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Topology Optimization, Part Orientation, and Symmetry Operations as Elements of a Framework for Design and Production Planning Process in Additive Manufacturing L-PBF Technology

Slobodan Malbašić [1,*], Aleksandar Đorđević [2,*], Srđan Živković [3], Dragan Džunić [2] and Vlada Sokolović [4]

[1] Department for Defence Technologies, 11000 Belgrade, Serbia
[2] Faculty of Engineering, University of Kragujevac, 34000 Kragujevac, Serbia; dzuna@kg.ac.rs
[3] Military Technical Institute, 11000 Belgrade, Serbia; srdjan.zivkovic@mod.gov.rs
[4] Military Academy, University of Defence, 11000 Belgrade, Serbia; vlada.sokolovic@va.mod.gov.rs
* Correspondence: slobodan.malbasic@mod.gov.rs (S.M.); adjordjevic@kg.ac.rs (A.Đ.)

Abstract: This paper investigates the possibility of the application of different optimization techniques in the design and production planning phase in the metal additive manufacturing process, specifically laser powder bed fusion (L-PBF) additive technology. This technology has a significant market share and belongs to the group of mature additive technology for the production of end-use metal parts. In the application of this technology, there is a space for additional cost/time reduction by simultaneously optimizing topology structure and part orientations. Simultaneous optimization reduces the production time and, indirectly, the cost of parts production, which is the goal of effective process planning. The novelty in this paper is the comparison of the part orientation solutions defined by the software algorithm and the experienced operator, where the optimal result was selected from the aspect of time and production costs. A feature recognition method together with symmetry operations in the part orientation process were also examined. A framework for the optimal additive manufacturing planning process has been proposed. This framework consists of design and production planning phases, within which there are several other activities: the redesign of the part, topological optimization, the creation of alternative build orientations (ABOs), and, as a final step, the selection of the optimal build orientation (OBO) using the multi-criteria decision method (MCDM). The results obtained after the MCDM hybrid method application clearly indicated that simultaneous topology optimization and part orientation has significant influence on the cost and time of the additive manufacturing process. The paper also proposed a further research direction that should take into consideration the mechanical as well as geometric, dimensioning and tolerances (GDT) characteristics of the part during the process of ABOs and OBO, as well as the uses of symmetry in these fields.

Keywords: topology optimization; build orientation; time and cost optimization; additive manufacturing process planning; symmetry operation; MCDM

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1. Introduction

The modern market imposes new requirements for products. In order to meet these requirements, it has been important to overcome certain limitations that exist in the design and production of these products. In addition to that, the modern market also requires companies to launch innovative, high-quality products to the market quickly and cost-effectively.

In connection with the design, it is necessary to improve existing or develop new design capabilities that will enable the design of parts with increased performance, complex design, and simplified structure in a short time and in a cost-effective way.

To design parts with the mentioned characteristics, it is necessary to use production technologies that can ensure the rapid production of parts (requires a quick release to the market) and to enable production in small quantities as well as to respond to requests for personalized products. Also, it would be of great benefit if the production technology could produce complex functional and hierarchical structures, a faster distribution of products to the end user, and the optimization of the production process through the elimination of redundant tools, as well as digital data storage. It seems that additive manufacturing technologies could provide most of these requirements.

In situations characterized by increasing product complexity, tighter development budgets, and a competitive business environment, manufacturers are required to better understand product behavior during the design phase. The usual approach meant that after the end of the design phase, the initial design was moved to a dedicated group of simulation experts for further design iteration and optimization. It turned out that this approach was not good because it creates bottlenecks and slows down process efficiency. One of the requirements is that it is necessary to solve as many challenges as possible, in connection with the validation and constraints for performance and manufacturability, even in the design phase.

These conditions impose the need for companies to look for solutions to overcome these issues. A key strategy to implement simulation into the broader workflow is to put simulation-driven design early in the development cycle. This helps in reducing operating costs by preventing time and money spent fixing design flaws in later stages. Benefits of simulation design applications early in the development process are as follows [1]:

- Better achievement of the quality targets (prior to verification and testing it is possible to simulate new design under different conditions (vibration and pressure) and based on the preliminary results some structural issues could be fixed early in the design process);
- Meeting customers' expectations (time-to-market, zero defects, performance, cost expectations, etc.);
- The creation of cost-effective products (for example simulation in a virtual environment can decrease costs of creating physical prototypes, etc.).

Also, it should be noted that there are case studies in which the prototypes need to be made. After the optimization process, the prototype could be made using one of the methods of additive technology, which is becoming economically more profitable compared to the traditional approach.

The advantages and some disadvantages of PBF technology were explained in [2,3]. Several positive aspects were highlighted, including the possibility of creating functional metal prototypes, capability of building complex shapes and structures, production of end products with high parts accuracy (including high material mechanical properties and integrating functional design), production of different components in one build job, increased design freedom, fabrication of the lightweight parts as a result of topological optimization, consolidation of the parts into one assembly, etc.

