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Process Planning and Optimization Techniques in Additive Manufacturing

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Additive manufacturing, as a production technology and a scientific field, offers a lot of potential for new research, attracts the attention and interest of manufacturing companies and the academic community. With a new approach in product design, a digital connection chain, and the possibility of producing final products with complex configurations, it has significant advantages in relation to conventional production.

However, the initial investment and production costs make this technology still inaccessible to a certain number of users, with the tendency for this to change. In this sense, great attention has been paid to additive manufacturing planning, cost analysis and the possibility of optimizing structural and process parameters of production and processes.

This paper is intended to explain, in a clear and concise manner, the basic assumptions of the technology, its advantages and certain disadvantages, ongoing and future trends in development as well as current areas of research (cost estimation, multi criteria decision making (MCDM), topology optimization) and applied methods and concepts.

The authors believe that this paper will provide additional help in process planning for additive manufacturing as well as promote the necessity for introducing and application of different optimization techniques when designing technology for additive manufacturing.

Key words: **additive manufacturing, cost estimation, MCDM techniques, topology optimization.**

Introduction

ADDITIVE manufacturing (AM) has evolved over the past three decades, and now it is not just a technique to produce prototypes in a fast and low-cost way, but it is becoming an actual manufacturing option where serial production is considered and evaluated seriously as an option.

According to [1], AM has experienced tremendous growth from a promising technology in the early 1980`s up to the market worth about 4 billion USD in 2014 with the prediction to exceed 23 billion USD by 2026.

The cost of the introduction and adaption of this technology is still questionable for some users. As said by [1] and [2], in some cases the advantages and benefits that AM technology brings in terms of light-weight, parts number reduction, complex shape productions, advanced performances, end-use (functional) parts and components production, spare parts production from digital warehouse, etc., outweigh the cost issue.

Besides the cost issue, [2] clustered other barriers into three groups that prevent adoption of AM technology: high price and investment, lack of capability and know-how, technology limitation. The following parts of the papers we will explore some other important areas in order to shed light on the complexity and versatility of the AM.

AM market is full with different Original Equipment Manufacturers (OEM) and service providers that offer different hardware and software solution, as well as types of material. Evolution in these areas is very fast. Since the material is depositing “layer by layer”, the whole procedure needs careful attention related to the process parameters, walls thicknesses, minimization of volumes, structural evaluation, etc. [1].

Design for Additive Manufacturing (DfAM) is not just a shape optimization based on material distribution, but rather a completely new design approach. In some cases the rethinking of the existing design solutions does not provide valuable solutions for AM and, starting from the beginning, is the only possible solution.

In order to reach the full and functional realization phase, a lot of effort needs to be invested in the planning phase through optimal part orientation, support generation, process parameters choice. For the full functional part post treatment is mandatory in order to improve quality [1].

Regarding the standards for traditional production processes, the standards and best practices have been developed in order to avoid complications and inefficiencies during the production. Same approach is worth for the AM. In parallel with the development of additive technological processes, machines and supporting equipment, the International Standardization Organization (ISO) and American Society for Testing and Materials (ASTM) worked intensively on the development and application of standards in the AM field.

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Previously explained is just one part of the wide range of AM research areas. In addition to this, an analysis of the available literature indicates that researchers have focused their attention on the following areas in additive technologies: digital thread, data models and formats plus data interoperability, design for additive manufacturing, cost model estimation, additive manufacturing industrialization and AM technologies integration into the manufacturing system, multi criteria decision making application in AM, etc.

Next chapter is dedicated to the presentation of the AM categories and technologies, current evolution steps in 3D printing, standardization processes and digital tread. Then, in the following chapter, the overall strategy for design for AM with its steps is explained in details. After that, the next chapter is devoted to explanation of the actual scientific research in the AM field, emphasizing the cost estimation process, MCDM models and role of topology optimization. The paper is finished with a conclusion and suggestions for further work.

Classification of AM technologies and further evolution

In order to precisely define AM, as well as to list the AM categories, almost all authors usually refer to the official statement and definitions from ASTM group ASTM F42 and the ISO 17296 Committee. Having this in mind, and according to [3], AM is "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies".

Table 1. AM categories and characteristics (Adapted from [3] and [4]).

