GRANT journal
ISSN 1805-062X, 1805-0638 (online), ETTN 072-11-00002-09-4
EUROPEAN GRANT PROJECTS | RESULTS | RESEARCH & DEVELOPMENT | SCIENCE

Economic Evaluation of Preparation and Building Stage of Additive Manufacturing Process

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Grant: SGS14/185/OHK2/3T/12
Name of the Grant: The evaluation of digitization benefits of manufacturing systems
Subject: AH Economics; JP Industrial processes and processing

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Abstract Additive manufacturing is a very perspective manufacturing technology being still at the beginning of its life cycle. Provisionary deficiencies like low speed at higher volumes production, high investment costs and general unawareness of technology may, together with inaccurate calculations, lead to incorrect decisions on investments in this technology. This article focuses on clarification and specification of cost calculation model used to specify costs of component production by way of example, a steering mast of a racing car. The cost model is primarily meant for technologies based on powder material fusion and after slight modification can be used for other types of additive manufacturing technologies. The example is complemented with sensitivity analysis.

Keywords Additive manufacturing, economic evaluation, sensitivity analysis.

1. INTRODUCTION

Additive manufacturing (AM), known as 3D Printing or Rapid Prototyping, is in general terms a technology of 3D objects production by means of material layers fusion. It is used to manufacture prototypes and tools (casting moulds in particular) and nowadays also to manufacture finished goods. AM is largely used in aircraft and space industry as well as in jewel-making. AM has been perceived as another, fourth industrial revolution, owing to its indisputable assets, particularly manufacturing of products with difficult geometry, efficient production of small series and fast response on customer demand, which is a reaction on current trend, i.e. the switch from mass production to job-order manufacture.

AM has not come up to expectations of turn of millennium, regardless of its considerable benefits. Its growth and development were not as fast as expected, as the technology has not developed further, beyond the beginning of its life cycle. The barriers are the following: insufficient material offer, failure of material to meet environmental standards, difficult quantitative repetition of production, insufficient standardization, unawareness of this technology and low manufacturing speed together with high investment.

The last three barriers may, in conjunction with inaccurate calculation methods, lead to incorrect decision to invest in this technology. This article therefore focuses on clarification and specification of cost calculation model used to specify cost of preparation and building stage of additive manufacturing process. Its practical use is shown on an example of a racing car steering mast. The presented cost model is intended primarily for technologies based on the process of powder material fusion and after slight modification can be used for other types of additive manufacturing technologies. The example is complemented with a sensitivity analysis.

2. COST CALCULATION FOR PREPARATION AND BUILDING STAGE

First of all, we will describe additive manufacturing process of the component with the aim to define the building stage correctly. The other stages will be dealt with by the sensitivity analysis. Further on we will explain additive manufacturing based on powder bed fusion processes. Finally, we will describe cost calculation for component building stage.

2.1 Additive Manufacturing Process Chain

The whole process usually consists of 5 to 8 stages (Fig. 1) in dependence on the type of literature [2,3,4,5].

1. Creation of Concept and its 3D CAD Model

A design is set up first of all (design, functionality, …), based on which a 3D CAD model is created and analyses made. Model quality is a critical element for resulting product quality – model must not be defective (no cracks, no gaps, etc.). Design principles relevant for additive manufacturing must be respected if we want to use their potential to the utmost.

2. Transformation to STL Format

3D CAD model is converted to STL format, which is a standard format of AM equipment. It is simpler than common CAD formats and its function is to balance information quality and size of the file. High-performance computers handle such conversion within few minutes.

