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Production cost model of the multi-jet-fusion technology

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Abstract

The paper presents a model of the production costs of the multi-jet-fusion technology that is based on a model of production costs of the selective laser sintering technology. The model is developed using the methodology of analysis of the event-driven process chain, which consists of modeling, batch assembly, setup, building, removal, and blasting activities. Production costs of each of the activities are separated to direct (labor, material, and energy) costs and indirect (equipment, overheads, and other indirect) costs. The developed model represents a basis for the development of algorithms and software tools for the calculation of the production costs of the multi-jet-fusion technology, since it defines all the necessary inputs and calculation procedures that enable the calculation of the total costs of a batch of products. Besides, the paper presents a procedure for the estimation of production costs that are attributed to a single product or product type.

Keywords

Production technologies, additive manufacturing, production costs, powder bed technologies, multi-jet-fusion technology

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Introduction

Once additive manufacturing (AM) technologies became a tool for rapid manufacturing applications,[1] it became clear that the new manufacturing concept has enormous potential for transformation of not only the industry,[2] but also the world of business[3] with implications to the whole of society.[4] Each analysis of developments in the AM technology, therefore, has to consider their economic aspects.

For these reasons, the Horizon 2020 project "Advanced design rules for optimal dynamic properties of additive manufacturing products", which is concerned with dynamic behavior of AM products made by maraging steel[5,6] and stainless steel,[7] also studies the production costs of the AM technologies that have potentials for the manufacturing of mechanical structures and components. Due to the superior mechanical properties, selective laser sintering (SLS) technology dominated industrial applications for more than two decades. However, multi-jet-fusion (MJF) technology recently entered the market with promise of high-speed AM technology that rivals SLS technology by mechanical properties of plastic products. The lack of published analysis of production costs of the MJF technology motivated the research presented here.

The cost models for AM technologies are being developed for almost two decades. An extensive overview of the cost models of the AM is recently given in the literature.[8] The progress in the development of AM technology cost models consisted in the expansion of the considered number of factors that influence the AM costs. The initial cost models were based on experiences of injection molding, and they considered only variable AM costs, including machine costs per part, labor costs per part, and material costs per part.[9] Such models, which influenced comparisons with other technologies,[10] neglected important aspects of AM technologies, such as the ability for recycling of the used material and requirements for extensive post-processing. An important breakthrough in the development of cost models was the separation of the AM costs to direct and indirect costs, which led to the proper consideration of high indirect costs of the AM technologies,[11] which

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exposed the importance of the proper treatment of the utilization of the capacity of the used machine.[12] While these general concepts and models of costs of AM are established, the differences between the specific AM technologies make specific models more suitable for application in practice.

The production process of each AM technology consists of a sequence of cycles for the production of individual horizontal layers of products. With powder-bed-fusion technologies, to which both SLS and MJF technology belong, each of the layers is manufactured by joining particles of a thin layer of a powder. The production cycle of a powder-bed-fusion technology starts with the addition of a small amount of the production powder mixture to the production chamber (Figure 1, top left image). The image shows that the addition is achieved by rising of the movable bottom of the powder container, but other solutions exist as well. Using a recoater with horizontal motion, the added production powder is then distributed uniformly over the surface of the production chamber (Figure 1, top right image), thus forming a thin layer of the production powder that covers the area where the products are built, which is called the powder bed. The powder in the powder bed is then exposed to a selective action of some agent, which causes joining of the powder particles that belong to the respective layer of the manufactured products (Figure 1, bottom left image), and joining of the layer to the previously manufactured layers of the product. After the manufacturing of a layer of products, the bottom of the production bin, which contains the products and the powder, which was exposed to the action of the agents during the process, is lowered so that the top of the production bin may be covered by the powder added for the manufacturing of the next layer of products in the following production cycle.

An important feature of the powder-bed-fusion technologies is that the powder processed during a production process may be used to prepare production powder mixture for the following production processes. However, since the properties of the processed powder are changed in the process of pre-heating,[13] the powder used for production processes has to be mixture of the processed powder and fresh powder. The process of mixing of the processed powder and fresh powder is called refreshment, and the ratio between the masses of fresh powder and the production powder mixture is called the refreshment rate (denoted as r).

In all powder-bed-fusion technologies, the particles of the powder are joined by melting and solidification of the pre-heated powder at the powder bed. In the SLS technology, the melting of the particles is performed by the exposition of selected points of the powder bed to a laser beam. On the other hand, in the MJF technology the particles of the powder are melted by exposition of the complete powder bed to infrared light after previous deposition of both heat-absorbing and heat-deflecting (called "fusion and detailing") agents over the selected areas of top surface of the powder bed.[14] The similarity between the described manufacturing concepts lead to the following important similarities between the SLS and MJF technologies:

- Both SLS and MJF are industrial technologies that offer high-dimensional accuracy and mechanical properties superior to other AM technologies for polymer materials;
- The main polymer material used in both technologies is polyamide PA 12 (nylon);
- As the powder in the powder bin supports the products, neither of the technologies requires support structures for the manufacturing of products from polymer materials; this common feature allows the manufacturing of complex shapes, and an almost unlimited freedom to designers; however, products of both of the technologies are susceptible to warping, and large flat areas should be avoided;
- Products manufactured by both of the technologies have grainy surface structure, but the surfaces may be post-processed to satisfy high mechanical and aesthetic requests.

On the other hand, the differences between the manufacturing concepts lead to some differences between the technologies. The first important conceptual difference between the SLS and MJF technologies is the difference between the principles of selection of the melted powder: in SLS a laser beam acts on the powder that is to be melted, while in the MJF the powder that is to be melted is covered by a fusion agent using printheads similar to those used in the ink-jet printing technology. This conceptual difference has two consequences:

- As the resolution of the deposition of the fusion agent by the MJF printheads enables definition of spots smaller than the laser spots of typical lasers used for SLS, the accuracy of the parts manufactured by MJF technology is usually better; the application of the detailing agent also contributes to better accuracy of small features and sharp edges;
- As the fusing agent used in MJF technology is black (for better absorption of the infrared light), the products manufactured by MJF technology have a light grey appearance with nonuniform surface color after blasting; the product of the SLS technology are usually white, and can easily be painted to any color.

