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Selection of additive manufacturing process using the AHP method

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Abstract: The term Rapid Prototyping means creating a physical prototype or the basic model from which would later emerge newer models and finally the final product. Over time, the term Rapid Prototyping is replaced by term Additive Manufacturing. The higher quality of workpieces and similarity to finished products lead to pieces which can be used, immediately after the completion, in practical applications, or can completely replace products made by traditional technological processes. Unlike traditional technological processes of removing material (turning, milling, drilling, etc.) in these processes all the parts are made by applying material in layers. Each applied layer is a thin cross section of a model generated in some of the software for 3D modelling. Because in the real world each deposited layer has a certain thickness, the resulting worpiece will be an approximation of original model. Today, on the market, there are several additive manufacturing processes. These processes differ according to the type of material used for making pieces and according to the manner in which the layers of material are applied and joined together. These differences affect on dimensional accuracy of workpiece, mechanical properties, surface roughness, speed of technological process, necessity of postprocessing and the overall costs associated with the machine and technological process. In this paper will be shown production of CAD 3D model with three different additive manufacturing processes: 3D printing, Fused Deposition Modelling and Selective Laser Sintering. The objective of this work is to choose one of these three processes that is most suitable for practical application. According to this, there are defined certain criteria and AHP method is used for making decision.

Izvorni znanstveni rad

Sažetak: Termin brza izrada prototipova podrazumijeva kreiranje fizičkog prototipa ili osnovnog modela iz kojeg će kasnije proizići noviji modeli i naposljetku konačan proizvod. S vremenom se ovaj termin zamijenio terminom aditivna proizvodnja. Veća kvaliteta izradaka i sličnost s gotovim proizvodima dovodi do toga da se izradci odmah po završetku izrade primjenjuju u praksi te u cijelosti zamjenjuju proizvode izrađene tradicionalnim tehnološkim procesima. Za razliku od tradicionalnih tehnoloških procesa uklanjanja materijala (tokarenje, glodanje, bušenje,…) kod ovakvih procesa se svi dijelovi izrađuju nanošenjem materijala u slojevima. Svaki naneseni sloj je tanki poprečni presjek modela generiranog u nekom od CAD softvera za 3D modeliranje. Budući da u stvarnom svijetu svaki naneseni sloj ima određenu debljinu, dobiveni izradak će biti aproksimacija originalnog modela. Danas je na tržištu zastupljen veliki broj aditivnih postupaka. Ti postupci se razlikuju prema vrsti materijala koji se koristi za izradu te prema načinu na koji se slojevi materijala nanose i međusobno spajaju. Ove razlike utječu na dimenzijsku točnost dobivenog izradka, mehanička svojstva, površinsku hrapavost, brzinu procesa izrade, nužnost naknadne obrade te cjelokupne troškove vezane za stroj i proces izrade. U ovom radu bit će prikazana izrada CAD 3D modela s tri različita aditivna postupka: 3D printanje, taloženje rastaljenog materijala i selektivno lasersko sinteriranje. Cilj je od ta tri postupka odabrati onaj koji je najprikladniji za praktičnu upotrebu. U skladu s tim definirani su određeni kriteriji te je za odlučivanje upotrebljena AHP metoda.

1. Introduction

The term ''rapid prototyping'' is used in various industries to describe the process of rapid development of a representative system or product before its final implementation and commercialization. In the context of product development, this term includes modern technologies that are used to create physical prototypes directly from digital data.

The users of these technologies are eventually concluded that this term is not suitable because it does not describe well enough the current application of these technological solutions. Improvements in the quality of the workpieces obtained from such machinery and equipment contribute to workpieces that are very similar to the finished product. Many parts after the completion on that machines have practical application so it is not longer possible to speak about them as prototypes. Also, the term ''rapid prototyping'' ignores the fundamental principle on which is based this technology, and that is that all parts are made additive. Accordingly, there was a change, and today instead of ''rapid prototyping'' it is more often used the term ''additive manufacturing''.

The basic principle on which is based this technology is to first generate the model which should be made in CAD software for 3D modeling and then the same model produce the appropriate device without the need for detailed planning of technological processes and production. Hereby is significantly simplified the process of creating complex 3D objects directly from CAD files. Other manufacturing processes require careful and detailed analysis of the geometry of the object to determine detailes such as for example the order of technological operations, tools and equipment that are necessary in the production process, a way of accepting and clamping workpieces, etc. On the other hand, additive manufacturing requires basic dimensional data of the workpiece and a basic understanding the way the machine works and applies material.

