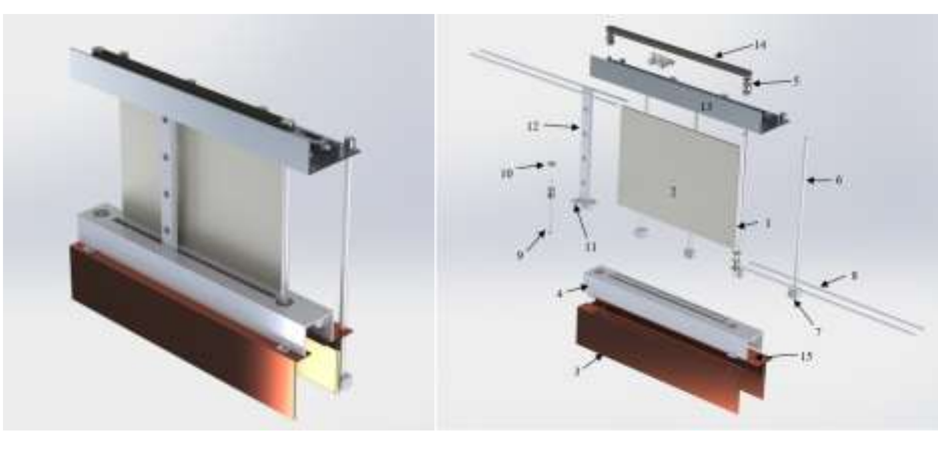


Fig. 1. CAD concept model of an automatic wiping board: a) assembled view; b) exploded view.

Table 2. Mechanical components of the automatic wiping board concept model

Nr. Crt.	Component name	Nr. of parts	General dimensions [mm]	Remarks
1.	Shaft 1	1	Ø8 x 280	-
2.	Table plate	1	280 x 200 x 5	-
3.	Base support	1	80 x 80 x 400	Model was split in 2 sections for 3D fabrication
4.	Intermediate support	1	50 x 40 x 400	Model was split in 2 sections for 3D fabrication
5.	Gear	4	Ø16 x 20	-
6.	Shaft 2	4	Ø8 x 320	Model was split in 2 sections for 3D fabrication
7.	Shaft support	4	20 x 20 x 15	-
8.	Shaft guide	4	Ø8 x 380	Model was split in 2 sections for 3D fabrication
9.	Shaft 3	2	Ø8 x 100	-
10.	Bearing	4	Ø23 x 8	Metal bearings were purchased
11.	Guide	2	30 x 30 x 15	-
12.	Sponge support	1	8 x 19 x 220	-
13.	Top support	1	40 x 85 x 400	Model was split in 2 sections for 3D fabrication
14.	Transmission belt	2	Ø15 x 8 x 350	Parts were purchased
15.	Screw	8	M8 x 25	Metal screws were outsourced to the CNC laboratory

Five build plates were created to optimise the AM economic objectives within three specific sets requirements, namely:

- Manufacturing requirements: two available AM machines (Creality CR 20-Pro, Zortrax M300+); 5 filament types from Zortrax; 5 filament types from Polymaker; heated build plates; 8-hour shift; one shift per working day; one technician; one engineer;
- Client requirements: 5 working days delivery time; one batch production;
- Functional requirements: the assembly is set to be used as a testing concept in an experimental stand.

Using Cura and ZSuite the five optimised build plates are presented in Figure 2 below.

Optimisation of the build plates was done in correspondence with the requirements and with the AM design rules imposed by the MEX technology.