PROCESS CATEGORY	CHARACTERISTIC	MATERIAL	APPLICATION	TECHNOLOGIES
VAT PHOTOPOLIMERISATION	Solidification of photo-curable polymer liquid or ceramic paste through selective scanning by a light source	Polymer Ceramic	Prototyping Functional testing Tooling patterns Detailed parts Presentation model	SLA – Stereolitography, DLP – Direct Light Processing, CLIP – Continues Liquid Interface Production
MATERIAL EXTRUSION	Deposition of filament or paste on a build platform selectively with a nozzle	Polymer Metal Ceramic Composite	Prototyping Functional testing Tooling patterns Personnel use	FDM – Fuse Deposition Modeling, FFF – Fuse Filament Fabrication, ADAM – Atomic Diffusion AM
MATERIAL JETTING	Deposition of droplets of build material selectively with a printing head	Polymer Metal Ceramic Composite	Concept model Limited Functional Testing Colored Design Model	Polyjet MJP – Multijet Printing
BINDER JETTING	Deposition of droplets of liquid bonding agent selectively in material powders to bind them together	Polymer Metal Ceramic	Prototyping End use parts Casting/forming tools	MJF – Multijet Fusion SPJ – Single pass Jetting
POWDER BED FUSION	Selective scanning and melting of a specific area of a powder bad with a heat source	Polymer Metal Ceramic	End use parts Functional testing Rapid tooling High temperature application	SLS – Selective Laser Sintering, SLM – Selective Laser Melting or DMLS – Direct Metal Laser Sintering
DIRECT ENERGY DEPOSITION	Deposition of powder or filament melted by a heat source	Metal	End use parts Functional testing Rapid repair / overhaul High temperature applications	LENS – Laser Engineered Net Shape, EBAM – Electron Beam AM, LMDw – Laser Metal Deposition with wire, WAAM – Wire Arc AM
SHEET LAMINATION	Binding of material sheets to create objects with a cutting source	Polymer Ceramic Composite Metal Paper	Form testing Tooling patterns Less detailed parts	LOM – Laminated Object Manufacturing, UAM – Ultrasonic AM

Following the same referring methodology and authors, there are seven categories of AM technologies: 1) Vat photopolymerization including SLA (Stereolithography) and DLP (Direct Light Processing) 2) Material jetting, 3) Binder jetting, 4) Material extrusion including FDM (Fused Deposition Modeling) and FFF (Fused Filament Fabrication), 5) PBF (Powder Bed Fusion) including SLS (Selective Laser Sintering), SLM (Selective Laser Melting) and DMLS (Direct Metal Laser Sintering) 6) Sheet lamination including LOM (Laminated Object Manufacturing) and 7) Direct energy deposition including 3D laser cladding and WAAM (Wire Arc Additive Manufacturing), [3]. The review of the process categories and characteristics, materials, applications, and representative technologies of AM is presented in Table 1.

The paper [4] explains that due to lower prices of machines as desktop solution and wide range of process able materials, the most preferable process categories for the rapid prototyping are vat photopolymerization, material jetting, binder jetting and material extrusion. Other AM categories (PBF, Direct Energy Deposition and Sheet Lamination) are appropriate for tooling and direct manufacturing mainly due to the possibility to produce metal parts.

Evolution in 3D printing

According to [5], 3D printing associated software solution and materials have gained huge evolution and steps forward.

As for the concerning materials for AM, the cooperation among OEM printer manufacturers and material producer in order to create so called "open material models" (greater material diversity, possibility for new material development) is noticeable. This is a response to the obstacles imposed by companies EOS and Stratasys and their proprietary nature of printing materials (known as "closed system").

Polymer 3D printers are the most prevalent in use, while metal 3D printers are catching up. The demand for industrial systems that are smaller and cost-effective lead to the rise of the desktop 3D printers (FFF and SLA technology) as well as compact metal 3D printers (for entry-level industrial customer). We are witnessing the rise of the metal binder jetting technologies, too. There are other newcomers in 3D printing environment, they are in the early stage of the development (ceramic, electronic and composite 3D printers) but are greatly promising. The trend shaping the hardware market is the enhancement of quality monitoring and assurance process through the integration of 3D printers with sensors/cameras and machine vision.

Besides platforms and materials, same focus should also be pointed to the software solution for the AM. In this field there is a growing intention in developing of multi-functional software solution which can perform printable checks, orientation of the part at build plate, optimization of the part structure, add support elements or run simulation analysis. Running the simulation analysis, users avoid expensive trial and error approaches and also provide repeatable and reliable 3D printings.

Standards in the area of AM

For new and still emerging technology like AM it is very important to build customer trust and confidence and this can be achieved through standard development and communication.

In parallel with the development of additive technological processes, machines and supporting equipment, several standardization organizations (international, regional and national) are involved in development of AM standards and ASTM and ISO have the leading role among them.

From the industry perspective, the standards are used in areas like testing, inspection, certification, material validation, process and material qualification, etc.