The other important conceptual difference between MJF and SLS is between the heating methods: while SLS uses a laser beam to heat and sinter a point of the

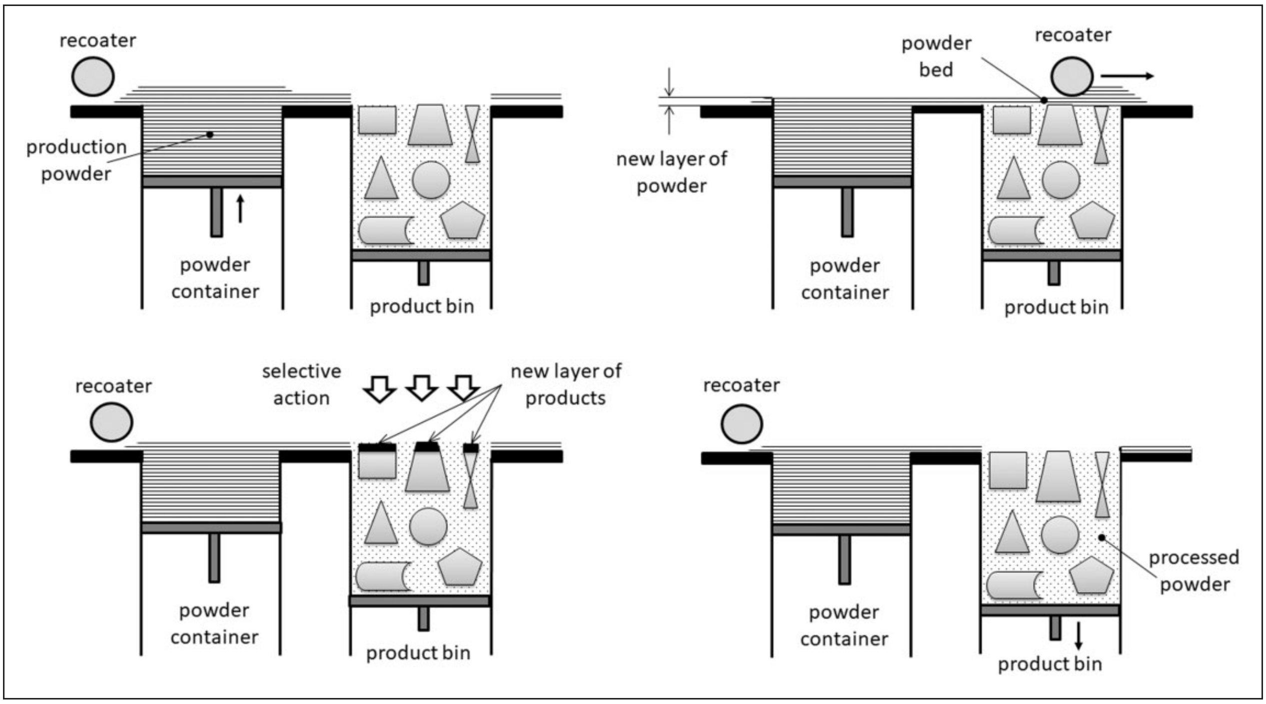

Figure 1. Production concept of the powder bed technologies.

powder bed, MJF uses an infrared energy source that simultaneously heats whole lines of the powder bed. The difference in the heating principle leads to several important consequences:

- A product layer is fused much faster by the MJF technology than by SLS technology; however, since the layer thickness and duration of a recoating step (which, in principle, do not depend on the technology) play even more important role in determining of the building time, the building time of the MJF technology, in general, is not much shorter than for the SLS technology;
- Due to the concentration of the absorbed heat, the SLS technology may be used for processing of wider set of materials, and the identical principle is used even for direct laser sintering of metals;
- Due to the smaller temperature gradients, the products manufactured by MJF technology show more isotropy than the products of the SLS technology, which are weaker along the building direction;
- The refreshment rate of PA12 production powder for MJF technology is around 20%, while for the SLS technology it is around 50%.

Apart from the conceptual differences, there are, at the moment, also some practical differences, which are expected to diminish or change with time. They arise mainly because the SLS technology is more mature, as it is present at market for more than two decades, while the MJF is a new technology, which is from the start combined with other advanced AM concepts. The consequences are that more polymer materials are available for the SLS technology, and that their mechanical properties are better known. On the other hand, the application of the removable product bins and dedicated processing stations for material handling and product cooling significantly reduce cooling time and increase the productivity of the MJF systems present in the market.

The first step in the development of the cost models of powder bed technologies was extensive study of the energy consumption.[15] Due to the complexity of the SLS technology, the refinement of the AM cost model was performed by modeling of the AM technology process using the event-driven process chain methodology. The model considered metal additive manufacturing by DMLS technology. It was the first model that considered post-processing as an important aspect of the AM technology, and it was further used for activity-based calculation of AM costs.[16] According to the model, the AM production process may be divided into preparation phase (consisting of the CAD preparation and machine preparation activities), manufacturing phase that features the build process, postprocessing phase (consisting of the support removal and surface treatment), and quality control phase (consisting of the verification and documentation). Further improvement of the cost model was the development of an algorithm for the calculation of the production time fraction for each of the parts in a single AM job,[17] which enabled the calculation of the total costs of a product of the SLS technology C_{Total} as a sum of costs of the preparation phase C_{Prep}, job assembly costs $C_{Buildjob}$, setup costs C_{Setup}, building costs C_{Build}, part plate removal costs $C_{Removal}$, costs of removal of the part from the plate $C_{Substrate}$, and the post-processing costs C_{Postp}

$$C_{Total} = C_{Prep} + C_{Buildjob} + C_{Setup} + C_{Build} + C_{Removal} + C_{Substrate} + C_{Postp} \tag{1}$$

The elaboration of each of the members of the sum features nine equations with almost 40 input parameters. A further elaboration of the model of the AM costs led to the state-of-the-art model of the SLS technology costs, which considers recycling of the used powder[18] and uses 77 input parameters to describe the production process. The model serves as the starting point for studies of various costs specific for the SLS technology.[19] In this paper, the successful cost model of the SLS technology is used as the starting point for development of a cost model of the MJF technology.