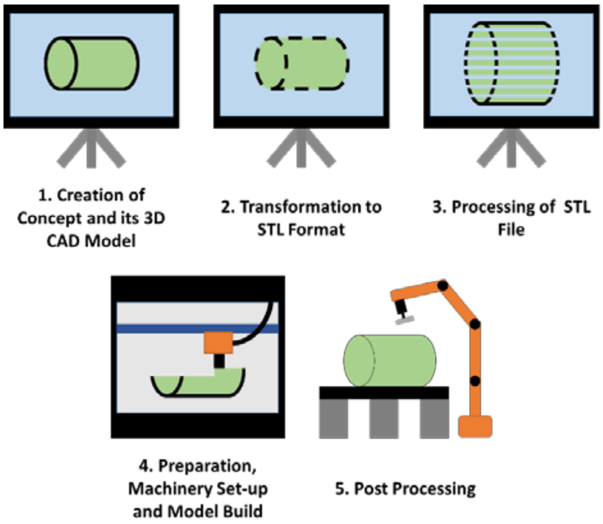

Fig. 1: Additive manufacturing process (created according to [1,3])

3. Processing of STL File and its Transfer to the Machine

An STL file is first of all verified in „CAM software“ for additive manufacturing with the aim to detect possible errors. Then it is processed for production: position and orientation of component, creation of support and similar. Subsequently the file is divided into particular layers. Sometimes it is possible to set up technological parameters (laser output, hardening output, etc.). Manufacturing file for machine control is generated in the end.

4. Preparation, Machinery Set-up and Model (Component) Build

Sequence is the following, machines set up in operating condition, material replenishment in cartridges followed by check of sufficiency of gas for inert atmosphere, parameters of manufacturing process set up and start of operation. Designing is an automated process in majority of cases and no attendance is needed in the course of it. Time of production depends on type, size and number of manufactured components and on parameters of manufacturing process. It consists of time of preheating a chamber or laser up to operating temperature, time of filling the chamber with inert atmosphere, time of component build and time of component removing and cleaning the machine. And time of component cooling, as the case may be.

For the sake of overall cost calculation, we have to know how to set time needed for component build. We also need to be familiar with function of manufacturing technologies based on powder bed fusion processes. The process is described in chapter 2.3.

5. Post Processing

Post processing is the following part of the process in most instances. It includes component cleaning (separation of component from work desk, removal of supports and excessive material). A finish (heat treatment, non-heat treatment and finishing operations like tumbling, milling and drilling, etc.).

2.2 Technologies Using Powder Bed Fusion Processes

AM technologies divide into several groups according to a state of material used (liquid-based systems, solid-based systems and powder-based systems) or according to way of individual layers build (Material Extrusion, Powder Bed Fusion, Photopolymerisation, …). There are several different technologies within each group. For more details on individual groups and relevant technologies see [2,4,5].

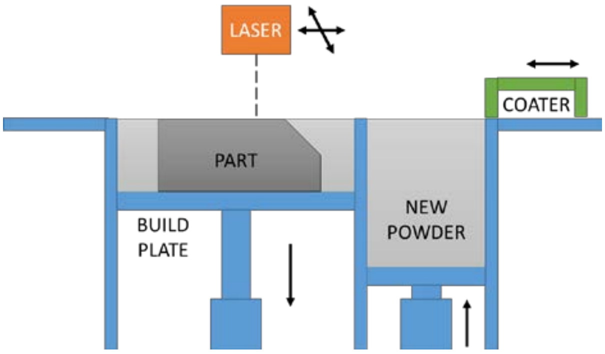

Fig. 2: Building process principle (created according to [2,4])

Let us have a closer look at group of technologies based on Powder Bed Fusion processes as mentioned earlier. Technologies of this group function on the following principle (Fig. 2). The machine is equipped with minimum two chambers (cartridges or platforms), that move up and down. One chamber contains material prepared, the other chamber contains a pallet, on which component production takes place. Building process always starts by a movement of the pallet chamber down by the depth of one layer. At the same time the material containing chamber moves up by the depth of one layer. Subsequently loose material is spread over the pallet chamber by a coater. This part of the process is called recoating. A delay that may occur at the beginning or at the end of recoating may be needed to heat up the material, calibrate sensors or regulate temperature in the working chamber. As soon as layer of material is prepared, it is melted on by laser or electron beam to intended component position. This part of the process is called scanning. The whole process repeats when a layer is finished – material chamber moves up, pallet chamber moves down, etc. [2,3,5]

2.3 Cost Calculation for Preparatory Stage, Set-up of Machine, Build of Component

In the following part we focused only on cost calculation of 4th stage of additive manufacturing process, as it is the most demanding and specific stage from the point of view of costs and time setting. Hereunder we present relatively simple calculation based on [3,6]. We made several changes in the calculation process. On one hand we merged depreciation, operational costs and service costs under one item, which gives us a possibility to assess rates across various machines and technologies in a simpler way, on the other hand we added an item of cost of energies and inert atmosphere and we modified setting of machine capacity.