For AM technologies numerous standards for test methods, design guides, materials, processes, data and terminology have been developed so far. Brief reviews of some standards are given in the continuation [6]:

- Terminology: ISO/ASTM 52900:2015 Additive manufacturing — General principles — Terminology; this standard has been revised by ISO/ASTM 52900:2021 Additive manufacturing — General principles — Fundamentals and vocabulary.
- Design: ISO/ASTM 52910:2018 Additive manufacturing — Design — Requirements, guidelines and recommendations (the standard provides requirements, guidelines and recommendations for using additive manufacturing (AM) in product design)
- Purchase AM Parts: ISO/ASTM 52901:2017 Additive manufacturing — General principles — Requirements for purchased AM parts (*the standard defines and specifies requirements for purchased parts made by additive manufacturing).*
- Data Format: ISO 17296-4:2014 Additive manufacturing — General principles — Part 4: Overview of data processing, the standard has been revised by ISO/ASTM 52950:2021, Additive manufacturing — General principles — Overview of data processing.
- Testing: ISO/ASTM 52921:2016 (MAIN) Standard terminology for additive manufacturing - Coordinate systems and test methodologies (ISO/ASTM 52921:2013).
- Materials:
- ISO/ASTM DTR 52913-1 Additive manufacturing — Feedstock materials — Part 1: Parameters for characterization of powder flow properties (Under development)
- ASTM F2924-14(2021) Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion.
- Parts positioning and finished part properties
- ISO 17295:2023: Additive manufacturing — General principles — Part positioning, coordinates and orientation. (The standard provides specifications and illustrations for the positioning and orientation of parts with regards to coordinate systems and testing methodologies for additive manufacturing (AM)).
- ISO/ASTM 52909:2022: Additive manufacturing of metals — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion.

Digital connection

In the process of applying additive methods in the production process, the connection and exchange of information between all participants is achieved by a digital chain/tread. Digital connection is the communication framework that enables connections among involved parties (designers, customers, AM providers, OEMs) providing material and manufacturing information, according to [7]. Information exchange occurs in both directions, feed-forward and feed-back loops, and connects the process stages from design, through simulation and build plan, process monitoring, control and verification, [7] and [8]. All information need to be a part of a single digital thread, accessible, traceable and interoperable with all machines within the process chain.

Digital connection is a prerequisite for application of philosophy of Industry 4.0 (I4.0). I4.0 embraces digitalization and enhances it to the high levels supported with nine pillars. One of the nine pillars of I4.0, beside AM, is “cloud computing” and AM service providers use it in order to satisfy consumer demands and needs (short deliver time, quick respond to customer, smart supply chain, etc.) by outsourcing their AM products (offering AM services through on-line manufacturing). I4.0 in manufacturing plays a key role in three areas: smart supply chain, smart manufacturing and metrology as well as in smart products [9].

Overall strategy for design for AM

It is an indisputable fact that better methods and tools are necessary to help in the process of designing or making decisions for designing in order to identify the relationship between functional and economic requirements and the possibility of applying additive technology methods for production.

In relation to classic/subtractive production, additive production provides new opportunities as well as some limitations, but ultimately it requires different approaches in the preparation and execution of production.

Additive technology is expected to enable more cost-effective production of the products with different geometries and different types of materials. To achieve these effects, it is necessary to clearly define the connections and relationships between project requirements, production process requirements, as well as the ability of additive technologies to respond to these challenges.

Overall strategy for design for AM is presented in the standard [11]. All processes are further explained as it follows:

- *Design/engineering task*: Initial design of the product is performed on the basis of the defined tactical-technical requirements for the product. AM gives new opportunity for designing of the products, with the introduction of the DfAM framework which deals with the design of the product, focusing on manufacturing and assembly of that product at the same time.
- *Identification of general AM potential*: It is necessary to determine the possibilities or "potential" of a product

(design in previous phase) for production with additive technology (for this step there is a separate procedure in the standard, where the main decision criteria is focusing on the material availability and then identifying at least one of the following features of the part (new functionality, customization, light structure, complex geometry, etc.) for which AM technology is particularly suited. More information about AM potential can be found in [10].