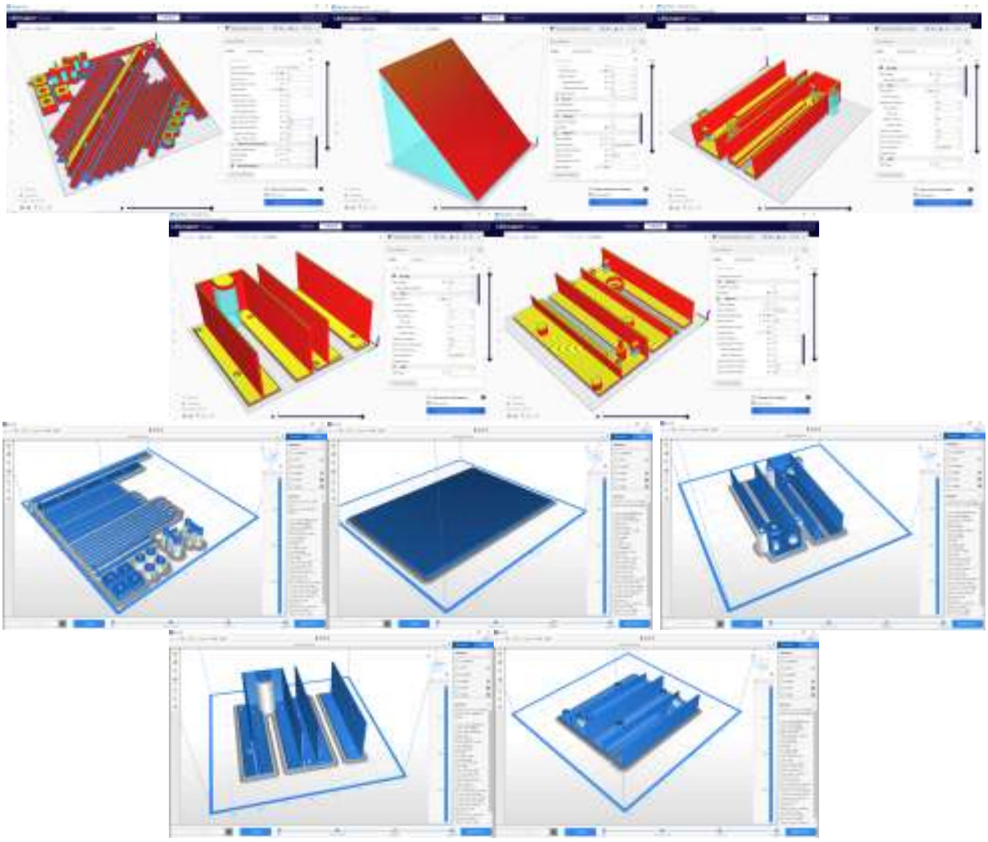


Fig. 2. Build plates layout using Cura (top red) on Creality CR20-Pro and using ZSuite (bottom blue) on Zortrax M300+

3 Results and discussions

Based on the optimised build plate layouts, all AM build parameters were optimised in order to meet the requirements. Table 3 presents the optimised parameters for five build plates generated on Creality CR20-Pro using PLA. Similarly, in Table 4 the optimised parameters are detailed for manufacturing of the five build plates in the Zortrax M300+ using Z-PLA. The optimisation process was undertaken for a total of 50 build plates. Next, the support structures were added (where necessary) and the slicing software was run for all 50 simulations, using two AM machines. Thus, for the Creality CR 20-Pro Table 5 was compiled, and for the Zortrax M300+ Table 6 was put together.

Table 3. AM fabrication characteristics for the Creality CR 20-Pro equipment using PLA filament

Parameters	Build plate 1	Build plate 2	Build plate 3	Build plate 4	Build plate 5
Material	PLA	PLA	PLA	PLA	PLA
Profile	Super Quality – 0.12 mm	Standard Quality – 0.2 mm	Dynamic Quality – 0.16 mm	Low Quality – 0.28 mm	Standard Quality – 0.2 mm

Layer Height	0.12 mm	0.20 mm	0.16 mm	0.28 mm	0.20 mm
Wall Thickness	1.20 mm	1.80 mm	0.8 mm	1.20 mm	1.00 mm
Infill Density	80%	20%	50%	70%	60%
Infill Pattern	Grid	Cubic	Triangles	Grid	Concentric
Extrusion Temperature	210^0C	210^0C	210^0C	210^0C	210^0C
Fabrication Speed	50 mm/s	30 mm/s	60 mm/s	40 mm/s	50 mm/s
Support	Yes	Yes	Yes	Yes	Yes
Support Placement	Everywhere	Touching build plate	Everywhere	Everywhere	Everywhere
Support overhang angle	30^0	45^0	35^0	45^0	45^0
Support pattern	Lines	ZigZag	Lines	Grid	Lines
Support density	5%	5%	10%	5%	5%
Build plate adhesion type	Raft	Raft	Raft	Raft	Raft
Estimated fabrication time	1d 17h 54min	2d 8h 23min	1d 1h 41min	1d 9h 55min	18h 55min
Material usage	225g	603g	193g	412g	219g
Material cost [euro]	6.74	18.06	5.78	12.34	6.56

Table 4. AM fabrication characteristics for the Zortrax M300+ equipment using Z-PLA filament

