

Cost optimization of additive manufacturing in wood industry

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Software packages for 3D design and additive manufacturing (AM) technologies, initially known as rapid prototyping (RP) have emerged during the last years, as a cutting edge solutions for custom prototyping. These new tools and technologies lower the design costs, but also allow rapid creation of fully functional components. This paper describes the FDM and 3DP rapid prototyping technologies that were used to create elements and tools in the wood industry field. Total costs of manufacturing related to the fabrication of sample elements and tools are analysed. One of the main recognised issues of wider application of rapid prototyping technologies is their still very high costs related to all production aspects, starting with a lack of available materials, material cost, up to high cost of available commercial equipment, usually focused only on specific solutions and limited range of materials. Generally, AM costs can be divided into the group of fixed costs and variable ones. This paper deals with the optimization of the production costs of fabricated elements in case of small-scale production, and optimization of variable costs (processing and post-processing, costs of enforcement, and material costs).

Keywords: Additive manufacturing, Wood industry; Custom prototyping

1. INTRODUCTION

Additive manufacturing involves a series of procedures that enable rapid fabrication of prototypes based on a 3D CAD model. The great advantage of this process is the timely detection of defects or quick correction of the errors during the processing of parts. Additive technologies (until recently referred to as RP technology) include forming parts layer by layer. The process that is analyzed in this paper is based on fused deposition modeling (FDM) technology (part of additive technology) [1-4].

2. REVIEW OF TECHNOLOGIES USED FOR RAPID PROTOTYPING

FDM technology belongs to additive technologies also uses printing layer by layer. FDM printer uses plastics in the form of a thin wire led to a specially designed head, upon which it melts and is applied to the desktop where parts are printed [5]. The Center for Information technology (CIT) at the Faculty of Engineering, University of Kragujevac uses two printers based on FDM technology, as given in Figures 1 and 2:

- RapManv3.1(www.cubify.com/en/products/rapman) and
- Up Plus 2 (www.pp3dp.com)

The increasing use of 3D printing has found its place in the wood industry, and it needs the development of new materials that will have properties

compatible to those of the wood and will be able to replace conventional ABS plastic used [6-9].

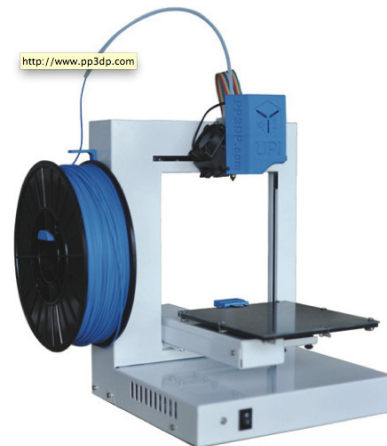


Figure 1: UpPlus 2 3D printer



Figure 2: RapMan v3.1.

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3. FDM TECHNOLOGY COSTS

The term "cost" here comprises the monetary value of all the inputs used in the production process for the whole production time. Determination of the cost is of great importance for every economic decision-making. This paper analyzes the total cost required for the printing of element given in Figure 1. The term "total costs" includes all the cash flows necessary to produce such a part. It can be divided into two sections:

- Fixed costs – independent of the increase or decrease in volume of production and they are stable within certain limits.
- Variable costs – all costs that vary with the volume of production. Increase of production volume, results in the increase of these costs also. Xu, Wong and Loh (2000) suggested one cost analysis model for rapid prototyping [10]. This model is based on a prototype where the cost of production has been classified into three sub-processes:
 1. File processing in CAD software
 2. Printing of a part and
 3. Post processing

a. Fixed costs

The most significant fixed cost for the FDM technology is the cost of equipment and 3D modeling software, as well as the depreciation cost, especially high for the equipment.