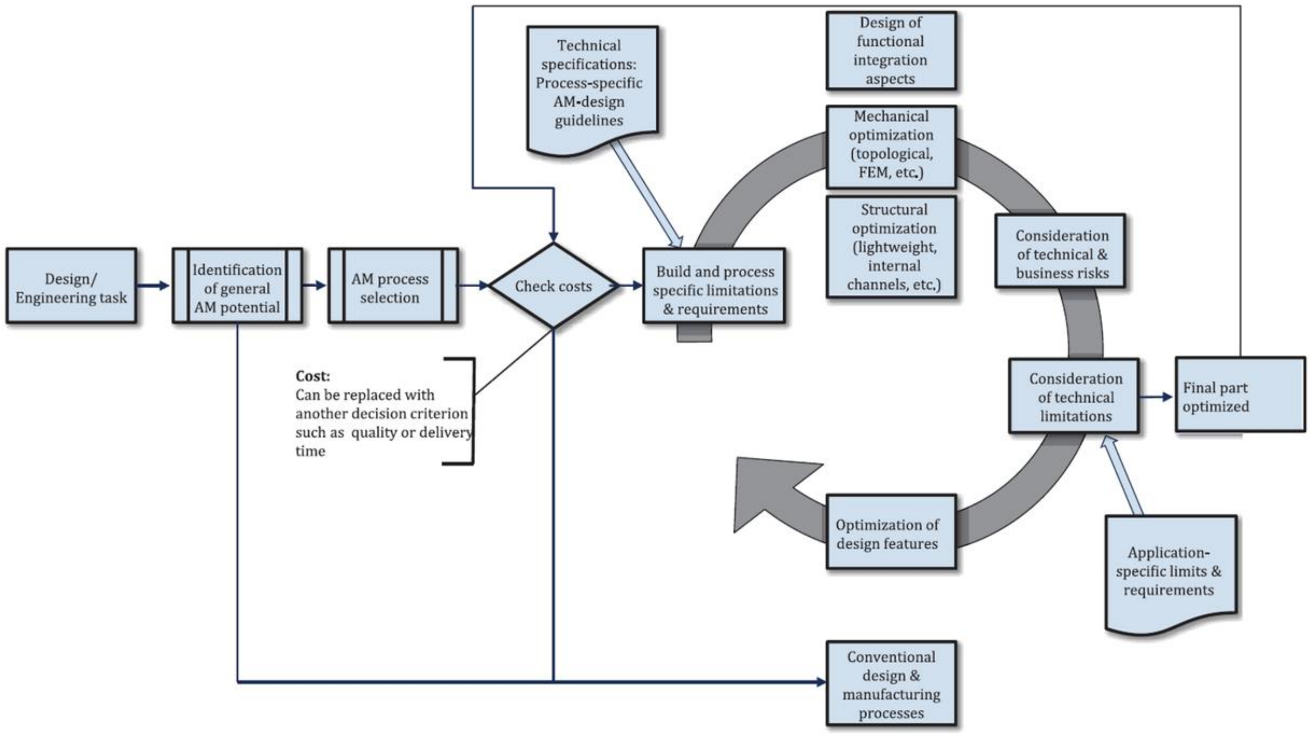

Figure 1. Overall strategy for design for AM

- *AM process selection*: Selection of an adequate process is made within the categories of additive technology and, the selection of the appropriate technology is made within the same category, Table 1.
- *Check cost*: Costs are also analyzed as one of the decision criteria. The producer could replace the cost criterion with quality, delivery time or some other relevant decision criterion, if the selected criterion is applicable in the specific case.
- *Build and process specific limitations and requirements*: Process planning is one of the critical activities in AM production chain and is related to the definition of the process variables necessary to build the part on AM machine. Variables to be defined in planning process step are: part orientation, support definition, slices process, tool path designation and process parameters definition, etc.
- *Design of functional integration, mechanical and structural optimization*: Within this phase, the techniques for optimization of product geometry based on DfAM are being performed. As published in [10] and further explained in details in [12], appropriate DfAM techniques are: 1) Light-weight design (Complex design) including: topology optimization, application of bionic principles and transformation of shapes from nature and lattice and cellular structures, 2) Component consolidation (design of integrated geometries - several parts connected into one functional unit), 3) Design for functional integration – multi functionality achieved by shape, 4) Design to improve the function and performance of the work, 5) Tool optimization and 6) Customization.
- *Consideration of possible risks and limitations*: The next step is the analysis of technical and business risks associated with the chosen technology and process as well as some technical limitations, and the final outcome after all steps are performed is optimized final part.

If during the phase of determining the potential for AM, as well as the initial costs, it has been determined that the AM technology is neither adequate nor economically profitable, a decision is made to apply the classical methodology. Also, if the costs of producing the final part are too high, a decision can be made to switch to classic production methods.

Although the application of additive technologies has certain advantages compared to conventional methods, their application is still debatable from the point of view of the cost efficiency, variation in quality, process planning. There is still a consideration that it is not possible to economically make a justification for AM application, especially for serial production. There are some opinions that each angle and holistic approach should be accepted when considering the AM application.

Planning process for AM provides several areas for further consideration from the optimization point of view. This means that, despite the fact that AM is not always economically viable (large volumes production cannot recoup the cost and provide profit), some other aspects/benefits of AM applications (weight reductions, complex geometry, late-stage changes, cycle time savings through optimized design, eliminating cost tooling through direct serial production) justify the AM application.

Some of the barriers to a wider application of AM (especially PBF) is the automation of some of the processes (load and unload process, post processing procedure as well as time linked to this processes). When the quality and technical characteristics of the final part is in question, there are some differences between part produced for automotive industry or for aerospace or medical.

DfAM application in design process, tooling elimination, new strategies in laser application, automation of some processes, build and process optimization (different building envelope, part orientation to eliminate support structures and enhance quality, time, etc.), application of new alloys and powder morphology, are some of the examples of improvements which can help closing the gap between AM use in serial or low-volume application. Cost break down structure for AM process can further help in evaluation and reducing the steps that contribute to higher time and cost consumption.

In the next chapter current scientific research related to the cost estimation/optimization, design and part orientation problem is explained in more details.

Cost analysis considerations and current state

On the way to a more comprehensive adoption of AM processes, certain barriers need to be overcome, among which one of the critical issues is a large initial investment cost for establishing AM processes (including equipment and material), especially for small and medium-sized enterprises. Currently, high machinery and material costs make this technology more expensive than conventional and initial estimates indicate that its use is only good for small scale production. Researchers, who have directed their research towards additive technology cost models, base them on the analysis of different AM cost structures/separation.