Costs were divided in the following categories for the purposes of further analysis:

1. Material cost (M)
2. Machine cost (PO: P = machine purchase cost, O = machine operation cost)
3. Energy and inert atmosphere cost (EA: E – energy cost, A –atmosphere cost)
4. Machine attendance cost (L = labour cost)

Cost of one pallet build is calculated as follows:

$$Cost = M + PO + EA + L \tag{1}$$

Cost calculation formula (without company overhead expenses) per one piece will be the following in the case of more components on a pallet (N – number of components on a pallet):

$$cost = 1/N \cdot (M + PO + EA + L) \tag{2}$$

1. Material Cost (M)

Material cost depends on component mass (v), material density (ρ) and price (C_m – material cost per unit mass). The formula will be multiplied by a coefficient k_s (usually between 1,1 and 1,5), if supporting structures are needed. Problems occur with recyclable powder material. Gradual degeneration of such powder in production cannot by excluded, therefore we must multiply the resulting formula by coefficient k_r (between 1,0 and 7,0).

$$M = v \cdot \rho \cdot C_m \cdot k_s \cdot k_r \quad (3)$$

2. Machine Cost (PO)

Machine cost include machine depreciation and operating costs. It will be assigned as hourly cost rate ($HCR_{Machine}$) and time consumption per build of one pallet (T_b – calculation of time need to build one pallet will be explained in chapter 2.4).

$$PO = HCR_{Machine} \cdot T_b \quad (4)$$

Hourly machine cost rate is determined as follows:

$$HNS_{Machine} = \frac{Annual\ depreciation\ of\ machine + Annual\ operation\ cost}{Capacity_{Machine}} \quad (5)$$

Annual machine depreciation may be set in a simplified way as a ratio of machine purchase price and service life:

$$Annual\ depreciation\ of\ machine = \frac{Purchase\ price\ [CZK]}{Service\ life\ [years]} \quad (6)$$

Annual capacity represents number of hours, for which the machine will be actually used in the given year, which is primarily influenced by number of orders in a week and their time intensity.

$$Capacity_{Machine} = Number\ of\ weeks \cdot \sum Number\ of\ orders\ in\ a\ week \cdot Duration \quad (7)$$

Annual operation cost consist of cost of premises [CZK/m2.year], maintenance cost (usually an annual fee) and spare parts.

$$\text{Annual operation cost} = \text{cost of premises} + \text{maintenance cost} + \text{spare parts} \quad (8)$$

3. Cost of Energy and Inert Atmosphere (EA)

Cost of energy and inert atmosphere (EAA) are calculated as follows:

$$EAA = E + A \quad (9)$$

Energy consumption cost (E) is calculated as product input in individual operation regimes (I [kW]), time of machine operation in individual regimes (T) and electric energy price (P):

$$E = (I_{Set-up} \cdot T_{Set-up} + I_{Warm-up} \cdot T_{Warm-up} + I_{scan} \cdot T_{scan} + I_{recoat} \cdot T_{recoat} + I_{Unpacking} \cdot T_{Unpacking}) \cdot P_{Electrical\ energy} \quad (10)$$

Indices of individual formula terms, that is input and times, mean the following: Set-up – machine set-up, Warm-up – machine warm-up to operating temperature and refill with inert atmosphere, Scan – sintering of material layer, Recoat – preparation of new material layer, Unpacking – removal of component and cleaning of machine. Cost of inert atmosphere (A) is calculated as product of inert atmosphere consumption (C_A), time of operation (T) and price of inert atmosphere (P_A):

$$A = (C_A \cdot T_{start} + C_A \cdot T_{build}) \cdot P_A \quad (11)$$

4. Machine Attendance Cost (L)

Cost of machine attendance (L) is determined depending on worker´s hourly cost rate (HCR) and time consumption – machine setting, preparation, production control, and taking out the component. The worker does not have to be present all the time, random checks via a computer are sufficient – such control takes 10 minutes per day.