3.1.1. Cost of processing (C_p)

In equation (1) the formula is given for the cost of processing (C_p):

$$C_p = \left(\frac{0.2x_{pc}}{W_{at}} + \omega_d + PC_e x P_{kh} + \frac{0.2x_{csl}}{W_{at}} \right) x T_p \quad (1)$$

where: C_{pc} -PC price (RSD); C_{is} - the cost of software licenses (RSD); ω_d -designer price per hour (RSD/hour); W_{at} - PC availability times per year (hours); PC_e -PC energy consumption rate per hour (kWh/hour); P_{kh} -average local price of energy (RSD/kWh); T_p - Design time (hours).

3.1.2. Cost of execution (C_e)

Xu, Wong and Loh (2000) have suggested the timing model for calculation of costs of execution. However, in our case it is not necessary to use it, because these costs are the sum of the running costs of the machine and therefore it comprises both the cost of the function execution time and material resources, respectively. equation (2) represents calculated budget costs:

$$C_e = T_e x r_f \quad (2)$$

where: r_f - is the price of the machine that is obtained based on the equation (3):

$$r_f = \left(P_e x P_{kh} \right) + \frac{0.2xP_{mp}}{W_{at}} + \omega_0 + \left(\frac{M_m}{W_{at}} \right) x 12 \quad (3)$$

Where: r_f - is the price of the machine per hour; ω_0 - operator costs per hour with benefits (RSD/hour); P_e - the machine's energy consumption rate per hour (kWh/hour); P_{kh} - average local price of energy (RSD/kWh); M_m - monthly costs of machine maintenance (RSD); P_{mp} - price of machine (RSD); W_{at} - annual availability of the machine (hours) – (8 hours per day, 22 days per month, 12 months per year);

The warranty on the machine is 3 years, and this data can be used to calculate the monthly maintenance fee expressed in equation (4) and respectively amortization, when the price is divided by the number of months of guarantee:

$$M_m = \frac{P_{mp}}{3} \quad (4)$$

This machine does not require additional maintenance costs.

3.1.3. Cost of Material (C_m)

Material costs are related to the total material used during the printing. For the UP Plus 2 printer, material costs are calculated as described in equation (5):

$$C_m = V_m x P_m \quad (5)$$

Where: V_m - quantity of recovered materials (cm) and P_m - price per unit volume of material.

3.1.4. Cost of post-processing (C_{pp})

The cost of basic post-processing is reduced to the cost of the operator based on equation (6):

$$C_{pp} = \omega_0 x t \quad (6)$$

where: ω_0 - operator cost (per hour) and t - the time required for post-processing part.

In our case, post-processing refers to the separation of the main part from the raft (substrate), cleaning of the part and the removal of the supports, if necessary (in case of the example showed here, it is not necessary to remove the supports).

In order to fabricate the element which could be commercially used, it is necessary to perform additional post-processing, in a form of bonding, surface treatment (improving the quality of the surface layer - polishing, lacquering), etc. These operations further increase the quality of the product (different characteristics, strength and visual appearance), and accordingly it is necessary to include the additional costs:

1. Lacquering - using these types of additional processing of part, it is possible to get a part visually quite similar to the real part (part of which is usually done in large scale production and that fits into the environment depending on the purpose). Most commonly used for these purposes are "Golden matte acrylics" and "Liquitex glossies - acrylic enamel" which cost about 1700 RSD per bottle.
2. Surface Treatment - this type of additional treatment involves a process that will lead to

improved quality of the surface layer and it usually comprises polishing. Processing can be carried out in a vibratory or centrifugal barrel. These machines cost around \$ 40,000.

3. Bonding - bonding is suitable for elements which exceeds the physical size of the printer production size. The most commonly used is two-part epoxy paint. Bonding process takes around 20-70 minutes, and the solidification of 1-5 days. The solvent can also be used, which chemically melt the plastic on the surfaces to be bonded.
4. Galvanizing plastic - This process is suitable when a thin metal layer is applied on the surface. The coating may be decorative and functional, providing strength, abrasion resistance and the commonly used materials are chrome, nickel, copper and other metals [11].

Depending on the needs, it is possible to use some of the additional techniques of post-processing, and those would contribute to increase of the cost of the finished product. For the purposes of this work, calculation of basic postprocessing (C_{pp}) has been made.