Model

An important characteristic of the AM is the simultaneous manufacturing of several products during a single production process (using the same machine), which is frequently called a job. A collection of the products that are manufactured during a job is called a batch. Since AM is often used for small-scale production, a batch usually consists of different products. However, it was shown that even in the cases when the products in the batch are identical, the marginal material costs of AM production are not constant or monotonously decreasing.[11,12] The explanation is that material costs of an AM job essentially depend on the number of layers of the material deposited during the job; therefore, the material costs attributed to a product manufactured during the job depend on the increment of the number of layers of material caused by the presence of that product in the product bin. While that increment of the number of layers depends on dimensions of a product (that are inherent to the product), it also depends on the orientation of the product during production process and its position within the production bin (which are inherent to the batch, and not to the product). In other words, even the material costs of two identical products manufactured during the same job may be different, so that "an inherent material cost of a product" does not exist. The most important consequences of the result are that costs of AM technologies should always be calculated as production costs of a batch, and that the production costs of a single product may only be estimated with respect to the batch it belongs.

A batch generally consists of t types of products, and the number of products of type kth type of products will be denoted as n_k ($k = 1, 2, \ldots, t$), while the total number of products in the batch will be denoted as N, so that

$$N = \sum_{k=1}^{t} n_k \tag{2}$$

The total volume of all products in the batch V, and the total surface of all the products in the batch S, may be calculated as

$$V = \sum_{k=1}^{t} n_k V_k \text{ and } S = \sum_{k=1}^{t} S_k \cdot n_k \tag{3}$$

where V_k and S_k ($k = 1, 2, \ldots, t$) represent the volume and the surface of the kth type of the products in the batch, which are calculated by 3D modeling and batch assembly software tools.

A simple event-driven process chain of the MJF production is shown in Figure 2. The flowchart lists only the events (hexagons), functions (shaded rounded rectangles), and the resources (rectangles) used in the process, since the ownership of processes and internal organization are not of relevance for the presented cost model. Full lines indicate process flow, dashed lines indicate inputs, and dotted lines indicate outputs of the functions–activities.

The flowchart in the diagram represents the MJF production process as a sequence of the following activities:

- Checking and (if necessary) adjustment of the raw 3D models of the products for batch assembly; the activity is performed by a mechanical designer who understands both the product and the characteristics of the production process; the mechanical designer uses a special software and a PC workstation;
- Assembling of the batch using the 3D models of the products; the activity is also performed by a mechanical designer who understands characteristics of the production process and uses another special software and a PC workstation;
- Setting up the machine for the production process – job, which is performed by a machine operator using the processing station;
- Building of the products by the machine with use of the powder;
- Removal of the products from the product bin, which is done by an operator who uses the processing station;
- Blasting of the powder that remained attached to the surface of the powder; it is performed by an operator who uses a blasting cabinet and an abrasive.

Apart from the above-mentioned resources, all the operations require electric energy consumption.

The raw parts may be further post-processed depending on its application and the requests of the end-users. The post-processing most often consists of inexpensive painting by textile colors because the surface color of the products is not uniform, but sometimes it may include machining, various forms of mechanical or chemical surface treatment, deposition of protective and aesthetic layers, and other procedures. While the complex post-processing procedures

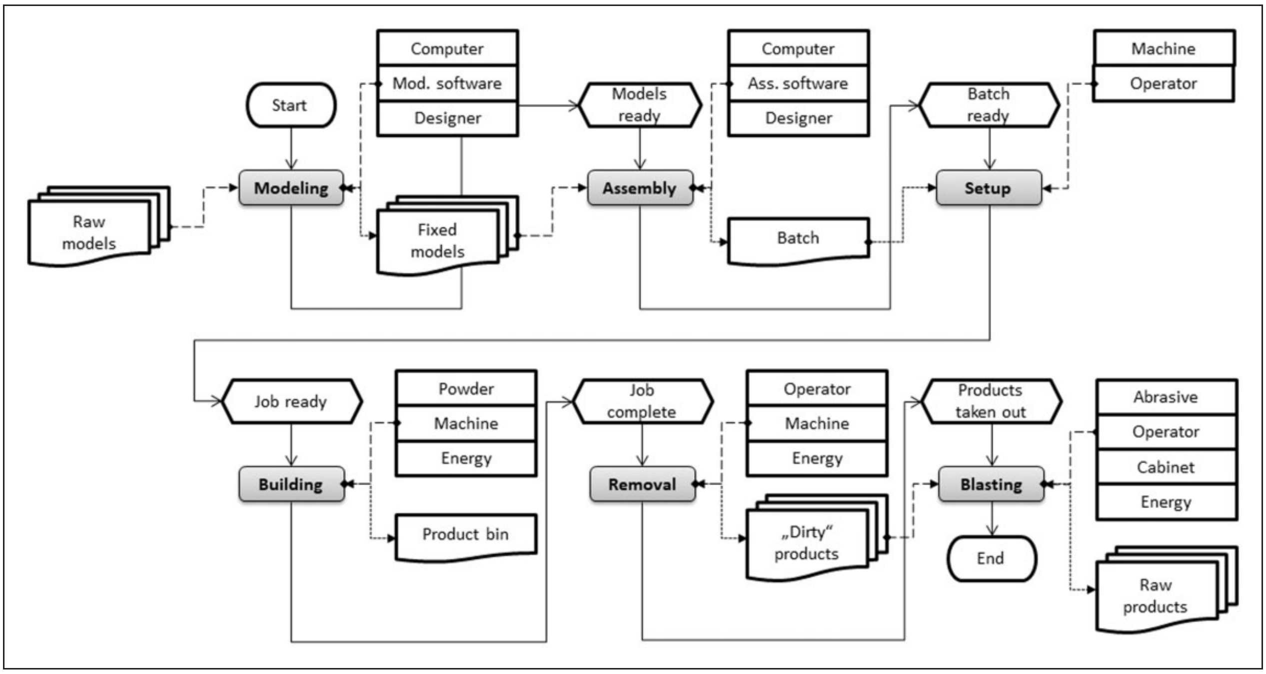

Figure 2. Flowchart of the event-driven process chain of multi-jet-fusion technology.

affect product costs, these costs are not anymore the costs of the MJF technology, and they will not be the subject of analysis presented in this paper.