$$L = HCR_{Worker} \cdot (T_{set-up} + T_{Unpacking}) \quad (12)$$

Where worker´s HCR is calculated as quotient worker cost and capacity of worker:

$$HCR_{Worker} = \frac{Worker\ cost}{Capacity_{Worker}} \quad (13)$$

Worker cost includes wages, bonuses, cost of training, meal allowances, etc.

2.4 Times Setting Procedure

Times setting procedure is based on [3,6], although here it has been simplified for the purposes of chapter 3 example, as the component and its support are manufactured at the same time. Delay times included in recoat time were deleted from here.

Overall Time of Pallet Building

One of the cost model key variables is production time (T_b), a function of component size, shape, number of components manufactured on a platform and speed of production. Production time consists of three partial times: overall model building time (T_s), overall material (coating) preparation time (T_r) and overall delay time (T_d). Production time calculates as follows:

$$T_b = T_s + T_r + T_d \quad (14)$$

Recoat time

Recoat time is time needed to add a new material layer on a pallet (T_{rp}). L_p parameter means number of material layers needed to build a component, it depends on thickness of one layer (LT) and size of so called „bounding box", that is a box having a dimension bb_x, bb_y and bb_z, that encloses the manufactured component.

$$T_r = L_p \cdot T_{rp} = bb_z / LT \cdot T_{rp} \quad (15)$$

Total Time of Model Build

Production time is a function of manufactured surface in one layer depending on component mass and number of components on one working pallet. It is also a function of number of layers and way of layer manufacturing. Parameter of manufactured surface (A_{avg}) is taken as an average that will be corrected by factor γ, which is a ratio between component mass (v) and volume of bounding box (v_{bb}). 1,5 is usually substituted for coefficient α.

$$A_{avg} = bb_x \cdot bb_y \cdot A_{fn} = bb_x \cdot bb_y \cdot \gamma \cdot e^{\alpha \cdot (1-\gamma)} = bb_x \cdot bb_y \cdot \frac{v}{v_{bb}} \cdot e^{\alpha \cdot \left(1-\frac{v}{v_{bb}}\right)} \quad (16)$$

We have to determine average scan length (sl) that needs to be covered in production of one layer:

$$sl = A_{avg} \cdot \left(\frac{n_{st} \cdot L_p}{hr \cdot d} + supfac \cdot \frac{L_s}{d}\right) \quad (17)$$

The distance is determined as a quotient of average manufactured surface (A_{avg}) and laser beam diameter or material fiber diameter (d), or, as the case may be, a quotient of average manufactured surface (A_{avg}) and distance between centres of two neighbouring

ISSN 1805-062X, 1805-0638 (online), ETTN 072-11-00002-09-4

melted segments (hr – average % of individual sintered sections overlapping). Parameter n_{st} will be applied, if the laser head processes individual sections of one layer several times. Average distance of supporting structures has to be calculated, we need to determine their surface (suppfac), which is usually about 30 % of component surface and (hr) parameter is usually not applied.

The last parameter we need for production time calculation (T_s) is the average weighted speed (ss_{avg}), which consists of two elements: speed of laser head movements (ss_s) and speed of leaping from between individual manufactured surfaces (ss_j). Factor γ or more precisely (1 – γ) stands for weight.

$$ss_{avg} = ss_s \cdot \gamma + ss_j \cdot (1 - \gamma) \qquad (18)$$

Resulting formula for calculation of production time is the following (constant 3600 converts seconds on hours):

$$T_s = \frac{N \cdot sl}{3\,600 \cdot ss_{avg}} \qquad (19)$$

Overall Time of Delay
Overall time of delay is a sum of time needed before the start of production for machine set up, warming up chamber and laser, removing a component and cleaning the machine.

$$T_d = T_{Set-up} + T_{Warm-up} + T_{Unpacking} \qquad (20)$$

3. CALCULATION OF STEERING MAST COST

Cost calculation is demonstrated on racing car steering mast. The original welded steel mast was rather heavy and not rigid enough, therefore a new steering mast was designed and manufactured by means of additive manufacturing. The new mast is lighter and 9 times stiffer. We cannot show the mast and mention the manufacturer´s name owing to product protection.