Machines used in additive manufacturing make objects by applying material in layers. Each applied layer is a thin cross section of a model generated in some of the software for 3D modelling. Because in the real world each deposited layer has a certain thickness, the resulting workpiece will be an approximation of original model. If layers of material are thinner and more densely applied, workpiece will be more similar to the original model. All machine that are used today for these purposes are based on additive processes. Today on the market there are a high number of these processes and constantly find new methods of additive manufacturing. Existing processes vary according to the type of material used to build models and the way in which the layers of material are applied and joined together. These differences affect on dimensional accuracy of workpieces, mechanical properties, surface roughness, speed of technological process, necessity of postprocessing and the overall costs associated with the machine and technological process.

In this paper will be shown production of CAD 3D model designed in CAD software PTC Creo/ProEngineer with three different additive manufacturing processes: 3D printing, Fused Deposition Modeling and Selective Laser Sintering. The model will be made on machines owned by the Department of Production Engineering of the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture in Split. After completion of production, the objective is to choose one of these three processes which is most suitable for practical application. For this purpose there are defined certain criteria and for making decision is used AHP method.

2. Application of additive manufacturing

Additive manufacturing is usually used in order to visualize the products that are still under development. It is generally accepted that the spatial model is much more useful for the understanding of the conceptual design and the intentions of designers and constructors of the draft and rendered representations of product. Although, drafts today can be quickly made in modern CAD softwares, in most cases for the validation and final approval of the design is required a spatial model of the product.

Additive manufacturing technology has two key levels of application (Figure 1): rapid prototyping and rapid manufacturing. Rapid prototyping means, such as the term refers to that, creating various prototypes, test models, samples, models, etc. while rapid manufacturing means producing finished products, equipment, tools, components or parts that immediately after the technological process find its implementation in practice.

2.1. Rapid prototyping

Rapid prototyping includes conceptual modeling and functional prototyping. Conceptual prototyping refers to an additive manufacturing of a model that spatially shows the basic concept of some idea or innovation. In most cases these workpieces can not be loaded by force. They are used to illustrate the physical appearance of the future product and its dimensions and proportions. Also, they are often used to verify the accuracy of CAD documents and drafts, and to stimulate discussion within the group of experts, which can result in design modifications. Often these models are produced in a variety of colors for the evaluation of the concept and to highlight some specific parts of the model. This is also a way to encourage discussion. Functional prototypes are made to perform an inspection and control of individual functions of future products over them and to make it easier to decide about the start of production. They are often used to test ergonomics and suitability of the future products for handling. Also, neither of these workpieces can not be treated and used in practice as finished products.

2.2. Rapid manufacturing

Rapid manufacturing refers to all additive processes where workpieces are final products or different parts that must be assembled and that immediately after the production process find their application in practice. Rapid manufacturing includes direct tooling and direct manufacturing. Direct manufacturing means that as a result of additive process gets the final product. Today there are different types of materials that can be used in direct additive manufacturing processes such as metals,

plastics, ceramics, etc. It is important that the additive process and material achieve mechanical properties of the workpiece on which was based engineering design, product development and testing.
Figure 2 (above) shows aircraft engine cover hinge made by Selective Laser Melting process. That hinge fulfills its function as successful as it would do it a product made by the traditional production process.

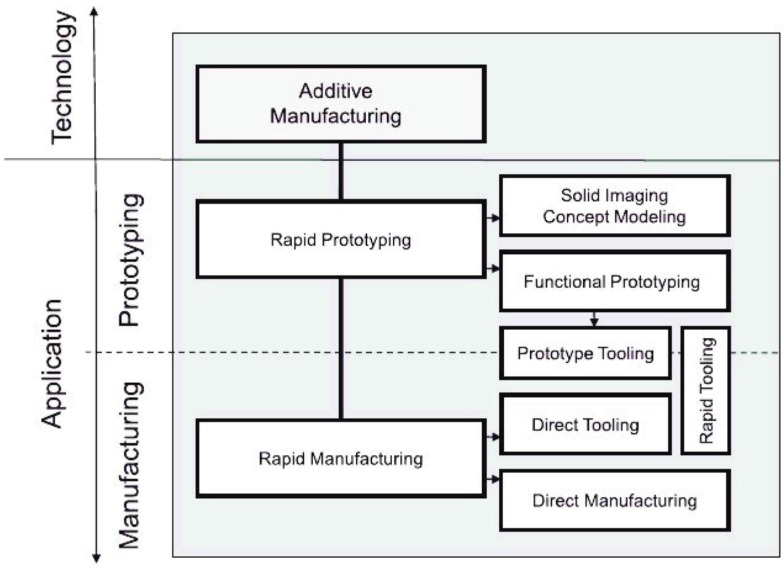


Figure 1. Levels of application additive manufacturing technology [1]
Slika 1. Razine primjene tehnologije aditivne proizvodnje [1]