3.2 Variable costs

Variable costs that most affect the total cost, are the following ones:

- Material
- Human operator cost and
- The price of electricity

It is now possible to perform division and variable cost including:

- Costs of processing
- The costs of enforcement
- Material costs
- Costs of postprocessing

3.3 Calculation of the cost by using FDM technology

The following formula was made for the calculation of the cost depending on the phases of the product fabrication. As compared to the original formulation set by Xu, Wong and Loh (2000), made some modifications, and they are more related to the part for post-processing, because in this paper focus is given to the total cost of developing one complete functional part, who can replace product created in a factory, i.e. the production line which produces a large number of parts per day.

4. THE APPLICATION OF FORMULATION FOR THE CALCULATION OF COSTS

Based on the previously given formulations, calculation of the printing costs in case of using the printer UP Plus 2 and RapMan v3.1 is performed using input calculation data given in Table 1.

All calculations were performed in order to understand which will be the final price of the chosen part after printing. Shown in Figure 3 is the final part after printing, that represent the junction for the furniture elements [12].

4.1 Processing costs – UP Plus 2 printer

Table 1: Input calculation data

Printer	UP PLUS 2
Printer price	240000 din
The time required for printing work	55 min - 0.92 h
The quantity of materials needed for printing (software calculated)	8.5 g
Material	Plastics with 40% recycled wood
Material price per kilogram	240000 RSD

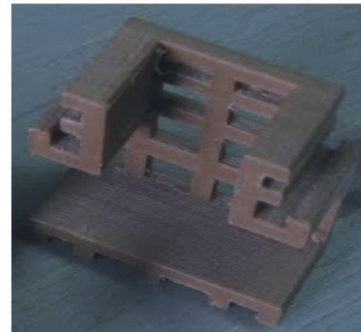


Figure 3: Final printed T carrier

4.1.1 Processing Cost

We used the first equation at this stage. To calculate the price of computers per hour (C_{pc}) it is necessary to know the price of a computer. The computer that is used as the hardware support for the printing costs around 35.000 RSD, and the rate of maintenance per year is 20% and the annual availability - about 2.020 hours. As far as the electricity consumption, the average power is about 600W or 0.6 kW/h. The local price of electricity on average is 10 RSD/kWh.

The price of the software license is 0 RSD because we used free software for modeling, Google SketchUp and this provided significant savings if the price of CATIA software license is considered to be around 1 million RSD.

Price of designers per hour is 140 RSD. This price applies to the operator, a total of 280 dinars/h. The availability of machines and computers is about 2.020 hours annually. Creation of 3D model in Figure 1 takes around 1 hour.

Finally, by using Equation 1, the price of the processing can be calculated as $C_p = 150$ RSD.

4.1.2 The calculation of executive costs

The calculation of executive costs is done based on the equation 2. First, we used Equation 3 where the current consumption of the machine is calculated.

To calculate the price operators, the assumption is taken that the timetable is the same as for the designers.

Electricity consumed by machines for making the element directly depends on the strength of machines and time needed to finish work.

In case of UP Plus 2 printer and based on information by the manufacturer the forces are of order 250 W or 0.25 kWh per hour, to be multiplied by the average local specific costs (P_{kh}) as 10 din/h. Monthly

maintenance fee (M_s) is calculated by using Equation 4 and the machine cost given in Table 1, producing the monthly maintenance fee amount of 6670 RSD. When these values are entered into Equation 3, the total price of the machine per hour is $r_f = 205$ RSD.

The production time for the element shown in Figure 3 is 0.92h, and accordingly, the cost price of the machine per hour, results in the total cost C_e and amount of 188.6 RSD.

4.1.3 Calculation of material costs

For these calculations we used the equation 5. The material used for printing is shown in the Figure 4. The material resembles the PLA plastic, and consists of 40% recycled wood and the polymer bonding.