3.1 Input Parameters

All parameters for cost calculation must be determined first of all. These parameters are based on calculation process presented under 2.4 and 2.5. The parameters are applied on the steering mast and material it is made of (Tab. 1a, Tab. 1b).

Tab. 1a: Steering mast parameters

Parameter	Unit	Value
Component mass	[mm3]	128 716
Bounding box dimension		
X	[mm]	130
Y	[mm]	135
Z	[mm]	240
Supporting structures height	[mm]	120
Suppfac	[%]	10

Tab. 2b: Steering mast material parameters

Parameter	Unit	Value
Used material	[-]	AlSi10Mg
Density of material	[g/cm3]	2,67
Price of material	[EUR/kg]	100,00
k_r	[-]	1,00

Parameters of the machine and manufacturing procedure set up (Tab. 2 and Tab. 3).

Tab. 3: Parameters of machine/workplace

Items	Unit	Value
Building chamber dimensions		
X	[mm]	250
Y	[mm]	250
Z	[mm]	280
Machine price	[thous. EUR]	540
Service life of machine	[years]	7
Average number of orders per week (53 weeks)	[-]	2
Average time of order manufacturing	[hour]	22
Workplace area	[m2]	30
Area cost	[EUR/hour·m2]	10
Attendance staff costs	[EUR/year]	16 560
Annual attendance capacity of worker	[hour]	1 725
Maintenance costs	[EUR/year]	25 000
Laser		
Lifespan	[hour]	10 000
Price	[EUR/pc]	60 000
Construction sheet (pallet) made of tool steel		
Lifespan	[number of constructions]	20
Price	[EUR/pc]	400

Tab. 4: Manufacturing process parameters

Item	Unit	Value
Diameter of laser beam	[mm]	0,15
Hatch spacing (beam overlapping at sintering)	[-]	0,7
Speed of laser beam movement	[mm/s]	2000
Speed of laser beam leaps	[mm/s]	7000
Layer thickness	[mm]	0,045
Number of times a layer is scanned to fabricate a layer	[-]	1
Time		
Set-up state	[hour]	0,5
Preheating + Creating Inert Atmosphere)	[hour]	0,25
Recoat time	[sec]	8
Build job unpacking	[hour]	0,5
Machine input		
Set-up state	[kW]	0,7
Preheating + Creating Inert Atmosphere	[kW]	2,1
Build state	[kW]	3,1
Recoat time	[kW]	3,4
Build job unpacking	[kW]	0,7
Electrical energy price	[EUR/MWh]	58,5
Inert atmosphere consumption		
Time of consumption before construction start	[min.]	10
Inert gas N2		
Consumption before construction start	[l/min]	60
Consumption of atmosphere maintenance	[l/min]	14
Price	[EUR/m3]	0,07

3.2 Cost Calculation

We can approach to cost calculation based on the input parameters. The following Tab. 4 mentions partial values of individual cost items and overall cost of component build as calculated by Microsoft Excel. Every line mentions number of formula used for calculation.