Therefore, forecasting and estimating production costs in the context of AM are important topics for the research. As for the cost separation there are two distinctive approaches.

First cost separation [13]: Costs are separated into direct and indirect costs. Mainly, direct cost is related to materials and depends on the amount of material used in the process, while indirect cost comprises a wide range of costs like machine cost, labor, administration cost, overhead cost, energy, etc., and these costs depend on the process duration.

Second cost separation is explained in [14]. The author has divided cost as “well - structured” costs were he put labor, material and machine cost, and “ill - structured” costs like inventory, machine set up, build failure, etc.The “well – structured” costs are easy to track and measure unlike other “ill-structured” costs that are difficult to monitor but can significantly contribute to cost savings.

Cost drivers are needed to be identified in order to define factors affecting the cost in chosen AM category. The paper [15] identified main activities in PBF production process and also identified cost drivers for each of them, Fig.2. Also, the paper [15] further explains that beside cost drivers some other aspects should also be considered, for example: machine types and machine process parameters, product specifications, customer requirements, etc. Overhead and ill structured costs also need to be reflected on, but that depends on the cost estimation models and applied perspectives.

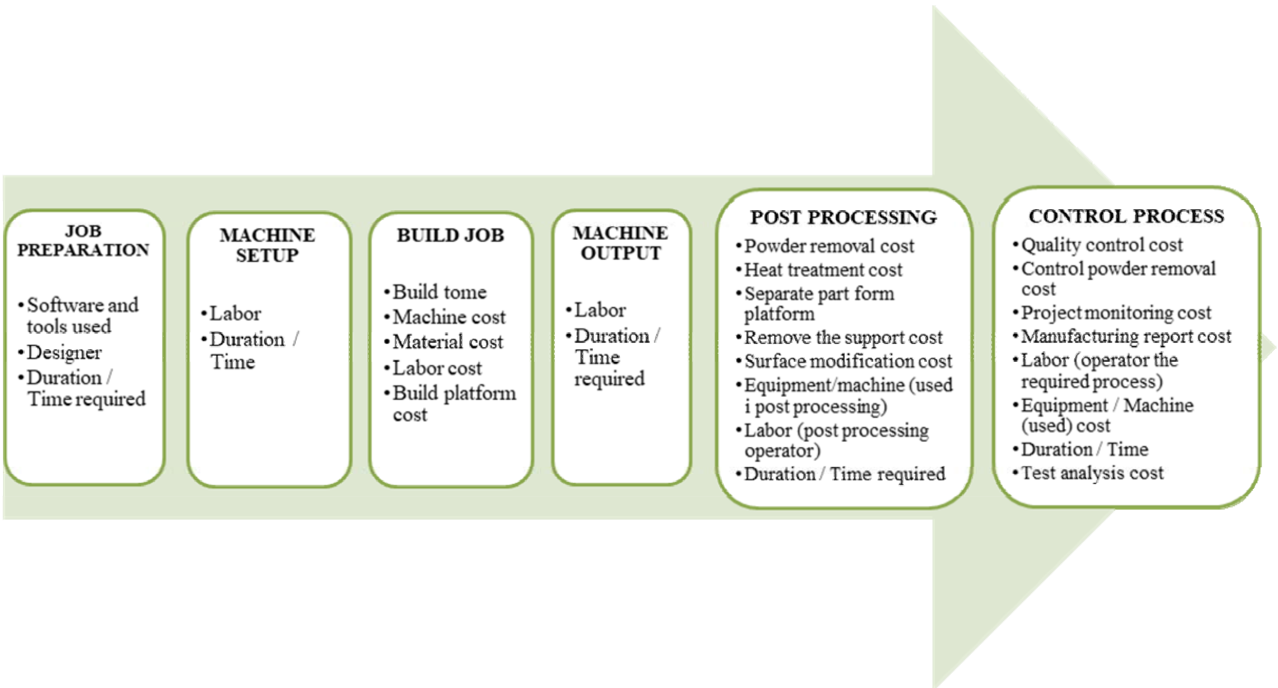

Figure 2. Main cost drivers in PBF chain, [15].

Before studying the costs in more detail and defining their mathematical expressions, it is necessary to define the perspectives from which the costs are analyzed. In that view, it is worth mentioning three major perspectives explained by [16]: finance/accounting perspective (uses techniques known as Intuitive, Analogical, Parametric or Analytical), manufacturing perspective (includes few phases of product development and manufacturing task) and management perspective (cover product cost associated with product life cycle management, maintenance, remanufacturing, inventory, etc.). In its review of different cost estimation techniques [16] concluded that most of the analyzed cost estimation techniques actually use manufacturing perspective.

With different perspective at disposal and defined almost all cost drivers in AM chain, the techniques that directly connect cost drivers with actual processes and activities in AM chain are ABC (Activity Based Costing) and PBC (Process Based Cost Modeling).