Figure 2. Aircraft engine cover hinge (top) produced by Selective Laser Melting process [1]
Slika 2. Šarka poklopca avionske turbine (gore) izrađena aditivnim postupkom selektivnog laserskog taljenja [1]

2.3. Rapid tooling

Rapid tooling includes additive processes in which are made final products that can be used later as a mold cores, mold cavities, various tool accessories and inserts in dies and molds. There are two sub-application of rapid tooling: direct tooling and prototype tooling.
Direct tooling is actually equivalent to direct manufacturing. Direct tooling includes making dies, molds, tools and tool accessories and direct manufacturing generating all other products.
Prototype tooling includes additive processes in which are made tools that can be used later for producing other workpieces, mostly by injection molding technology, individually or in small batches. The prototype of tool is used to verify and validate design and suitability of tool before its finalization but also to cheapen individual and small-scale production (in cases where a tool made by additive manufacturing process completely replaces the right tool).

Figure 3. Mold for making golf balls produced by Direct Metal Laser Sintering process[1]
Slika 3. Kalup za izradu loptice za golf izrađen aditivnim postupkom direktnog laserskog sinteriranja metala [1]

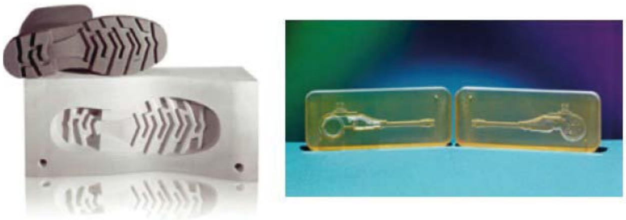


Figure 4. Molds for injection molding produced by additive manufacturing processes [1]
Slika 4. Kalupi za injekcijsko prešanje izrađeni aditivnim postupcima [1]

3. Phases of aditive manufacturing process

Each modern department for product development and design should possess a machine for generating workpieces by additive process (in most cases it is a 3D printer). These machines are characterized by ease of use, mobility and the ability to create complex and geometrically demanding models. Each step in the work of such machines to the operator does not mean a great effort or require long-term training. It is enough to know the principle on which machine works and applies material and have a basic information about the size and geometry of the workpiece. Before and after the generation of the model in such machine, there are a number of actions that should be made in order to have a model that will be later acceptable and applicable in practice. Phases of additive manufacturing process are shortly mentioned in this chapter.

Phases of additive manufacturing process:

1) Conceptualization and Computer Aided Design of model;
2) Conversion to STL format;
3) Transfer to additive manufacturing machine and STL file manipulation;
4) Machine setup;
5) Building the part;
6) Removal;
7) Postprocessing;
8) Practical application.

Figure 5. Phases of the additive manufacturing process [2]
Slika 5. Faze procesa aditivne proizvodnje [2]

4. Additive production of constructed CAD model

In this chapter will be shown production of model (Figure 6) constructed in CAD software PTC Creo/ProEngineer with additive processes: 3D printing, Fused Deposition Modelling and Selective Laser Sintering. Each of these processes is briefly described.

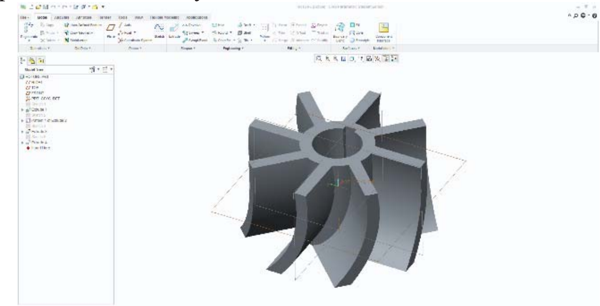


Figure 6. CAD model
Slika 6. CAD model

Figure 7. Workpiece made by Selective Laser Sintering process
Slika 7. Izradak dobiven postupkom selektivnog laserskog sinteriranja

4.1. 3D printing

3D printing process is based on inkjet nozzles which apply liquid adhesive supply to a powdered polymer material. After conversion into STL format CAD model should be sliced, using the appropriate computer program, to hundreds of digital cross sections. Printing process begins by heating the chamber and applying the layer of the polymer powder thickness 3,18 mm on which the model should be made and after the completion easily removed. This means the preparation for the printing process. Next, slider apply along the chamber a new layer of polymer powder thickness 0,1 mm. After that, inkjet print head pass through the chamber and apply adhesive supply and color. The first layer of powder is solidified according to form of the first section of the STL model. The rest of the powder which is outside contours of the model serve as supporting structure during printing process. After completion of the process that powder can be recycled. The same process is repeated until the development of the entire model. Once the model is built the rest of powder from the chamber should be sucked into the tank and the model blown with compressed air in a separate chamber.