Tab. 5: Calculation of steering mast construction costs

Calculation	Units	Formula	Value
Calculation of material cost			
Cost of material	[EUR]	3	37,80
Calculation of machine hourly cost rate			
Machine capacity	[hour]	7	2 332
Annual depreciation amount	[EUR]	6	77 143
Operating costs	[EUR]	8	41 412
Hourly cost rate of a machine	[EUR/ hour]	5	50,84
Time consumption			
Number of material layers	[-]	15	5 333
Time for material preparation	[hour]	15	11,85
Average surface corrected by γ	[mm2]	16	2 296
Average scan length	[thous. mm]	17	120 700

GRANT journal
ISSN 1805-062X, 1805-0638 (online), ETTN 072-11-00002-09-4
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Average weighted speed	[mm/s]	18	6 847
Building time	[hour]	19	4,90
Delay time	[hour]	20	1,25
Total time	[hour]	14	18,00
Machinery cost calculation			
Machinery cost	[EUR]	4	915,01
Calculation of energies and inert atmosphere costs			
Inert atmosphere cost	[EUR]	10	1,03
Energy cost	[EUR]	9	3,32
Energy and atmosphere costs	[EUR]	8	4,34
Attendance cost calculation			
Hourly cost rate of attendance	[EUR/ hour]	12	9,6
Attendance costs	[EUR]	11	11,14
4th stage cost calculation			
Total cost	**[EUR]**	1	**968**
Conversion to CZK	**[CZK]**		**26 136**

Based on the above calculation process we arrived at a conclusion that construction of steering mast costs about EUR 969. The component cost amounts to CZK 26 136 at the CZK 27 Euro 1 exchange rate. We must not forget that following costs are not included: overheads of the company (marketing cost, company management, etc.), costs of component design and 3D modelling, conversion to STL format, processing of STL file and post processing.

3.3 Sensitivity Analysis

The sensitivity analysis focuses on two important factors that have an impact on costs of steering mast manufacturing. One factor is capacity.

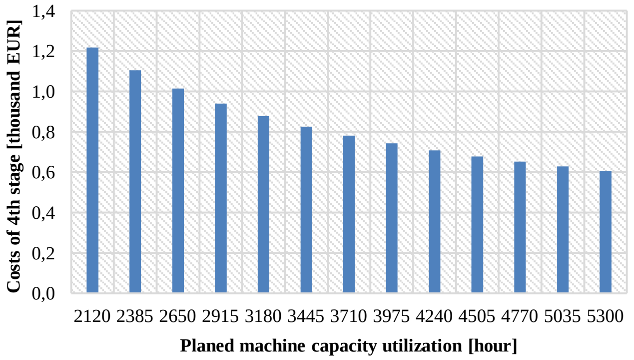

Fig. 3: Costs of 4th stage in dependence on planed machine capacity utilization

Previous chart (Fig. 3) shows manufacturing costs that are changing in response of changes of planned real use of machine capacity. In one extreme case the planned capacity utilization makes 2 120 hours per year (40 manufacturing hours/week in average) and the cost amounts to EUR 1 200. In the other extreme case the capacity utilization makes 5 300 hours per year (100 manufacturing hours/week) and the costs attack the level of EUR 600. The higher the machine utilization, the lower the cost of steering mast production. This is a result of economy of scale, when fixed costs are dissolved in higher number of production hours. We should however see, that the resulting cost value may be slightly distorted, as the construction sheet cost depends on number of constructions and type of parts and it is difficult to include it into consideration.

The other factor is selected layer thickness. Thickness does not impact the cost directly but through resulting production time. The lower the thickness, the longer the production time and the higher the production cost (Fig. 4). If the thickness is as high as 0,045 mm, cost will amount to EUR 968. If the thickness is as low as 0,030 mm, cost will amount to EUR 1 400. The difference makes EUR 450 of cost incurred and 6 hours of time spent.

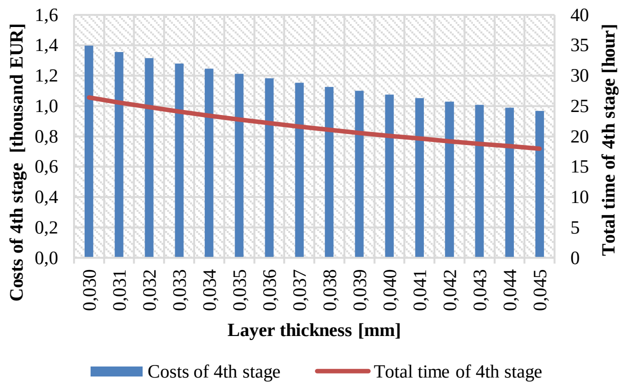

Fig. 4: Costs of 4th stage in dependence on layer thickness

We can state, based on the sensitivity analysis, that amount of cost is to a large extent dependant on both selected factors (planned capacity and thickness of layer).