Through the paper, the capital letter C will denote the total production cost of a batch. The small letter c will denote estimated production cost of a single product, which reduces to marginal production costs if all the products in a batch are the same. A subscript will indicate a type of the costs (e.g. C_M denotes material costs), and a superscript will indicate unit costs of certain type (e.g. $C_M^Q = C/Q$ denotes material cost per weight unit, e.g. per kilogram of the material).

Based on the presented event-driven process chain, direct costs of manufacturing of a batch may be identified as those costs that may be attributed only to the production of the batch, such as the costs of the material that is used for its production. Further, the event-driven process chain also enables the identification of some indirect costs as those costs that are shared between the activities of the production of several batches, such as the costs of equipment. However, there exist indirect costs that may not be identified using the event-driven-process chain, because they arise due to the activities that represent establishment of pre-conditions of any business process. These costs are classified as overheads and they are shared between all business processes, including the production processes. The presented classification suggests that the total cost of a batch C may be expressed as the sum of the total direct (C_D) and total indirect (C_I) production costs

$$C = C_D + C_I \tag{4}$$

and that direct and indirect production costs should be analyzed separately.

Direct costs modeling

Since the direct costs may be attributed to individual batches and specific activities in the event-driven process chain, the total direct costs may be calculated as the sum of direct costs of the activities

$$\begin{aligned} C_D = C_{model-D} + C_{ass-D} + C_{setup-D} + C_{build-D} \\ + C_{rem-D} + C_{blast-D} \end{aligned} \tag{5}$$

with C_{a-D} ($a = model, ass, setup, build, rem$, and $blast$) denoting the direct costs of modeling, batch assembly, job setup, building, and blasting activities.

The event-driven process chain analysis shown in Figure 2 shows that the direct costs of any of the activities consist of its labor costs C_{a-L}, its material costs C_{a-M}, and its energy costs C_{a-W}

$$C_{a-D} = C_{a-L} + C_{a-M} + C_{a-W} \tag{6}$$

Labor costs. Without the loss of generality, the labor efforts of the MJF may be divided by the necessary skills in two groups. To the first group belong the efforts due to the modeling and batch assembly activities, which are performed by mechanical designers, who understand product design and the influence that the MJF production process may have on the product design and functionality. The mechanical designers are performing an essentially creative work, they need to be trained in using specialized software, and their time unit cost is C_{des}^T. To the second group belong the efforts made due to the setup, removal, and blasting activities, which are performed by the operators who are trained to follow the prescribed procedures. Their efforts are essentially routine, and their time unit cost is C_{oper}^{T}. Therefore, the labor costs of each of the activities are given by the following equations

$$C_{a-L} = C_{des}^{T} \cdot T_a, \quad a = model, ass \quad \text{and} \\ C_{a-L} = C_{oper}^{T} \cdot T_a, \quad a = setup, rem, blast \tag{7}$$

where T_a represents the duration of the respective activity.

Material costs. The direct material costs of the MJF technology arise in the building and blasting activities.

The material costs of the building activity consist of costs of powder, the fusion agent, and the detailing agent

$$C_{build-M} = C_{build-M-powder} + C_{build-M-agent} \tag{8}$$

The material costs of powder used for the production of a batch $C_{build–M–powder}$ are product of the weight unit cost of the powder C_{powder}^{Q} and material consumption of the batch Q, $C_{build–M–powder} = C_{powder}^{Q} \cdot Q$. The material consumption depends on the density of the powder ρ_{powder} and volume of the material in the product bin, which is, in turn, equal to the product of the cross-section of the powder bed S_{bed} and height of the powder bed h. Due to the refreshment, the powder that is not used for the creation of the products is used again, so that only the consumption of the fresh powder represents the material consumption of the batch

$$C_{build-M-powder} = C_{powder}^{Q} \cdot r \cdot \rho_{powder} \cdot S_{bin} \cdot h \tag{9}$$

It should be noted that the material cost of the used powder is zero because the user does not pay for it, and the costs of the preparation of the powder for the production and the handling of the used powder are calculated as the labor, energy, and equipment costs of the setup and removal activities.

The manufacturer of the MJF equipment declares that the consumption of both fusion and detailing agents is proportional to the volume of the products.[20] Therefore, the material costs of the agents ($C_{build–M–agent}$) may be calculated using the agent consumptions per unit volume of products (V_{fus}^{V} and V_{det}^{V}) and the unit costs per volume of the agent (C_{fus}^{Vf} and V_{det}^{Vd}) for the fusion and the detailing agents

$$C_{build-M-agent} = V \left(C_{fus}^{V_f} V_{fus}^{V} + C_{det}^{V_d} V_{det}^{V} \right) \tag{10}$$

It should be noted here that the agent consumptions per unit volume of products (V_{fus}^{V} and V_{det}^{V}) depend on the selected printing mode.