Figure 4: Plastic with 40% recycled wood [www.lulzbot.com]

The price per kilogram of the material is given in Table 1 and it is 2400 RSD/kg. For printing of this element, the printer software calculated 8 grams of material, and accordingly, the total material costs is $C_m = 20.4$ RSD.

4.1.3 Post-processing costs

Post-processing costs are reduced to the cost price of the operator and the time it takes for the machine to cleaning and part processing (removing of supports, removing of the raft). The time needed for the post-processing was 30 minutes and according to the Equation 6, the result is $C_{pp}.5*140 = 70$ RSD.

For painting of the ABS and PLA plastics the most commonly used is "Golden matte acrylics" spray. The price per piece is about 1600 RSD.

It can be concluded that the overall cost for production of the part is $T_p = C_p + C_m + C_e + C_{pp} = 429$ RSD.

4.2 Processing costs for V3.1 RapMan 3D printer

The costs given here do not differ in the structure of costs for printing using the UP Plus 2 printer. The equations are the same, but the focus was on the different element fabricated and its processing which has effects on the total cost. Table 2 presents the input parameters that are fixed for this part.

Table 2 Input parameters for printing in case of RapMan v3.1 3D printer

Printer	RapMan v3.1
Printer price	120000 din
The time required for printing work	1 h and min
The quantity of materials needed for printing (software calculated)	8.5 g
Material	Plastics with 40% recycled wood
Material price per kilogram	2400 RSD

4.2.1 The cost of post-processing

The costs of this processing are the same as in section 4.1.1 because it is the same price designer and operator per hour, the same software for 3D modeling and same computers. These results in C_p 150 RSD.

4.2.2 The calculation of executive costs

This part is different from the part 4.1.2. The time required for printing is different. Fabrication of the same element but using RapMan v3.1 printer will allocate 1h and 15miNo. Which is about 20 minutes longer time for printing as compared to the UP plus 2 printer.

Electricity consumed by the device for making this part (if one takes into account that the machine power 60 W or 0.06 kWh per hour) also depends on the specified strength and the time needed to obtain work: 12:06 kWh/h is multiplied by the local specific costs 10 RSD/h.

Monthly maintenance fee (M_s) are calculated on the basis of the Equation 4. Price of this printer is 120.000 RSD, and from the equation 4, it can be concludes that M_s is 3333 RSD.

When all of these value are input in the equation 3, the total is the price of the machine per hour $r_f' = 171.5$ RS. If we consider that the work needed to produce it is 1.25h, we get that the total costs is $C_e = 171,75 \times 1,25 = 215$ RSD.

4.2.3 Calculation of material costs

The calculation of the material costs for printing by RapMan v3.1 printer is taken from Table 2 and the difference in the quantity of material required for printing, or 10 grams, which is 1.5 g more. The material is the same as for UP Plus 2 printer, so the price is the same. When these data are input in the amount of $C_m = 24$ RSD is obtained.

4.2.4 Cost of the post-processing

The process of post-processing and cleaning the printer is the same as in the first case and in the application of UP Plus 2 printers. Therefore, it is necessary to plan 30 minutes for postprocessing process to afford to $C_{pp} = 0.5*140 = 70$ RSD.

The conclusion is that the total cost of developing the works using the RapMan v3.1 $T_p = C_p + C_m + C_e + C_{pp} = 459$ RSD.

4.3 Comparison and analysis of results prototyping printer UP Plus 2 and RapMan v3.1

Table 3 presents the comparative results obtained using the proposed formulation, as well as the basic input unchangeable parameters used for the calculation.

It can be concluded that the costs for printing of such part is lower for the printer UP Plus 2 for 30 dinars. Costs are maximally optimized in both cases because it uses free software for 3D modeling, and the operator of the machine is also the designer. Slippage of the press is only reflected in the time it takes for the printing, because the UP Plus 2 significantly faster compared to RapMan v3.1. However, if we look at other aspects, there is a big difference in accuracy and quality printing, so in that case that the advantage has UP Plus 2 3D printer.