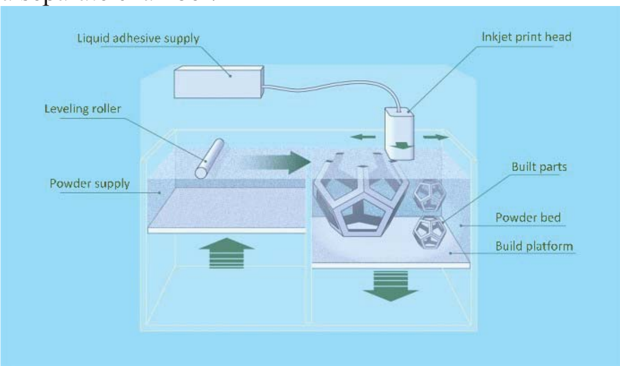


Figure 8. 3D printing process [3]
Slika 8. Postupak 3D printanja [3]

4.2. Fused Deposition Modeling

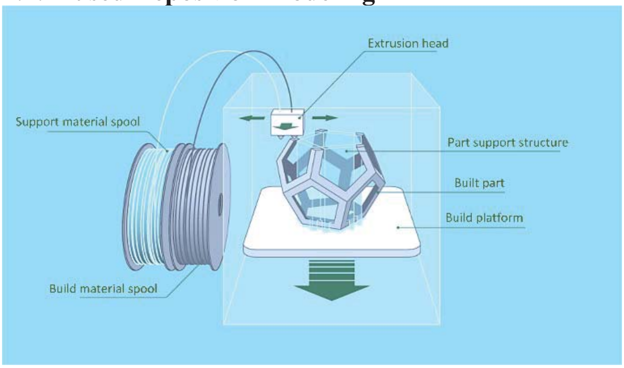


Figure 9. Fused Deposition Modeling process [3]
Slika 9. Postupak taloženja rastaljenog materijala [3]

A Fused Deposition Modeling process today on the rapid prototyping market takes up more than 50%. In this process the polymer material in the form of a wire passes through the nozzle. That material comes out of the nozzle in a molten state. Also, it quickly solidifies at room temperature and because of that it is necessary to maintain the temperature of the molten material just above the solidification temperature. After making the first layer the build platform moves down by the thickness of the new layer (z axis) and after that new layer applies. Extrusion head moves in x-y plane. If some complex geometric models should be created by this process then it is required a supporting structure. In that case it is good to use a double extrusion head. In the first nozzle is located a build material and in the other support material. Once the model is built supporting structure can be very easily removed by melting in water or fracturing. Also models can be further processed by turning, milling, grinding or by some other process. Materials that can be used in this additive manufacturing process are: ABS, PLA, PC, PP, PE-HD, PE-LD, etc.

4.3. Selective Laser Sintering

Selective Laser Sintering process is based on the laser beam action. Laser beam sinters a powder material such as polyimide, polystyrene, metal powders, thermoplastics, etc. The entire process takes place in a strictly controlled gas atmosphere in the chamber inside the machine. After converting CAD 3D model into standard STL format the machine starts making the first layer. A thin layer of powder is applied on build platform. After that a leveling roller flatten that layer in order to be more evenly distributed. In the next step the laser heats the powder at a temperature lower than the melting point in order to achieve connection and solidification of material particles.

After the first layer was created the build platform moves down from 0,05 to 0,12 mm (z axis). The process is repeated until desired geometry of the model is created. After the final model is obtained, the last step is cleaning and removing the rest of material.

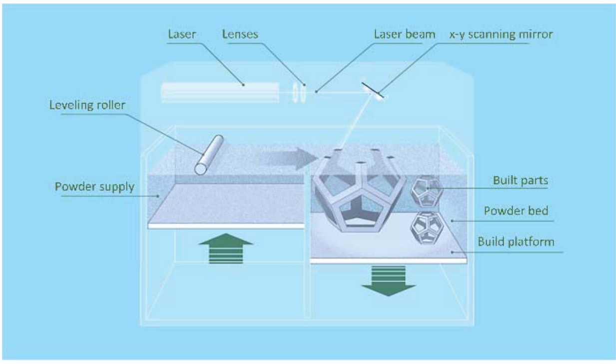


Figure 10. Selective Laser Sintering process [3]
Slika 10. Postupak selektivnog laserskog sinteriranja [3]

The rest of powder should be blow out and recycled. Most of the models obtained by this process is ready for use immediately after cleaning. In this process there is no need for creating a support structure because the powder that is outside contours of the model has a supporting function.