ABC technique implies a breakdown of the process into various activities, cost calculation of each activity and then summing up of all the costs. In these techniques cost is separated as direct and indirect cost [13].

Process-based cost modeling (PBCM) estimates cost by relating cost drivers directly to the processes involved in designing, developing, testing or producing. In this way, the changes in some design variables and operation conditions are best reflected on the production costs [18].

Based on the extensive research of the cost models presented in the scientific literature ([1], [13], [15], [17], [18] and [19]), certain conclusions and directions were made regarding development of the cost model for the PBF/SLM method. Some of the elements that the new cost model for PBF/SLM should include are:

- Calculating the unit price of the products of different geometries in the same build job. The analysis of production costs, for each step and for each geometry, allows the identification of the factors that have the greatest impact on costs.
- Pre-process (geometry preparation, assembly work task, machine setup) and post-process activities (parts and substrate plate removal) should be considered as a part of the cost estimation model.
- Post-processing activities such as thermal and surface treatments, material removal and quality control should also be considered.
- The cost of operator labor per hour depends on different skills required for each step.
- Introduction of a waste factor for metal powder (consider the possibility of reusing a part of the powder) as well as inert gas consumption.

These elements need to be incorporated in development of the new cost estimation model.

Part orientation problem

Part orientation is one of the essential additive manufacturing process planning variables. It has an important effect on total cost and build time, and influences the overall quality and part property of the end-use product (part accuracy, surface quality/roughness, tensile strength, yield strength). As the first "in a row" of the AM planning process, it has a tremendous influence on subsequent processes like support generation, slicing, and path planning [20].

Part orientation can be defined by experienced operators (which can lead to a variety of different solutions) or we can accept the software recommendation as an optimal one. In both cases stability and repeatability of the process need to be preserved.

According to [20] a part orientation refers to the use of specific techniques to determine adequate orientation for part building from a number of theoretical orientations. The first step is to determine the alternative build orientations and then to define optimal build orientation from the previously defined set of alternative build orientations.

[21] explained that part orientation is required for all AM processes. Same authors further explain that part orientation problem is represented as a 3D model of the production part with certain production objectives (build orientation factors) in specific data formats as input, and its output is the same part but oriented in the way that it initially optimizes a set of production objectives.

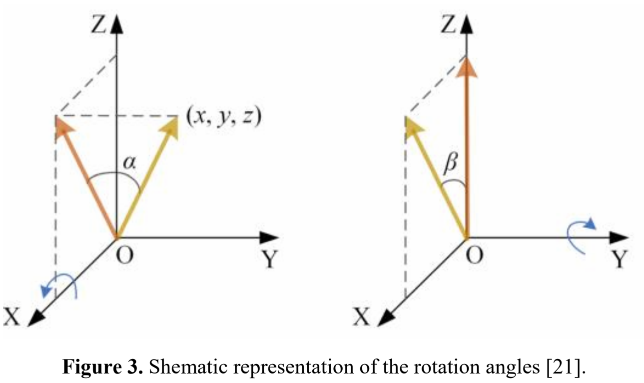

Figure 3. Shematic representation of the rotation angles [21].

Some examples from the real case study considered in [22] are shown in Fig.4.

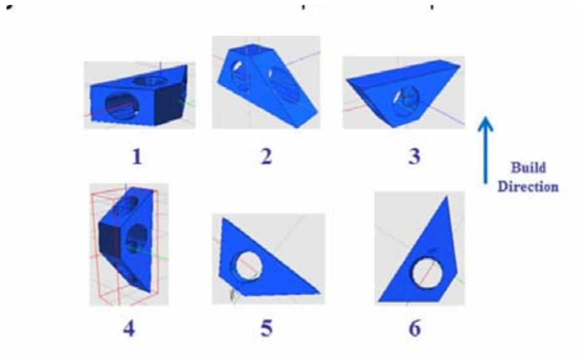

Figure 4. Examples of the possible part orientation position [22].

Build orientation is represented by a two angle (α, β) where the build orientation lines up along the Z axis. Part (or 3D model) is rotating around the X axis by an angle of α ($0^\circ \leq \alpha \leq 360^\circ$) and around the Y axis by an angle of β ($0^\circ \leq \beta \leq 360^\circ$), according to [21]. Translation movement on the build plate (either in the direction of the X or Y axis) is not considered as an orientation problem. Schematic representation of the rotation angles is presented in Fig.3.

For solving the part orientation problem, different methods and solution were investigated in literature. In the following chapter, a brief explanation of MCDM (Multi Criteria Decision Making) techniques will be given.

Application of MCDM techniques for solving the part orientation problem

For the support of the decision makers and solving planning problems which include multiple (usually conflicting) criteria, one of the the most appropriate solutions is the Multiple-criteria decision making (MCDM) models. There are two types of MCDM models: Multi Attribute Decision Making (MADM) models for ranking alternatives and Multi Objective Decision Making (MODM) models [23].