Small advantage of RapMan v3.1 compared to UP Plus 2 is "open-hardware" solution. Most of the parts of the printer can print, optimize, add, correct, and the like, which also gives great freedom in the optimization and improvement of the quality of printing. The only major backlog is the time of printing (about 20% slower printing).

Table 3: Comparing costs of printing part

Description	Parameters	UP Plus 2	RapMan v31
Basic information	Printer price	24000 RSD	120000 RSD
	Time required for printing part	0.92 h	1.15 h
Processing costs	Computer price	35000 RSD	35000 RSD
	Annual availability	2020 h	2020 h
	Electricity prices	10 RSD/kWh	10 RSD/kWh
	The price of software license	0	0
	Designer price	140 RSD/h	140 RSD/h
Executive expenses	TOTAL C_p	150 RSD	150 RSD
	Operator price	140 RSD/h	140 RSD/h
	Machine power	250W	60W
	Maintenance costs	6670 RSD /month	3330 RSD /month
	The price of the Machine per hour	205 RSD	171.75 RSD
Material costs	TOTAL C_e	188.6 RSD	215 RSD
	Material price	2400 RSD/kg	2400 RSD/kg
	Consumption of materials	8.5 g	10 g
Postprocessing costs	TOTAL C_m	20.4 RSD	24 RSD
	Time	0.5 h	0.5 h
Postprocessing costs	TOTAL C_{pp}	70 RSD	70 RSD
	TOTAL	$C_p+C_e+C_m+C_{pp}$	429 RSD

4.4 Lower cost of prototyping using FDM technology in comparison to traditional production

From this analysis, and a detailed presentation of Table 3, it can be concluded that the design time of functional prototypes using FDM technology is low. 3D printers on this scale using FDM technology are intended exclusively for the production of small series, or when production of tools for other companies (for the purpose of prototyping) is not cost-effective. In industrial production (series), there are many factors that influence the price of the product. First of all it is important to

take into account that the products are as many parts, and is therefore the technological elaboration in mass production quite detailed, and thus brings additional costs. Another limitation for serial production is that any delay in their production affects the cost of production, and consequently the price of the final product. For small batch production, when production of tools was not profitable, suitable use of additive technology, and 3D printing.

4.4.1 Making wood part on the CNC machine

A specific example of profitability is reflected if you take an example of making this part (as in Figure 3) on the CNC machine. Framework analysis was performed in S.Z.R. Ruzic of Bor in Serbia. As already mentioned, it is not suitable to do a part on machines that are designed for mass production, because the price is a lot higher (when the number of parts increases, the price of a decline). To create a model for CNC machine one needs a dry wood. Time of wood drying depends on the thickness and ranges from 15-30 days. Then the dry wood should be laminated (affix) in the press. Only after this process the final processing mills on the CNC machine can be done. Compared to models with the image on the CNC machine cannot get the interior angles below 90 degrees because of the cutter round. Approximate evaluation of the costs in case of model prototyping using CNC machine, with the added processing (varnishing, sanding, etc.) would be around 4700 RSD. However, an additional problem in this type of preparation is that part of these small dimensions would not have a good load-bearing characteristics, so it is very likely that part would not satisfy even the basic needs.

4.4.2 Production of the plastic part using casting technology

Plastic Injection is one of the most advanced and the most common method of making plastic parts and plastic parts processing. When casting, plastics are also purchased as a raw material is in the form of granules. This plastic is then put into an injection molding machine and heated to the melting temperature. Under the pressure a plastic flows into the tool, where it is cooled and then molded. This technology is also not suitable for prototyping, since the price of tools is extremely high for such a purpose. Tools for plastics are made of steel, in order to be durable. Endurance is an essential tool parameter, because the whole process is repeated several tens of thousands of times. The price of the complete tool for the production of the element given in Figure 3 would cost about 400.000 RSD (price information was gathered from the tool shop "Eroterm", Gornji Milanovac) while Figure 5 represent compressive budget for 3d printing and classic production of part obtained by casting plastic (observed as the total price of 3D printing in relation to only the cost of tools for plastic injection) [9,13,14].