The material costs of the blasting may be calculated as the product of the weight unit costs of the abrasive material C_{abras}^{Q} and the weight of the used abrasive, which may be estimated as the product of the time unit consumption of the abrasive by the blasting cabinet Q_{cab}^{T} and the duration of blasting T_{blast}

$$C_{blast-M} = C_{abras}^{Q} \cdot Q_{cab}^{T} \cdot T_{blast} \tag{11}$$

Energy costs. Since the electric power of machines is orders of magnitude higher than electric power of computers, energy costs of the modeling and batch activities will be calculated only through the indirect infrastructure costs. The energy costs of the setup, building, and removal activities may be calculated using the costs of energy unit C_{W}^{W}, based on the electric power of the processing station P_{stat} and electric power of the production machine P_{JF}

$$C_{setup-W} = C_{W}^{W} \cdot T_{setup} \cdot P_{stat}, C_{build-W} = C_{W}^{W} \cdot T_{build} \cdot P_{JF}, \\ C_{rem-W} = C_{W}^{W} \cdot T_{rem} \cdot P_{stat} \tag{12}$$

The consumption of energy, and the energy costs, of the blasting activity $C_{blast–W}$ has to take into account not only the energy costs due to the consumption of the blasting cabinet $C_{blast–W–cab}$, but also the energy consumption of the air compressor $C_{blast–W–comp}$, which has much higher electric power

$$C_{blast-W} = C_{blast-W-cab} + C_{blast-W-comp} \tag{13}$$

However, an air compressor usually supplies several pressurized air consumers, so that only a part of the energy consumption of the air compressor may be attributed to the blasting activity. If the electric power of the air compressor is P_{comp}, the air flow capacity of the compressor per unit time is v_{comp}^{T}, and the air flow consumption per unit time of the blasting cabinet is v_{cap}^{T}, then the energy consumption of the air compressor is

$$C_{blast-W-comp} = C_{W}^{W} \cdot T_{blast} \cdot P_{comp} \frac{v_{cab}^{T}}{v_{comp}^{T}} \tag{14}$$

The energy cost of the blasting cabinet is

$$C_{blast-W-cab} = C_{W}^{W} \cdot T_{blast} \cdot P_{cab} \tag{15}$$

where P_{cab} represents the electric power of the blasting cabinet.

Indirect costs modeling

It is already explained that the indirect costs are shared between different production jobs. Based on their connection to the activities in the event-driven process chain, two kinds of the indirect costs may be distinguished. To the first kind belong the equipment costs C_E, which are connected to specific activities in the event-driven process chain, but are shared between different production jobs. On the other hand, the overheads costs C_{over} and the other indirect costs C_X are not connected to any of the activities. Therefore, the complete indirect costs attributed to a production batch may be expressed as

$$C_I = C_{over} + C_X + C_E,$$
$$C_E = \sum_a C_{a-E} \ (a = model, ass, setup, build, rem \text{ and } blast) \tag{16}$$

Equipment costs. A general concept for the calculation of the equipment costs of a piece of the equipment e during an activity a, $C_{a\text{–}E\text{–}e}$, is to calculate the products of time unit costs of the used equipment $C_e{}^T$ and duration of the activity T_a, so $C_{a-E-e} = C_e{}^T \cdot T_a$. The calculations of the time unit costs differ for MJF machines, other machines, software, and consumables. In order to make an estimation of the equipment costs more realistic, it is important to assess the utilization ratio of the piece of the equipment e, defined as $u_e = T_e/T$, where T_e represents the average occupancy time (sum of the setup time and the working time) of the piece of the equipment within the selected interval T (which may be day, week, month, or a year).

All the machines have finite operating life, and if the depreciation period of a piece of the equipment e is d_e years, then its time unit cost may be estimated as

$$C_e^T = \frac{C_{e-p}\big/d_e + C_{e-m}^{ann}}{u_e T^{ann}} \tag{17}$$

with $C_{e\text{-}p}$ representing the purchase cost, and C_{e-m}^{ann} representing the annual maintenance costs, of the piece of equipment, while T^{ann} represents duration of one year. The previous equation may be applied to the purchased MJF machines, processing station, blasting cabinet, or an air compressor ($e = MJF, proc, cab, comp$). Considering the relatively small purchase costs and long deprecation time, as well as the lack of the maintenance costs, the equipment costs for computers used as the PC workstations may be neglected.

However, since the AM technologies develop fast, their obsolescence time may be considerably shorter than their operating life, and many companies opt for leasing of AM machines. In such a case, the costs of the leased machines ($e = MJF, proc$) should be estimated as

$$C_e^T = \frac{C_{e-l}^{per}}{u_e T^{per}} \tag{18}$$

with C_{e-1}^{per} representing the leasing cost (usually annual rent) per leasing period, while the T^{per} represents the duration of the leasing period (usually one year).

Software time unit costs, on the other hand, depend on the number of licenses that limit sharing of a software tool between different tasks, so that for the software for modeling and for batch assembly holds

$$C_e^T = \frac{C_{e-p}\big/d_e + C_{e-m}^{ann}}{N_{e-lic} u_e T^{ann}} \quad e{=}soft - model \text{ and } soft - ass \tag{19}$$

with $N_{e\text{-}lic}$ representing the purchased number of licenses for the software.

Consumables (like fusing lamps, print heads, cleaning rolls, etc.) in practice do not have depreciation period, and the time unit cost of the consumable $cons\text{-}k$ for the piece of the equipment e may be estimated as

$$C_{cons-k}^T = \frac{C_{cons-k}^1 \cdot n_{cons-k}^{ann}}{u_e \cdot T^{ann}} \tag{20}$$

where C_{cons-k}^1 represents the cost of purchase of a unit, and n_{cons-k}^{ann} represents the annual consumption of the consumable $cons\text{–}k$.

With these estimations of the time unit costs, the equipment costs of modeling, assembly and removal may be calculated as

$$C_{model-E} = C_{soft-model}^T \cdot T_{model}, C_{ass-E} = C_{soft-ass}^T \cdot T_{ass},$$
$$C_{rem-E} = C_{stat}^T \cdot T_{rem} \tag{21}$$

since these activities require just one piece of equipment.