5. AHP method

After model was made by additive manufacturing process the next step is making decision using the AHP method. For that purpose there are defined objective, six different criteria and possible alternatives. (Figure 11).

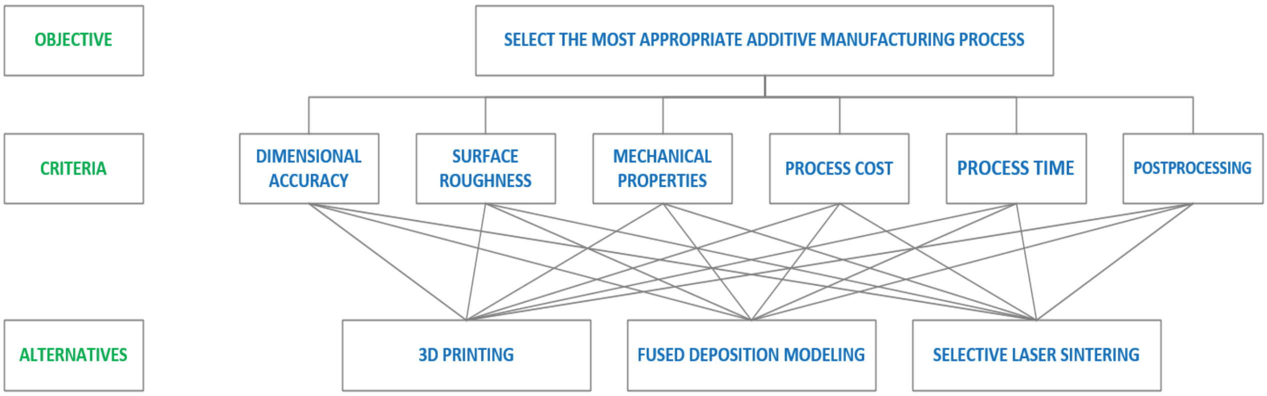


Figure 11. AHP model with objective, criteria and alternatives
Slika 11. AHP model sa ciljem, kriterijima i alternativama

Table 1. Informations available to the decision maker
Tablica 1. Informacije s kojima raspolaže donositelj odluke

ALTERNATIVES	CRITERIA					
	DIMENSIONAL ACCURACY *	SURFACE ROUGHNESS **	MECHANICAL PROPERTIES ***	PROCESS COST (HRK)	PROCESS TIME (min)	POSTPROCESSING (min)
3D PRINT	0,38	7,48	27	550,00	66	8
FDM	0,50	4,30	37	481,25	146	5
SLS	0,17	6,82	48	1378,96	195	13

* Deviation of bore diameter from the nominal value (in mm)

** Measured surface roughness (in µm)

*** Taken only tensile strength (in MPa)

Table 2. Saaty scale of relative importances
Tablica 2. Saatyeva skala relativne važnosti

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Table 3. Pairwise comparision matrix
Tablica 3. Procjene omjera težina kriterija

	DIMENSIONAL ACCURACY	SURFACE ROUGHNESS	MECHANICAL PROPERTIES	PROCESS COST	PROCESS TIME	POSTPROCESSING
DIMENSIONAL ACCURACY	1	1	3	7	9	7
SURFACE ROUGHNESS	1	1	3	7	9	7
MECHANICAL PROPERTIES	1/3	1/3	1	5	9	7
PROCESS COST	1/7	1/7	1/5	1	3	3
PROCESS TIME	1/9	1/9	1/9	1/3	1	3
POSTPROCESSING	1/7	1/7	1/7	1/3	1/3	1
∑	2,730	2,730	7,454	20,667	31,333	28,000

Table 4. Calculated weight criteria
Tablica 4. Izračunate težine kriterija

	DIMENSIONAL ACCURACY	SURFACE ROUGHNESS	MECHANICAL PROPERTIES	PROCESS COST	PROCESS TIME	POSTPROCESSING	w
DIMENSIONAL ACCURACY	0,366	0,366	0,402	0,339	0,287	0,250	**0,335**
SURFACE ROUGHNESS	0,366	0,366	0,402	0,339	0,287	0,250	**0,335**
MECHANICAL PROPERTIES	0,122	0,122	0,134	0,242	0,287	0,250	**0,193**
PROCESS COST	0,052	0,052	0,027	0,048	0,096	0,107	**0,064**
PROCESS TIME	0,041	0,041	0,015	0,016	0,032	0,107	**0,042**
POSTPROCESSING	0,052	0,052	0,019	0,016	0,011	0,036	**0,031**
	1,000	1,000	1,000	1,000	1,000	1,000	1,000