Among the shortcomings, the following stand out: part size limits and slow deposition rates; costs (of machines and powder material) make this technology still expensive, but there are signs that this trend is decreasing; the reliability of the processes is still in question (due to material defects, part distortion, and residual stress); etc. In addition to the above mentioned [4,5] add the following: poor surface integrity and marks from removed support structures, a staircase effect on inclined features, and the requirement for post processing and further finishing of all functional surfaces. The advantages of additive technology in relation to conventional production from the aspect of design and production are considered by [6]. Traditional production methods are still represented in the production of various products, of greater or lesser complexity. However, if a comparative analysis between traditional and additive technology were to be made, it comes to the conclusion that additive manufacturing has certain advantages.

In order to clarify and understand the terminology, terms such as 3D printing, rapid prototyping, direct digital manufacturing, rapid manufacturing, and solid freeform fabrication are often used to describe AM processes [7]. AM is the potentially disruptive manufacturing technology in which a structural component is fabricated layer by layer via digital information [3]. The AM processes are divided into the following seven categories according to [8]:

1. Vat photopolymerization including stereolithography (SLA) and direct light processing (DLP);
2. Material jetting;
3. Binder jetting;
4. Material extrusion including fused deposition modeling (FDM) and FFF (fused filament fabrication);
5. Powder bed fusion (PBF) including selective laser sintering (SLS), selective laser melting (SLM), and direct metal laser sintering (DMLS);
6. Sheet lamination including laminated object manufacturing (LOM);
7. Direct energy deposition (DED) including 3D laser cladding and wire arc additive manufacturing (WAAM).

Among the additive technologies developed so far, technologies for the production of metal parts known as MAM (metal additive manufacturing) stand out. According to [9], there are three primary technologies relevant for metal-based AM: directed energy deposition (DED), PBF, and binder jetting. All of these technologies have their relative advantages to certain applications based on material compatibility and manufacturing limitations. MAM technologies enable the production of complex structures with near-net shape capabilities (processes that aim to produce products that are close to the final shape) from different types of metal powders.

Depending on the energy source, the PBF technology is classified into two groups: laser powder bed fusion (L-PBF) and electron beam powder bed fusion (EB-PBF). The subject of the further investigation and explanation is L-PBF techniques. The L-PBF techniques are known as selective laser melting (SLM), direct metal laser melting (DMLM), or direct metal laser sintering (DMLS), according to [10]. The L-PBF techniques are an additive manufacturing technology intended for the production of metal parts (using metal or alloy powder). L-PBF is the process where a laser beam is used to fuse the metal powder particles on the powder bed [11]. The system of tree chambers (supply chamber, powder bad chamber, and collector chamber) and recoater provides manipulation with powder. Powder material is deposited on the powder bed (with recoater), the laser beam selectively fuses the deposited powder particles based on the layer profile, then the platform is lowered by a predefined layer thickness, and the same process is repeated until the whole part is finalized [12].

The L-PBF technology has reached its mature stage, and now it can produce functional end use parts, not only prototypes [9]. Also, there are several constraints that need to be addressed during the part design phase (minimum thickness, overhangs, holes, builds orientations, etc.). If these constraints exceed their limits, it would cause some failures during the manufacturing stage [13].

Additive manufacturing has gone through a certain development path from the initial focus on the production of prototypes to the production of parts in small series with a tendency towards occupying a larger market share in the segment of large-scale production. Certain obstacles have been overcome on that development path, but there are still segments in this process that could be optimized and improved, and the planning process is certainly one of them.

Additive technologies are characterized by the fact that there is a reduction in process steps, which indicates that the total number of processes and resources required could be significantly reduced, which ultimately leads to the simplification of processes [14]. All of these facts lead to the conclusion that it is necessary to carry out detailed planning of the process, from the design phase to the production of the final part.

Challenges in AM Process Planning and Research Gaps

Companies that have acquired additive technology for their business are facing some challenges in the planning of the design and production process for AM. Regarding the additive manufacturing planning process, it is still questionable how to establish a relationship between various process parameters and final part quality (GDT properties and mechanical properties). This is still a popular research goal. The reason is that the 3D printing process is characterized with several process deficiencies, like poor geometry, dimensional accuracy, deteriorated surface finish, part shrinkage, pores and micro-cracks, and residual stress-induced defects, which affect the design of the requirements for the finished product.

In addition to the production process, the key factor is also the mechanical part itself. A mechanical part is usually a multi-feature mechanical part (MFMP) which carries on the production and design knowledge. In order to solve the mentioned problems [15] considered additional improvements in the planning phase with the aim of reducing costs, through the part orientation process that affects the quality of the part or individual functional surfaces, i.e., through supports that have a significant effect on production costs. The author also mentioned the problem of the available space of the working chamber, and in that sense, the presented work considers the procedure for separating the parts and their orientation (PBF additive technology was applied), all with the aim of obtaining a cost-effective process. The developed procedure for the automatic separation of parts, taking into account the aspect of costs, reduced production costs by 54% [15].

The tendencies in the development of additive technologies go towards more efficient planning of the additive manufacturing process and the optimization of production parameters in order to obtain a final product of high performance, with optimized characteristics and produced in an optimized way. The key elements that provide additional value are topological optimization, parts consolidation, and the simultaneous optimization of several process parameters and the integration of topology optimization with additive technologies.