The setup activity requires the use of the production machine and the processing station, so the equipment cost of the activity is

$$C_{setup-E} = \left(C_{MJF}^T + C_{stat}^T\right) \cdot T_{setup} \tag{22}$$

While the building activity requires only the production machine, its proper work requires various consumables, and if the number of the consumables is N_c, then the equipment cost of the building activity is

$$C_{build-E} = \left(C_{MJF}^T + \sum_{k=1}^{N_c} C_{cons-k}^T\right) \cdot T_{build} \tag{23}$$

The blasting activity requires a blasting cabinet and an air compressor, but the equipment costs of the compressor should be shared between its users, in a manner similar to the sharing of the energy costs of the air compressor. Therefore, the equipment cost of the blasting activity is

$$C_{blast-E} = \left(C_{cab}^T + C_{comp}^T \frac{v_{cab}^T}{v_{comp}^T}\right) \cdot T_{blast} \tag{24}$$

Overheads. From the point of view of the estimation of the production costs of MJF technology, the overheads comprise all the costs that are not related to the production process, but which are needed to enable and support it. A major part of the overheads represent the business costs such as administrative and management costs, renting or purchase of rooms, heating, lighting, and water supply costs. As described, overhead costs are indirect costs that do not vary with the level of production, and they exist even without production.[21] One of the most used methods for the estimation of the overhead costs[21] is the application of the fixed overhead rate R_O to the other costs connected to a business process

$$C_{over} = R_{over} \cdot (C_D + C_E + C_X) \tag{25}$$

spreading the overhead costs over various production processes of a company. The overhead rates may be constant or determined using more complex costs drivers such as process duration or material consumption, but methodologies of sharing of the overhead costs between the products and services of a company are beyond the scope of this paper.

Other indirect costs. There are MJF technology costs that cannot be attributed to a specific production batch, such as the health and safety costs (including waste disposal), material and product handling, and similar costs. Unlike overheads, these costs do not arise without the production process, but similar to the overheads, they are needed to enable and support the production.

Since the indirect costs from this category do not arise due to an individual production batch or due to a specific production activity in the event-driven-chain methodology, they have to be assigned to the individual production batches using some cost drivers, and the duration of the activities in the event-driven-chain of the MJF technology seem as a rational choice. As the activities overlap in time, the sum of their durations does not represent the total duration of production process, and it is better to use the building time as the cost driver for the estimation of the other indirect costs attributed to a single production batch. Therefore, the indirect cost of type *X-k* assigned to a production batch, $C_{X\text{-}k}$, may be estimated as

$$C_{X-k} = \frac{C_{X-k}^{per}}{u_{MJF} \cdot T_k^{per}} T_{build} \tag{26}$$

where C_{X-k}^{per} represents the indirect cost of the type *X–k* during a period with duration T_k^{per} (usually a week, a month, or a year), for which the indirect cost is known. The amount of the other indirect costs attributed to a single production batch is then

$$C_X = \sum_k C_{X-k} \tag{27}$$

Analysis

The aim of the developed model is to serve as a basis for the development of algorithms for the calculation of the production costs and, eventually, quoting. It should be therefore noted that, while the presented calculation of the production costs of a batch is reasonably accurate and well-funded, it is still not sufficient for the purposes of quotation. That is to say, managements of companies are interested in estimations of production costs of individual products, even if the accuracy is lower than the accuracy of calculation of production costs of batches.

The estimation of the costs of the individual products in a batch is based on the following reasoning:

- the sum of the costs of all products in a batch is equal to the cost of the batch;
- the costs of modeling are divided equally between the types of the products because the handling of the models is performed once for each type;
- the overheads are also divided equally between the types of the products as overheads do not depend on production volume (i.e. number of products);
- the costs of assembling into batch, setup of the production, and removal of a certain type of the products are proportional to the number of the products of that type in the batch n_k, because these activities require individual handling of each product;
- the other indirect cost are also proportional to the number of the products of a certain type in the batch n_k, because the other indirect costs are affected by the production volume (i.e. number of products);
- the building costs are roughly proportional to the volume of the products; the reason being that these costs are driven by material costs and equipment costs; the material costs are determined by the volume of products, and the equipment costs are determined by the building time; since the building time increases with the height of a batch (due to the increase of the number of layers), the orientation of a product in a batch may be of crucial importance for its contribution to the production time;[17] nevertheless, an increase in the volume of a product also means an increase in the fusion time for its production and thus an increase in the building time of the batch; for these reasons, and for the sake of simplified estimation of product costs, the approximation of proportionality is adopted between the building costs and volume of products;
- the blasting costs are proportional to the surface of the products, because the duration of the blasting and the consumption of the abrasive increase with the increase in the amount of the powder that remains attached to the product surface after removing from the product bin.

An implementation of the previous reasoning requires the calculation of the total number of products using equation (2), and then the total volume and surface of the products using equation (3).

Further, the following weighting coefficients have to be calculated:

For the number of the products of certain type k

$$x_{n-k} = \frac{n_k}{N}, \quad k = 1, 2, \ldots, t \tag{28}$$

For volumes of the products of certain type k

$$x_{V-k} = \frac{V_k \cdot n_k}{V}, \quad k = 1, 2, \ldots, t \tag{29}$$

For surfaces of the products of certain type k

$$x_{S-k} = \frac{S_k \cdot n_k}{S}, \quad k = 1, 2, \ldots, t \tag{30}$$

Using the mentioned reasoning and the calculated weighting coefficients, the production cost of a single product of type k may be estimated as

$$c_k = \frac{1}{n_k} \left\{ \begin{array}{l} \frac{C_{model} + C_{over}}{t} \\ + \left(C_{ass} + C_{setup} + C_{rem} + C_X \right) \cdot x_{n-k} \\ + C_{build} \cdot x_{V-k} + C_{blast} \cdot x_{S-k} \end{array} \right\} \tag{31}$$

Once the methodology for the calculation of the production costs assigned to an individual product is known, an algorithm may be defined. While various solutions are possible, the algorithm should consist of five phases:

1. Description of the configuration, when the data that describe the manufacturing environment are entered as inputs; the environment comprises the policies (labor unit costs and overhead rate) of the company, energy unit costs, the equipment, and the materials used for the manufacturing process;
2. Setup calculations, when the various unit costs, which depend on the environment of the production process, are calculated;
3. Description of the batch by the input data that describe the duration of each of the activities, used materials, and building mode of the production job, then the volume and surface of each type of the products that should be manufactured, as well as number of products for each of the product types in the batch;
4. Auxiliary calculations, when the various unit costs and weighting coefficients that depend on the composition of the product batch are calculated;
5. Cost calculation, when the cost calculations are performed.