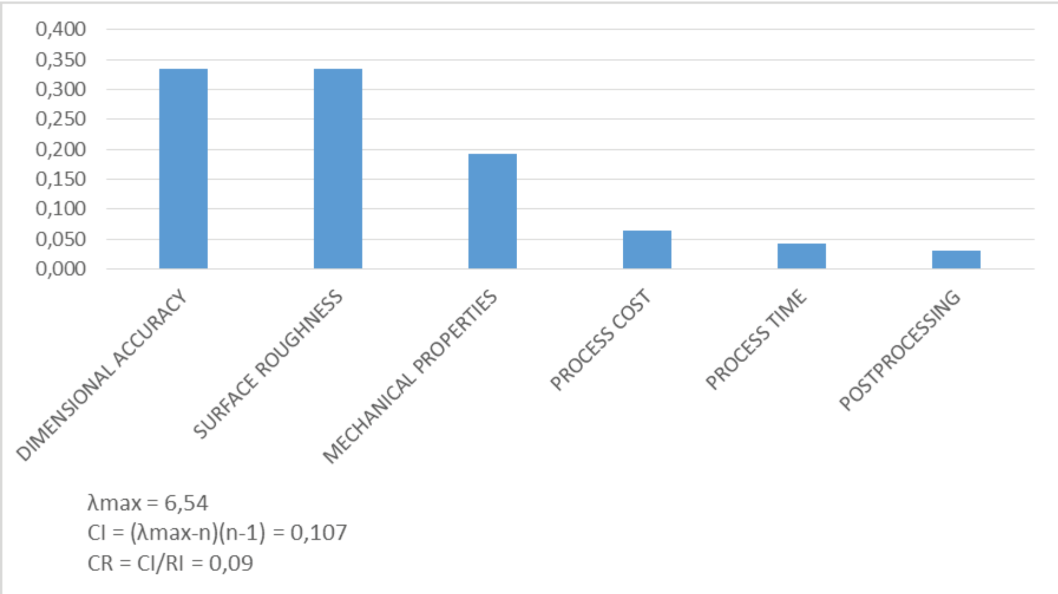
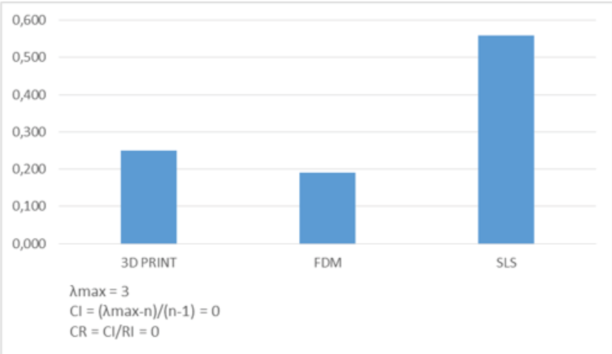


Figure 12. Weight of criteria
Slika 12. Težine kriterija

DIMENSIONAL ACCURACY

D.A.	3D PRINT	FDM	SLS
3D PRINT	1	1,316	0,447
FDM	0,760	1	0,340
SLS	2,235	2,941	1
∑	3,995	5,257	1,787

D.A.	3D PRINT	FDM	SLS	w
3D PRINT	0,250	0,250	0,250	0,250
FDM	0,190	0,190	0,190	0,190
SLS	0,559	0,559	0,559	0,559
∑	1,000	1,000	1,000	1,000



SURFACE ROUGHNESS

S.R.	3D PRINT	FDM	SLS
3D PRINT	1	0,575	0,912
FDM	1,740	1	1,587
SLS	1,096	0,630	1
∑	3,836	2,205	3,499

S.R.	3D PRINT	FDM	SLS	w
3D PRINT	0,261	0,261	0,261	0,261
FDM	0,453	0,453	0,453	0,453
SLS	0,286	0,286	0,286	0,286
∑	1,000	1,000	1,000	1,000