Parameters	Build plate 1	Build plate 2	Build plate 3	Build plate 4	Build plate 5
Material	Z-PLA	Z-PLA	Z-PLA	Z-PLA	Z-PLA
Support	Editable/ 55^0	Automatic	Automatic/ 30^0	Automatic/ 45^0	Editable/ 45^0
Nozzle diameter	0.4 mm	0.4 mm	0.4 mm	0.4 mm	0.4 mm
Layer thickness	0.14 mm	0.19 mm	0.19 mm	0.29 mm	0.19 mm
Quality	High	High	Normal	Normal	Normal
Fabrication type	Normal	Normal	Normal	Normal	Normal
Pattern	Patt. 0	Patt. 3	Patt. 2	Patt. 1	Patt. 1
Infill density	80%	20%	50%	70%	60%
Top Surface Layers	6	5	5	5	7
Bottom surface layers	6	3	4	5	4
Seam	Random	Random	Random	Random	Random

Max. Wall thickness	3.13 mm	2.73 mm	2.63 mm	2.63 mm	3.13 mm
First layer gap	0.35 mm	0.40 mm	0.30 mm	0.46 mm	0.35 mm
Raft	Enabled/ 7 layers	Enabled/ 4 layers	Enabled/ 4 layers	Enabled/ 4 layers	Enabled/ 7 layers
Estimated fabrication time	1d 8h 15min	12h 26min	15h 29min	23h 26min	20h 35min
Material usage	295g	183g	204g	367g	243g
Material cost [euro]	12.66	7.85	8.75	15.74	10.42

Table 5. Economic objectives for Creality CR 20-Pro equipment

Build plates	Materials	Estimated fabrication time	Material usage [g]	Material cost [euro]
Build plate 1	PLA	1d 17h 54min	225	6.74
	ABS	1d 17h 45min	204	6.11
	PETG	1d 17h 51min	256	7.67
	TPU95	1d 18h 19min	222	14.79
	PC	1d 17h 16min	205	7.16
Build plate 2	PLA	2d 8h 23min	603	18.06
	ABS	2d 8h 23min	535	16.02
	PETG	2d 8h 23min	671	20.10
	TPU95	2d 8h 43min	593	17.76
	PC	2d 8h 3min	535	18.70
Build plate 3	PLA	1d 1h 41min	193	5.78
	ABS	1d 1h 41min	171	5.12
	PETG	1d 1h 53min	215	6.44
	TPU95	1d 2h 6min	190	12.65
	PC	1d 1h 19min	171	5.98
Build plate 4	PLA	1d 9h 55min	412	12.34
	ABS	1d 9h 55min	366	10.96
	PETG	1d 10h 19min	459	13.75
	TPU95	1d 21h 0min	385	25.64
	PC	1d 9h 46min	366	12.79

Build plate 5	PLA	18h 55min	219	6.56
	ABS	18h 55min	194	5.81
	PETG	19h 19min	243	7.28
	TPU95	19h 3min	215	14.32
	PC	18h 48min	194	6.78

Table 6. Economic objectives for Zortrax M300+ equipment

Build plates	Materials	Estimated fabrication time	Material usage [g]	Material cost [euro]
Build plate 1	Z-PLA	1d 8h 15min	295	12.66
	Z-ABS	1d 9h 55min	254	13.67
	Z-PETG	1d 8h 28min	318	21.51
	Z-PCABS	1d 8h 25min	306	20.70
	Z-NYLON	1d 10h 18min	193	15.73
Build plate 2	Z-PLA	12h 26min	183	7.85
	Z-ABS	12h 13min	153	8.23
	Z-PETG	12h 14min	194	13.12
	Z-PCABS	12h 46min	185	12.52
	Z-NYLON	13h 2min	126	10.27
Build plate 3	Z-PLA	15h 29min	204	8.75
	Z-ABS	16h 38min	164	8.83
	Z-PETG	15h 8min	211	14.27
	Z-PCABS	15h 28min	203	13.73
	Z-NYLON	16h 0min	138	11.25
Build plate 4	Z-PLA	23h 26min	367	15.74
	Z-ABS	1d 0h 2min	317	17.06
	Z-PETG	1d 1h 34min	396	26.79
	Z-PCABS	1d 1h 43min	369	24.96
	Z-NYLON	1d 0h 14min	272	22.16
Build plate 5	Z-PLA	20h 35min	243	10.42

	Z-ABS	20h 34min	204	10.98
	Z-PETG	20h 16min	264	17.86
	Z-PCABS	20h 47min	250	16.91
	Z-NYLON	21h 21min	163	13.28

Study results were analysed in correspondence with the manufacturing requirements and the optimum fabrication scenario was selected. Graphical representations were used to discuss the best choice of manufacturing for the assembly, and are presented in Figures 3, 4 and 5 for both types of AM equipment utilised.