From the previous two examples of the traditional production of parts, it can be concluded that FDM technology for prototyping is cost efficient and can

make large savings. In case of large serial production, the FDM technology can be observed at the border of profitability. This primarily refers to the number of required parts (the higher the number, the greater the profitability of mass production). Table 4 illustrates the relationship between development of elements by using 3D printer (with an average price of 440 RSD) and by casting.

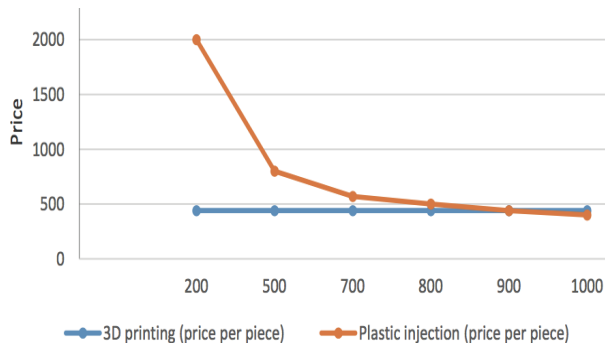


Figure 5: Budget 3D printing

From Table 4, it is noted that the price per piece using 3D printing does not depend on the number of printed parts, while the casting decreases with increasing the number of parts. Of course, the analysis of prices for plastic injection refers only to the tooling costs, excluding other expenses (cost of the machine, cost of labor, electricity, depreciation of equipment and many other costs) [15-17].

Table 4: Comparison of complete 3D printing costs and prices of plastic parts from molds where it is taken into account only the price of tools

Number of pieces	3D printing (price per piece)	Plastic injection (price per piece)
1	440	400000
200	440	2000
500	440	800
700	440	570
800	440	500
900	440	440
1000	440	400

5. CONCLUSION

A review of all analyses indicates that the FDM technology is definitely the most cost effective way of making prototypes. The paper analyzes two types of printers available at the Center for Information Technology at the Faculty of Engineering, University of Kragujevac. It was concluded that the UP Plus 2 3D printer has slightly lower price of fabrication compared to RapMan v3.1. When one takes the average cost of fabrication with both the printer and traditional technologies for fabrication of plastic elements, 3D printing exhibit great advantages, especially for prototyping. However, additional analysis costs for large scale production shows that up to some point 3D printing is cost-effective. Traditional technologies need extremely expensive tools and for production of small number of parts, 3D printing is a good choice.

In the future a significant decrease of the prices of printers can be expected leading to significant increase of FDM technology application in different areas.

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**ОПТИМИЗАЦИЈА ТРОШКОВА АДТИВНЕ
ПРОИЗВОДЊЕ У ДРВНОЈ ИНДУСТРИЈИ**

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П. Живић**

Софтверски пакети за 3Д пројектовање и адитивну производну технологију, у почетку познату као брза израда прототипова су се појавили током последњих година, као иновативна решења за уобичајене прототипове. Ови нови алати и технологије смањују трошкове дизајна, али и омогућавају брзо стварање потпуно функционалних компонента.

Овај рад описује ФДМ и ЗДП технологију брзе израде прототипова које су коришћене за креирање елемената и алата у области дрвне индустрије. Укупни трошкови производње који се односе на израду узорка елемената и алата су анализирани. Једно од главних питања шире примене технологије брзе израде прототипова је њихова и даље веома висока цена која се односи на све производне аспекте, почевши од недостатка доступних материјала, материјалних трошкова, до високе цене расположиве комерцијалне опреме, обично усмерене само на специфична решења и ограничен опсег материјала.

Генерално, АМ трошкови се могу поделити у групу фиксних и променљивих трошкова. Овај рад се бави оптимизацијом трошкова производње готових елемената у случају мини производње и оптимизације променљивих трошкова (прерада и пост обрада, трошкови извршења, и материјални трошкови).