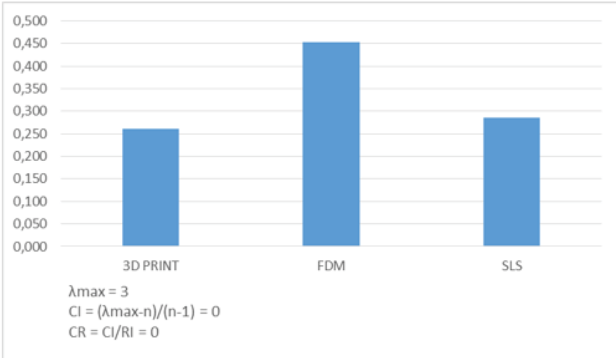
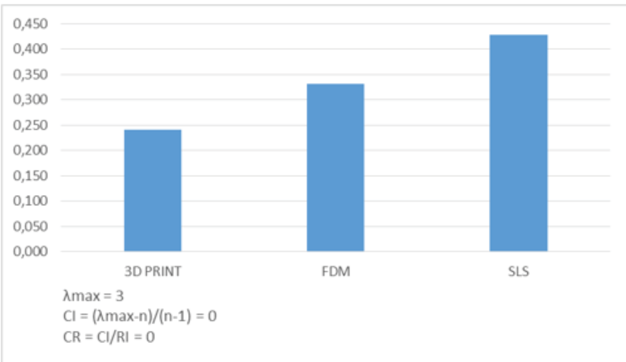


Figure 13. Ranking of alternatives according to the criteria "dimensional accuracy" and "surface roughness"
Slika 13. Prioriteti alternativa po kriteriju "dimenzijska točnost" i "kvaliteta površine"

MECHANICAL PROPERTIES

M.P.	3D PRINT	FDM	SLS
3D PRINT	1	0,730	0,563
FDM	1,370	1	0,771
SLS	1,778	1,297	1
∑	4,148	3,027	2,333

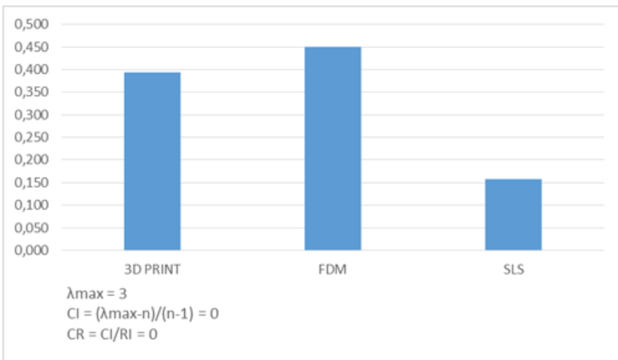
M.P.	3D PRINT	FDM	SLS	w
3D PRINT	0,241	0,241	0,241	0,241
FDM	0,330	0,330	0,330	0,330
SLS	0,429	0,429	0,429	0,429
∑	1,000	1,000	1,000	1,000



PROCESS COST

P.C.	3D PRINT	FDM	SLS
3D PRINT	1	0,875	2,507
FDM	1,143	1	2,865
SLS	0,399	0,349	1
∑	2,542	2,224	6,373

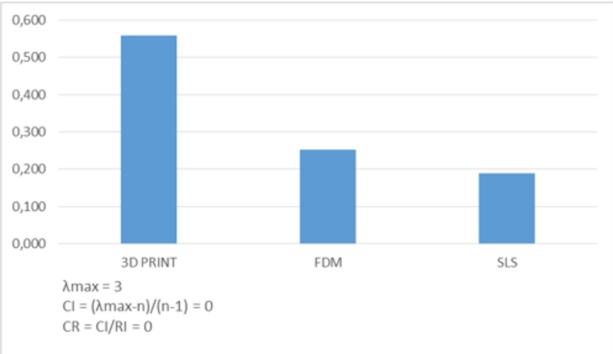
P.C.	3D PRINT	FDM	SLS	w
3D PRINT	0,393	0,393	0,393	0,393
FDM	0,450	0,450	0,450	0,450
SLS	0,157	0,157	0,157	0,157
∑	1,000	1,000	1,000	1,000



PROCESS TIME

P.T.	3D PRINT	FDM	SLS
3D PRINT	1	2,212	2,955
FDM	0,452	1	1,336
SLS	0,338	0,749	1
∑	1,791	3,961	5,290

P.T.	3D PRINT	FDM	SLS	w
3D PRINT	0,558	0,558	0,558	0,558
FDM	0,252	0,252	0,252	0,252
SLS	0,189	0,189	0,189	0,189
∑	1,000	1,000	1,000	1,000



POSTPROCESSING

POSTP.	3D PRINT	FDM	SLS
3D PRINT	1	0,625	1,625
FDM	1,600	1	2,600
SLS	0,615	0,385	1
∑	3,215	2,010	5,225

POSTP.	3D PRINT	FDM	SLS	w
3D PRINT	0,311	0,311	0,311	0,311
FDM	0,498	0,498	0,498	0,498
SLS	0,191	0,191	0,191	0,191
∑	1,000	1,000	1,000	1,000