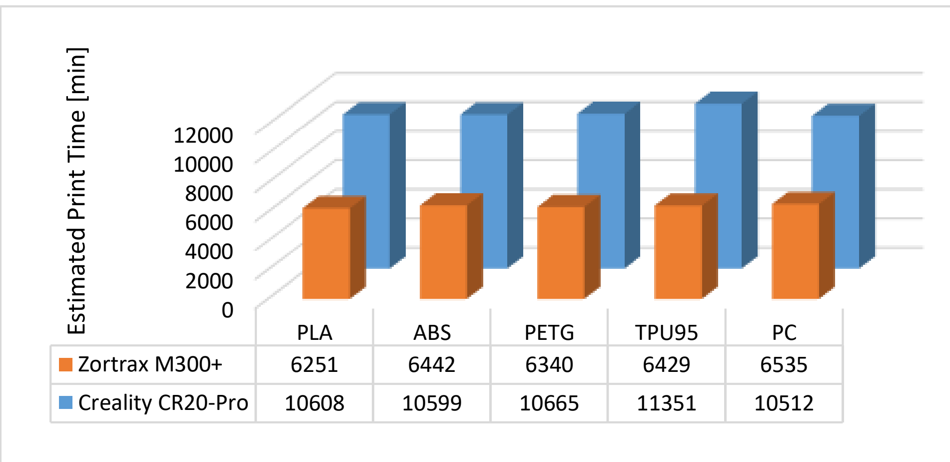


Fig. 3. Estimated fabrication time for manufacturing the automatic wiping board concept model

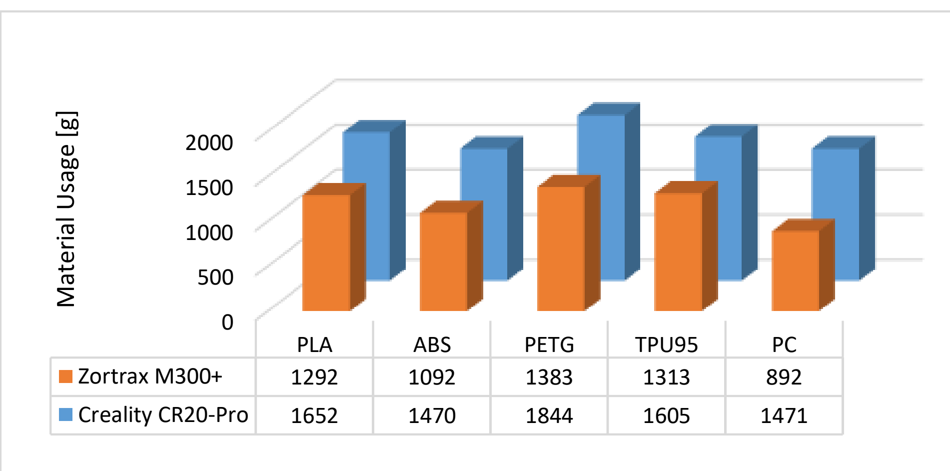
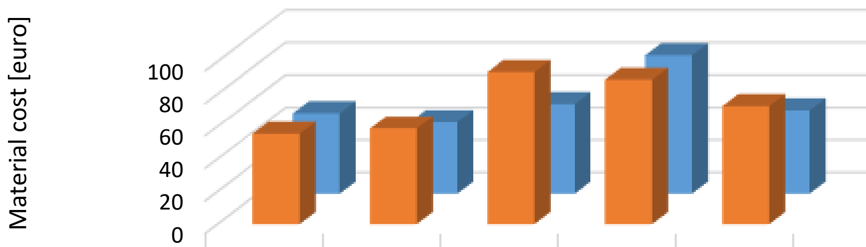


Fig. 4. Material consumption for AM fabrication of the automatic wiping board concept model

Figure 3 shows that the estimated fabrication time of the selected concept model is considerably lower overall and across all build plates if Zortrax M300+ is used for manufacturing. Also, on this equipment, PLA has the quickest cumulative fabrication time out of all building platforms, with almost 200 minutes ahead of all other materials. The Zortrax M300+ is faster than the Creality CR20-Pro with an average of 4347 minutes (approximately 3 days).