Discussion

The presented model of the MJF technology is rather general and comprehensive. However, some variations of the model are certainly possible, and there are some points to be discussed. For example, the costs of PC workstations may be included in the equipment costs, or their energy consumption may be included in the calculation.

The classification of consumables as a separate category of the equipment costs may be also a topic of discussion. It is obvious that consumables are indirect costs since their consumption is shared between many jobs, but they may be treated also as a part of the maintenance costs, since their consumption puts the equipment in the operational state. On the other hand, the annual regular maintenance costs are usually fixed (in most cases the matter of a purchase contract), while consumption of consumables depends on the utilization of machines. However, the difference is not substantial, and the authors believe that such a classification is also possible and would lead to similar results. Nevertheless, equations (17) and (20) show that even in such variation of the model, the total costs of a batch remain the same if the maintenance costs of the production machine C_{MJF-m}^{ann} are increased for the annual consumption $C_{cons-k}^{1} \cdot n_{cons-k}^{ann}$, which seems as a logical choice. Therefore, the discussion about the classification of the costs of the consumables is more of academic relevance.

A more important topic for discussion is the calculation of the production costs of building activity that are attributed to the individual products, because of the existence of a well-known algorithm for the calculation of the building costs attributed to individual products of SLS technology.[17] The basis for the calculation of share of the building costs attributed to a product in that algorithm is the number of the layers used to build the product (i.e. the height of the product). The authors reiterate here that the AM processes are essentially batch-oriented, and that a "true" production cost of an individual product in a batch does not exist. Therefore, when comparing different algorithms for the estimation of the production cost attributed to an individual product, one should always keep in mind that (since there is no correct value of the cost) there cannot be "more accurate" algorithm, so the comparison is always about the convenience (or even "impartiality") of the algorithms versus certain requirements. The main purpose of the procedure for the estimation of the production cost attributed to an individual product is quoting. For that purpose, a convenient procedure for the estimation of the production cost attributed to an individual product should result in equal production costs of identical products, at least when they are manufactured within the same batch. However, estimations of the building cost attributed to an individual product using the algorithms based on the height of a product depend on the orientation of the product within the product bin, which, in turn, also influences the dimensional accuracy of the products.[22] Therefore, algorithms based on the height of a product may lead to widely different estimations of building costs of identical products. It is quite possible to modify the algorithm based on the height of a product for the calculation of production costs of each product of the type k, then to sum them to have the total building cost, and finally to estimate the production cost of an individual product of type k by dividing the sum by the number of products of that type, n_k. However, the authors opted for a simpler approach based on the volume of the products because it is easier for implementation, and still keeps a reasonable amount of "impartiality", since the building costs increase with the increase in the volume of products.

Comparison to SLS production cost model

Finally, the proposed cost model and the algorithm should be compared to the cost model of SLS costs that served as a development pattern. It is important to point out that the following discussion is a comparison between two production cost models, and not comparison between the costs of the two technologies (as these costs substantially depend on the prices of the inputs and production volumes) or comparison between the technologies (which would require analysis of numerous other aspects of these technologies). Although the concepts of the cost models are the same, as both SLS and MJF are powder bed technologies, there are substantial differences caused by the differences between the technologies. The most important differences are those between the methods of calculation of the material and the equipment costs.

Material costs

While both of the technologies use polyamide for the manufacturing of polymer products, there are two important differences between the material costs of SLS and MJF technologies.

The first difference is that the MJF technology requires the application of the fusion and detailing agents, which are not used in the SLS technology. Therefore, the equation for the material costs of the MJF technology (8), includes the addition of the second term, described by equation (10), which does not exist in the respective equation for the material costs of the SLS technology. Rather high costs of the fusion agent and the detailing agent thus increase material costs of the MJF technology in comparison to the SLS technology.

On the other hand, the MJF technology has considerably lower refreshment rate than the SLS technology (typically around 20% former and around 50% latter), which reduces the material cost for production powder of the MJF technology in comparison to the SLS technology.

The two opposing trends mean that the presented models do not enable easy comparison of the material costs of the two AM technologies, as the material costs depend not only on the ratio between the costs of the agents and the powder, but also on the composition of the production batch, because it determines the consumption of the powder and the agents. As shown by equations (9) and (10), the powder consumption is determined by the height of the powder in the production bin h, while the consumption of the agents is determined by the total volume of the products V. Therefore, the ratio between the consumption of the agents and consumption of the powder rises with the increase in the ratio V/h. Compact arrangement of the products in a production bin have higher ratios V/h, so it may be concluded that the SLS technology production costs favor compact arrangements, while the MJF technology costs are less sensitive to the product arrangement within the production bin. Therefore, one may expect that the material costs, on average, may cause shorter lead times for the MJF technology in comparison to the SLS technology, as manufacturers who use the MJF technology will have smaller costs due to suboptimal use of the space within the production bin.

Equipment and energy costs

It is already explained that the present production systems for the MJF technology use dedicated processing stations for cooling of the production bin after a production process. On the other hand, the cooling of the production bins in SLS technology is performed in the production machine, and in general lasts as long as the building process. While the difference, as mentioned previously, is not the matter of the manufacturing principle, at the moment it causes two differences between the models of the equipment costs of the MJF and SLS technologies.

The first difference is that the utilization ratios of the building machine and the processing machine in equation (17) may be up to two times higher, thus reducing the time unit costs of the machines. The second difference is the cost of the processing station that affects the costs of the setup and removal activities of the MJF technology. Besides, the engagement of the processing stations increases energy costs of the activities. Due to the differences, the MJF technology equipment costs favor rapid manufacturing applications.