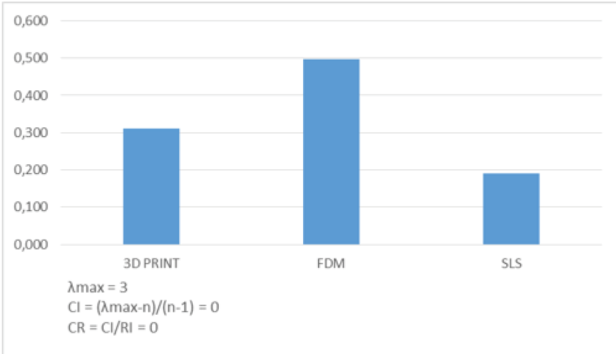


Figure 14. Ranking of alternatives according to the criteria "mechanical properties", "process cost", "process time" and "postprocessing"
Slika 14. Prioriteti alternativa po kriterijima "mehanička svojstva", "trošak izrade", "vrijeme izrade" i "naknadna obrada"

ALTERNATIVES	CRITERIA AND WEIGHTS						OVERALL PRIORITIES OF ALTERNATIVES
	DIMENSIONAL ACCURACY	SURFACE ROUGHNESS	MECHANICAL PROPERTIES	PROCESS COST	PROCESS TIME	POSTPROCESSING	
	0,335	0,335	0,193	0,064	0,042	0,031	
3D PRINT	0,250	0,261	0,241	0,393	0,558	0,311	0,276
FDM	0,190	0,453	0,330	0,450	0,252	0,498	0,334
SLS	0,559	0,286	0,429	0,157	0,189	0,191	0,390

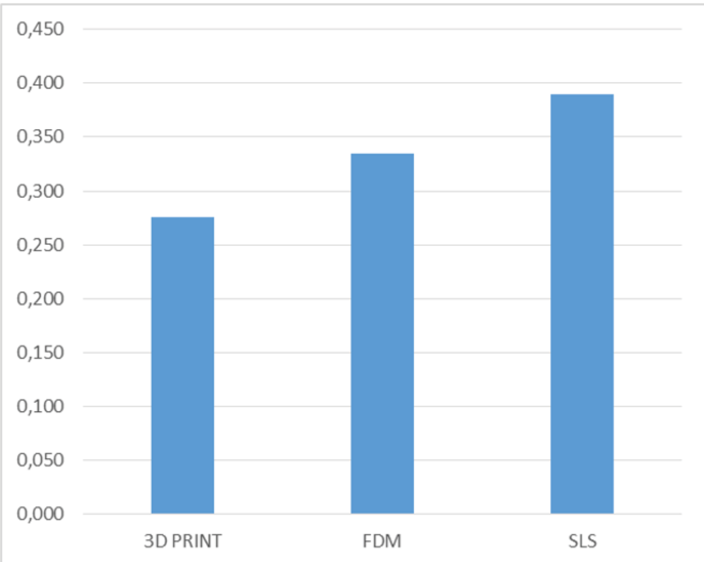


Figure 15. Overall priorities of alternatives
Slika 15. Ukupni prioriteti alternativa

6. Conclusion

Additive manufacturing technology is still relatively new and unknown. Making products by additive processes ensure savings in production time and costs. This technology can create geometrically complex models without using molds, CNC machines or manual processing, or it is possible to create products whose production by traditional processes is impossible or difficult. However, this technology is still underrepresented in the industry due to lack of information and standardization, high investment costs, limited dimensions of the working volume and limited number of available materials. It can be expected that these disadvantages will be removed by the time and that this technology will become more accessible, faster, more accurate and more economical. Although, the additive manufacturing can not compete with mass production techniques, it is clear now that future companies will have 3D printers that will work together with milling machines, presses, foundries, equipment for plastic injection molding, etc. and that printers will progressively replace those machines.

In this article constructed CAD model was made by three different additive manufacturing processes. The objective was to choose one of these three processes that is most suitable for practical aplication. For that purpose there were defined six different criteria as base for comparision of processes. For making decision was used Analytic Hierarchy Process (AHP method). On the beginning using the Saaty scale of relative importances were calculated weight criteria. After that, for each criteria was obtained ranking of alternatives. Finally, there were calculated and overall priorities of alternatives. It can be concluded from Figure 15. that, if we take into account positions of alternatives by all criteria of all three additive manufacturing process, the highest priority has the Selective Laser Sintering process, then follows Fused Deposition Modeling and at the end 3D printing process.

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