4. CONCLUSION

We have highlighted cost setting procedure for the stage of component build in this article. At the same time, we have streamlined the procedure and made it more accurate to be able to apply it on our selected example, i.e. cost calculation of production of a racing car steering mast. We have determined the costs at EUR 968. This amount applies to fixed values of parameters mentioned in chapter 3.1. Let us not forget that it is not a final cost amount. We have to add costs of other AM stages as well as company overheads and profit margin. We recommend to use a mix of Activity Based Costing and Hourly Cost Rate to determine costs of the other AM stages. However, we cannot evaluate AM advantages based on cost amounting to EUR 968. It only gives us an idea of cost amount compared to bounding box dimensions and component mass. Cost of conventional technologies and AM production should be compared. Cost amount is also impacted by so called α coefficient, usually substituted with 1,5 and research of its impact would be of a great interest.

We have also analysed cost sensitivity of planned utilization of machine capacity and layer thickness. Cost of steering mast production for 2 120 hours capacity make EUR 1 200 and EUR 600 for capacity of 5 300 hours. Cost of 0,03 mm thickness of layer made EUR 1 400 while cost of 0,045 mm thickness of layer made EUR 968. These two factors are critical for cost amount and it is of a critical importance to set them correctly, as they influence final decision to purchase or not to purchase additive manufacturing technology. Any company, that is considering a purchase, should pay attention to evaluation of the other AM stages (chapter 2.1):

1. Concept Design and 3D CAD Model

Products should be designed in compliance with design rules applicable to AM technologies, only such approach provides for the best use of AM. Possibility to change product design should be checked, as it might reduce manufacturing time and cost. Product parameters like roughness and material used should be checked as well. Excessive roughness results into low layer thickness, which prolongs manufacturing time, or finishing operations, which may cause damage. Subsequent need to use inert atmosphere would also increase cost.

2. Processing of STL File and its Transfer to Machine

Correct position of a component allows to place more components on a pallet, which prolongs manufacturing time but also spreads costs over more products. It is important to use the supports correctly to obtain quality product and to reduce production time. Layer thickness should be set up after due consideration.

5. Post Processing

Post processing may be needed depending on required roughness, thickness of layer, shape of component, hence the need to drill, and quality of STL file optimization – number and type of supports, etc. Post processing increases component cost and may damage the component.

Sources

1. COYKENDALL, John, Jonathan HOLDOWSKY a Monika MAHTO. 3D opportunity for aerospace and defense: Additive manufacturing takes flight. Deloitte University Press [online]. Deloitte University Press, 2014, June 2, 2014 [cit. 2015-12-09]. Accessible from: http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-aerospace/
2. GEBHARDT, Andreas. Understanding additive manufacturing: rapid prototyping - rapid tooling - rapid manufacturing. Munich: Hanser, c2012, ix, 164 s. ISBN 978-1-56990-507-4.
3. GIBSON, I., ROSEN, D. W. a STUCKER, B. Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. New York: Springer, ©2010. xxii, 459 s. ISBN 978-1-4419-1119-3.
4. GRIMM, Todd. User's guide to rapid prototyping. Dearborn, Mich.: Society of Manufacturing Engineeers, c2004, xvi, 404 p. ISBN 0872636976.
5. CHUA, Chee Kai a Kah Fai LEONG. 3D printing and additive manufacturing: principles and applications. Fourth edition of Rapid prototyping. xxviii, 518 pages. ISBN 9789814571418.
6. WILSON, Jamal O. a David ROSEN. Selection for Rapid Manufacturing Under Epistemic Uncertainty. In: Volume 4b: Design for Manufacturing and the Life Cycle Conference [online]. 2005 [cit. 2015-07-23]. DOI: 10.1115/detc2005-85264.