From Figure 4, is possible to state that the lowest material consumption is achieved by using the Zortrax M300+ for manufacturing of the automatic wiping board concept model. Across all build platforms the lowest material usage is registered for PC and the highest for PETG. The consumption distribution for material type on all platforms is similar for the Creality CR20-Pro.



	PLA	ABS	PETG	TPU95	PC
Zortrax M300+	55.4268	58.76325	93.55995	88.82445	72.68685
Creality CR20-Pro	49.4774	44.0265	55.2278	85.15955	51.41145

Fig. 5. Estimated material cost for manufacturing the automatic wiping board concept model

Overall material costs (Figure 5) were higher for the Zortrax supplier in comparison with Polymaker, with PETG having the top value with 93.56 Euros for building the entire concept model. The lowest value on this machine is attributed to PLA.

Fig. 6. Functional concept model fabricated on Zortrax M300+ using PLA

Based on the restrictions and on the functional role of the concept model the best choice of manufacture was using the Zortrax M300+ AM machine with PLA filament (Figure 6). Two of the three economic objectives have scored better values in the analysis undertaken for this equipment. Cost-wise, the average difference represents only 16.79 Euro, which is acceptable to the client if the imposed time frame is met.

4 Conclusion

There is a wide range of AM technologies, developed to meet both consumer and manufacturer requirements. Functional prototypes and finished parts manufactured with AM technologies have wide applicability in fields such as manufacturing of industrial and consumer products, automobiles, medicine and dentistry, aeronautics, etc. The materials used are varied, from polymers, metals and ceramics to new developments of composites. Usage of AM technologies offers companies multiple benefits in terms of time efficiency and cost reduction within the product life cycle, as well as increased flexibility in their design and customisation. All these benefits increase the rate of adoption of AM technologies for the entire life cycle of a product. Within this general background, the authors undertook a detailed study on the material type influence on three economic objectives in MEX fabrication which were presented, with the possibilities of result replication under different sets of requirements. The study showed that there are clear differences in terms of economic objective performance between equipment, but also in terms of studied materials. This result was consistent, regardless of the geometry and general dimensions of the fabricated parts.

Further research includes the analysis of multiple material manufacturers, in order to evaluate the influence of chemical composition on economic outputs.

References

1. K. B. Kahn, *The PDMA handbook of new product development (3rd ed.)*, John Wiley & Sons Inc. (2012)
2. K. Ulrich, S. Eppinger, *Product Design and Development (5th ed.)*, McGraw Hill Publishing Company Ltd. (2012)
3. T. Wohlers, *Wohlers Report 2018: 3D Printing and Additive Manufacturing State of the Industry*, Wohlers Associates (2018)
4. C. Barnatt, *The Next Big Thing: From 3D Printing to Mining the Moon*, CreateSpace Independent Publishing Platform (2015)
5. E. Kennedy, A. Giampetro-Meyer, *Loy. U. Chi. L.J.*, pp. 1-35, **46**, 4 (2015)
6. S. Chong, G.T. Pan, J. Chin, P.L. Show, T.C.K. Y ang, C.M. Huang, *Sustainability*, **10** (2018)
7. L. Cox, *Disruption*, available at: https://disruptionhub.com/disruptive-3d-printing-really/ (2016)
8. C. Öberg, T. Shams, N. Asnafi, *Technol. Innov. Manag. Rev.*, pp. 15-33, **8**, 6 (2018)
9. C. Moreau, *The state of 3D printing 2018*, Available at: https://www.sculpteo.com/media/ebook/State_of_3DP_2018.pdf (2018)
10. I. Gibson, *J. Manuf. Technol. Manag.*, pp. 10–17, **28**, 1, (2017)
11. A. Mohsen, *Bus. Horiz.*, pp. 677 – 688, **60**, 5 (2017)
12. D. Strong, M. Kay, B. Conner, T. Wakefield, G. Manogharand, *Addit. Manuf.*, pp. 159- 173, **21** (2018)
13. A.B. Nuță, *Mobile app implementation, web simulation and development of a physical model for an automatic wiping board*, Dissertation Thesis, University POLITEHNICA of Bucharest (2020)