Multi Attribute Decision Making (MADM). MADM is a proven and successful set of methods that enables evaluation and decision-making among multiple conflicting criteria during the planning and decision-making process. Based on the research of the available works, [24] makes certain conclusions:

- Orientation problems (with set criteria) can be solved as MADM.
- The application of MADM methods is still not overrepresented in advanced production technologies such as AM.
- The most prevalent AM techniques in the current works are (FDM and SLS) techniques.
- The authors suggest the improvement of quantitative and qualitative methods of evaluation in such a way as to include the perspective of decision makers.

In [25] general indication is given that MADM is capable of solving complex problems characterized by different conflicting criteria. MADM tools use both quantitative and qualitative factors equally. The techniques and approaches that are available enable efficient problem solving, and through an adequate selection from a set of solutions, they find the optimal solution.

A large number of authors suggest that the limitations of one MADM method can be overcome by combining it with another method, i.e. applying hybrid methods.

Based on the information from [26], popular MCDM techniques useful for solving the presented problem are: Weighted Sum Model (WSM), Weighted Product Model

(WPM), Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), PROMETHEE, ELECTRE, VIKOR, and Multi-Attribute Utility Analysis (MAUA).

Multi Objective Decision Making (MODM). Based on the exhaustive literature research, [21] distinguishes two methods for the application in decision making problems (one and two step methods).

One-step methods: for the search of an optimal build orientation this method uses in-depth search algorithm (direct search method) or optimization-based method. The most used optimization techniques are population-based optimization algorithm (PBOA), such as the genetic algorithm (GA), particle swarm optimization algorithm (PSOA), bacterial foraging optimization algorithm (BFOA), and electromagnetism-like mechanism algorithm (ELMA) [21].

As for the criteria or build orientation factor (BOFs), against which designated alternatives are comparing, there are several of them: build time, build cost, post processing cost, post processing time, support structure, surface quality, roughness, etc. For the evaluation of the BOFs within generated alternative build orientations there are several estimation methods and mathematical formulations, and this is valid for both (one and two step) methods.

The existing one-step methods currently do not provide an adequate answer to a question what the most appropriate rotation step size is, from which we get alternative build orientation. If this should be small or random value which in turn leads to a huge computational and searching time or sets the rotation step size to be 1 or 5 degrees, is still an open question. Anyway, the defined step size should be a balance between the accuracy and the efficiency.

For the one-step method the objected orientation function (OOF) can be formulated as: weighted sum model (WSM): $w_1F_1(O) + w_2F_2(O) + ... + w_mF_m(O)$, Pareto front analysis (PFA) $[F_1(O), F_2(O), ..., F_m(O)]$, and min-max functions (MMFs) (min/max$\{F_1(O)\}$, min/max$\{F_2(O)\}$, ..., min/max$\{F_m(O)\}$), where O stands for build orientation, m– the number of the considered BOFs, $F_i(O)$(i= 1, 2, ...,m) is the objective function of the ith BOF in O, and w_i is the weight of the ith BOF.

Two-step methods: Part orientation problems are divided into two steps (the first one: generation of the alternative build orientation (ABO) through the certain techniques; the second one: selection of an optimal build orientation from the generated alternative solution from the first step).

In the existing two-step methods, the generation of ABOs is realized by the following techniques: feature recognition, convex hull generation, quaternion rotation, or facet clustering.

As for the OOF for two-step methods, beside the above mentioned OOF for one-step methods, in literature it can also be found the implementation of two operators: OWAO (Ordered Weighted Averaging Operator) and FAO (Fuzzy Aggregating Operator), [20].

Concurrent structure and process optimization

The introduction part of the paper, as well as a statement mentioned in [24], have once again emphasized the fact that currently limited adoption of additive manufacturing technology is largely linked to the high production cost.

In papers [18] and [27] the authors paid special attention to decrease the production cost by concurrent optimizing MAM (Metal Additive Manufacturing) process variables and part structure.

Structural optimization (topological optimization) has proven to be one of the solutions for reducing production costs, directly through reduced use of materials (total volume), as well as indirectly through other factors such as reduced energy consumption, reduced waste, etc., but in combination with the process parameters (laser/beam energy power and speed, number of passes for laser/beam, etc.) there is a huge potential to further reduce the production cost.

To obtain an optimum part (which is lighter and stronger) topology optimization through the use of mathematical calculation is solving the problem of material distribution within design space (known as density-based topology optimization with Solid Isotropic Material with Penalization (SIMP) and Bi-directional evolutionary structural optimization (BESO) algorithms). Newer methods that have found their application for topology optimization are: the level set method (LSM), moving morphable components (MMC) and moving morphable voids (MMV) [29].

The case study presented in [18] showed that concurrent optimization of the part's structure and process parameters led to a reduction of total production costs by 15% and the production time was 21% better in comparison to the application of topology optimization alone. The above leads us to the conclusion that the part's topology and concurrent optimization of MAM process variables therefore has the potential to further reduce the production costs.