Activity costs

The presented comparison of cost categories in the cost models of the MJF and SLS production

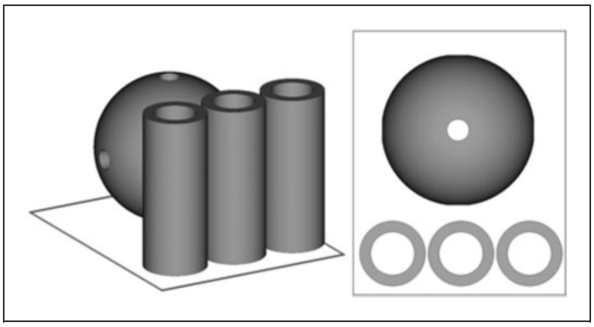

Figure 3. Isometric (left) and top (right) view to the test batch.

technologies reflects to the comparison of cost models for the activities in the event-driven-process chain:

- the cost models for the modeling and batch assembly are identical, as the activities essentially do not depend on selection of the technology;
- the cost models of the setup activities are similar because the setup of the MJF technology comprises use of the processing station and the production machine as shown in equation (22), while the setup of the SLS technology requires also sieving and mixing of the production powder before loading of the production machine;
- the cost models of the building activity are different because of the differences in the material costs (due to the use of the fusion and detailing agent and substantially different refreshment ratios) and equipment costs (due to the substantially different utilization ratios);
- the cost models of the removal activity differ because the removal activity for the MJF technology includes equipment costs of the processing station and increased energy costs;
- the cost models of the blasting activity are identical.

In order to get an idea about the differences between the cost models of the MJF and SLS technology, an example of the calculation of production costs is performed. The batch consists of three hollow cylinders and a hollow sphere with channels along three orthogonal diameters (Figure 3). The batch is selected so as not to be particularly compact and to have some lightweight structures, frequently met with AM technologies. The diameter of the sphere is 140 mm, while the diameter and the height of a cylinder are 60 mm and 150 mm, respectively. Since some powder layers should be deposited before and after the building of the products, the height of the product bin is 162 mm, and the volume of the material built into products is around 20% of the product bin.

The calculations of the duration of the activities depend on the machines that are assumed. Since the aim of the calculation is just to compare the structures of two cost models, the duration of the activities were taken for SLS production system EOS Formiga P100 and MJF production system HP Jet Fusion 3D 4200 in "balanced" production regime. The ratio between the labor costs, material costs, energy costs and equipment costs depend also on market conditions, and for the sake of this example, they were taken for the conditions of a SME that provides rapid prototyping and rapid manufacturing services in the Italian market. As the calculation of the production costs of the SLS process included 66 input parameters and calculation of the production costs of the MJF technology included 76 input parameters, their values will not be listed here.

Table 1. Relative costs of the activities in the event-driven process chain.

Technology	Total	Model	Batch	Setup	Build	Removal	Blasting
MJF	100%	4%	4%	3%	83%	3%	3%
SLS	100%	9%	9%	5%	65%	5%	6%

MJF: multi-jet-fusion; SLS: selective laser sintering.

Table 2. Relative costs of the cost categories.

Technology	Labor	Material	Energy	Direct	Equipment
MJF	16%	82%	2%	100%	31%
SLS	35%	63%	2%	100%	62%

MJF: multi-jet-fusion; SLS: selective laser sintering.

The results of the calculations are shown in Tables 1 and 2. Table 1 presents the comparison between the relative costs of the activities. As expected, the cost models predict that the majority of the costs are the building activity costs, representing more than 4/5 of the production costs of the test batch for the MJF technology and more than 3/5 of those costs for the SLS technology. Table 2 compares the results of the cost models for categories of costs, with respect to the total directs costs of production of the test batch. It explains the higher relative costs of the building activity for the MJF technology by showing that material costs represent more than 4/5 of the direct material costs for production of the test batch by the MJF technology and around 3/5 of those costs by the SLS technology. The other notable feature that Table 2 shows is that the equipment costs represent only 1/3 of the of the direct material costs for the production of the test batch by the MJF technology and around 2/3 of those costs by the SLS technology. The explanation lies in the increased utilization of the production machines in the MJF technology due to the application of the processing machine for cooling.

Conclusion

The present work discusses a model of the production costs for the MJF technology that is based on the one for the SLS technology. As both technologies belong to the powder bed fusion AM technologies, the selection of the starting point seems as a reasonable choice. The model is developed using the methodology of analysis of the event-driven process chain of the MJF technology, which comprises the adjustment of product models, batch assembly, setup of the production machines, building, removal, and blasting of the products as the process chain functions–activities. Production costs of each of the activities are separated to direct (labor, material, and energy) costs and indirect (equipment, overheads, and other indirect) costs.

The developed model defines all the necessary inputs and calculation procedures that enable the calculation of the total costs of a batch of products. Furthermore, one procedure is presented in this article for the estimation of production costs that are attributed to a single product or product type. The developed model of the MJF production costs, therefore, represents a basis for the development of algorithms and software tools for the calculation of the production costs of the MJF technology.

The comparison between the cost models of the MJF technology and the SLS technology show that both of the models recognize material costs and equipment costs as the key costs drivers of the respective technologies. However, the presented model for the MJF technology costs considers the material costs as dominant cost category, while the cost models for SLS technology costs predicts that both material and equipment costs have similar influence. As the material costs are the most variable parameter in the model, due to changes of prices in the market that vary with time and the ordered quantity of material, this conclusion may be of importance for the MJF technology users.

Since the MJF machines entered market around 2016, there are still some unknowns in the process of the calculation of the product costs, which open possibilities for the improvement of the model. Once more data about the production costs of the MJF technology are known, it will be possible to estimate margins of error of the calculations made using the proposed model. Due to the high costs of fusion and detailing agent, their consumption in practice is in this sense a research topic of primary interest, since more accurate estimations of agent consumption in various regimes of work will reduce the margins of error of any model of MJF costs.

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Note

Multi-jet fusion is a trademark of Hewlett-Packard Development Company, L.P.

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