Another hot spot topic in academic papers is a generation of support structure as topology optimization problem [28]. Key approaches here are length scale control and manufacturability constraints. With this implementation less material will be engaged for support generation and subsequently this will lead to lower build time and production cost. Fig.5 presents a clear example of this innovative approach.

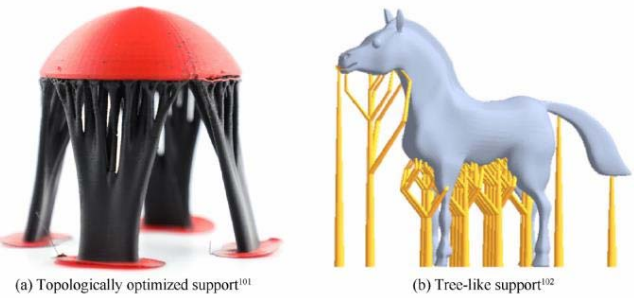

Figure 5. Innovative support design, topologically optimized support (left) and tree-like support (right) [28].

In addition to the previously said some researchers propose integration of overhang constraints into topology optimization problem to get self-support structure, Fig.6. The overhang constraints are imposed via "density projection in density-based topology optimization", and further detailed explanation of this approach can be found in [28].

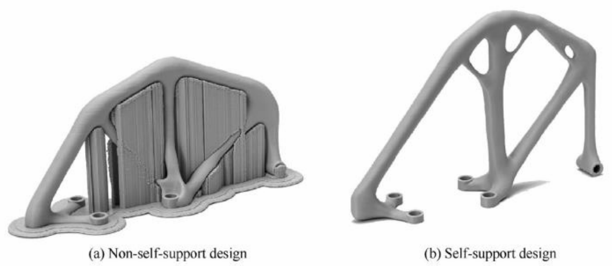

Figure 6. 3D printed topologically optimized industrial frame, non-self-support design (left) and self-support design (right) [28].

Conclusion

The paper presents the basic settings of additive technology, from the initiation of the production process with adequate planning, the selection of certain key parameters for decision-making, problems in decision-making from the aspect of costs, necessary resources (hardware, software and materials), standards and up to current process optimization and process improvement using modern scientific approaches (multi-criteria decision-making, optimization techniques).

New cost estimation model for PBF technology needs to be considered, with the inclusion of the steps presented in the paper as well as cost drivers. Manufacturing perspective and ABC technique should be adequate for this approach.

Special attention was paid to the key features of this technology that set it apart from others, topological optimization which, simultaneously with the optimization of other parameters, achieves better results in reducing costs and production time than individual approaches of each of them.

Part optimization problems should be further investigated, from the perspective of inclusion of as much as possible build orientation factors, decision maker opinions and adequate MCDM techniques for the alternative choice.

Further research should be focused on the analysis and more detailed research of the approaches, methods and techniques for optimizing the structure, costs and production time (by including in the analysis other process parameters: laser path, part orientation, batch size), as well as the selection of adequate decision-making methods, in order to define an optimal approach that would enable the achievement of the best effects.

It is evident that AM market is getting much percentage of the world production market and it will continue to grow. Together with the cost estimation and optimization techniques presented in the paper, the key growth drivers contributing to this are: expansion in 3D application for end-use goods, development of new type of materials, enhancing the role of service providers, evolution in the technology and raising of new business models.

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Planiranje procesa i tehnike optimizacije u aditivnoj proizvodnji

Aditivna proizvodnja, kao proizvodna tehnologija i naučna oblast predstavlja veliki potencijal za nova istraživanja, privukla je pažnju i interes velikog broja proizvodnih kompanija i akademske naučne zajednice. Sa svojim novim pristupom u projektovanju proizvoda, digitalnom lancu povezivanja, i mogućnostima da proizvede krajnji proizvod veoma kompleksnih geometrija, pruža značajne prednosti u odnosu na konvencionalne proizvodne tehnike.
Međutim, početne investicije i proizvodni troškovi čine ovu tehnologiju još uvek nedostupnu širem broju korisnika, ali postoje tendencije da se isto i promeni. U tom smilu, velika pažnja se poklanja procesu planiranja aditivne proizvodnje, analizi troškova i optimizaciji strukturnih i procesnih parametara proizvoda i procesa.
Ovaj rad ima za cilj da prezentuje osnovne postavke aditivne proizvodnje, njene prednosti i određene nedostatke, trenutne i buduće trendove u razvoju kao i aktuelne oblasti istraživanja (procena troškova, višekriterijumska analiza, optimizacija topologije), primenjene metode i koncepte.
Autori izražavaju uverenje da će prezentovani rad pružiti pomoć u procesu planiranja proizvodnje aditivnim tehnologijama i ujedno promovisati potrebu primene različitih optimizacionih tehnika prilikom projektovanja proizvoda za proizvodnju aditivnim putem.

Ključne reči: **aditivna proizvodnja, procena troškova, višekriterijumska analiza, optimizacija topologije.**