Simultaneous optimization involves considering the impact of topological optimization on production costs, together with the process optimization of additive manufacturing parameters to reduce total costs [16]. In [16] the simultaneous optimization of topology and process parameters (laser power and speed), which have a certain influence on the microstructure of the material, are demonstrated. This considers the production of metal parts using one of the PBF techniques. It is estimated that certain savings in the costs of additive manufacturing could be achieved. The benefits provided by the optimization of the topology were considered through the reduction in the volume of material used, which indirectly reduces the material costs. The final results indicated that by applying this approach, the total production costs were reduced by 15% and the production time was improved by 21% [16].

In [17] the simultaneous optimization of build orientation and topology for self-supported enclosed voids in additive manufacturing based on the heat-flux approach was proposed. With the implementation of the "surface slope dependent heat flux through a domain integral of a Heaviside projected density gradient" to the density-based topology optimization algorithm, the problem of designing self-supported enclosed voids in additive manufacturing was solved.

The simultaneous optimization of the geometric orientation and support structure were applied in [18]. The authors concluded that building direction has an important role in production cost determination. Innovation in this study was the introduction of an efficient thermal model for TO in AM and the integration of the support structures into the design and optimization process.

Topological optimization and its integration with additive manufacturing were also analyzed by [3]. The author states that additive manufacturing and topological optimization were carried out separately for several years, but the latest integration of topology optimization and additive technologies arises for the following reasons:

- Topology optimization parts have very complex shapes and cannot be manufactured with traditional technological processes. Instead they can only be produced by additive manufacturing technologies.
- The other reason is the fabrication cost, which is proportional to the material and weight, which benefits additional technologies.
- Topology optimization produces parts with enhanced performance and mechanical properties, without compromising the strength of the part.

There are a plethora of papers focusing their research on optimization problems in additive manufacturing. The best results were obtained by simultaneously optimizing at least two parameters. One of them is topology optimizations, and the others are either process parameters or part orientations at the build plate. However, when it comes to the part orientation, none of the authors explicitly described the choice of orientation in a situation where you have the option to choose between the solution offered by applying software (through, for example, an optimization orientation module) and an alternative solution based on the operator's experience.

This paper presents the simultaneous topological optimization and the part orientation on the working plate (the selection of the orientation of the part is based on the feature recognition method and symmetry operations) in order to obtain more cost-effective production with PBF technology. In addition to the symmetry operation, special focus is placed on the analysis and selection of the part orientation on the work plate in a way that, in addition to the orientation solution provided by the applied software, alternative solutions based on the operator's experience were also applied.

For the conduct of the optimization process (the selection of the best part orientation), a new framework for design and process planning is proposed with the inclusion of MCDM hybrid methods. Four build orientating factors were considered, including the total build time, total build cost, support volume, and support surface.

After the introductory discussion, the next section analyzes the planning process of designing and manufacturing parts by additive technologies, and presents a new framework for the AM planning process, as well as different parameters affected by L-PBF additive technology. In the following section, the theoretical assumptions and the importance of applying finite element (FE) analysis and topological optimization in the design of parts is explained. Also, the feature recognition method, which is used when choosing ABOs, is specially explained. The next section is dedicated to the symmetry elements and application of the symmetry principle in additive technology. The following section is devoted to the application of the selected MCDM process (hybrid approach) in determining the OBOs.

The subsequent section presents the proposed framework for the AM planning process together with a case study where the planning process and optimization techniques were applied on a real example from practice. Finally, at the end of the paper, there is a section where results from the case study are summarized and a section committed to the conclusions, where advantages and disadvantages of the presented approach and guidelines for further development of this topic are given.

2. The New Framework for the AM Planning Process

For the purpose of the explanation of the planning process for additive manufacturing, several papers dealing with the topic are analyzed. Also, a new framework for the AM planning process is presented.

In [4], the focus is on the importance of creating effective process planning for the designed component/part. The SLM process is considered; however, the proposed approach is general and can be applied to any additive manufacturing dealing with the production of metal parts. The author states that the application of additive technology methods requires a close integration of the design process and production planning.

The presented model for planning design and production consists of the following three processes:

1. 3D model preparation for printing;

2. Quality assessment and inspection activities;
3. The planning of necessary finishing processes.

One of the conclusions is that a proper, detailed, and thorough planning process, with the inclusion of all necessary factors in the 3D model, contributes to the increase in costs and production time. Based on this conclusion, key parameters (costs and production time) have been used as build orientation factors in the MCDM process performed in this paper.

Process planning from the aspect of part orientation is also discussed in [6]. It is pointed out that in comparison with conventional manufacturing processes, the process planning of AM processes is totally different, and that planning is a key step in order to ensure the quality of the final product. The methodology of planning and design for the additive manufacturing process presented in this work consists of the following steps:

- Design stage: the definition of the conceptual model, analyzing the function of the part, and the topology optimization of the conceptual model. The output is a geometry model with the required mechanical properties.
- The preparation of the set of process parameters (build orientation, layer thickness, build orientation, the design of the support structure, and the selection of AM methods, materials, and machines) in order to perform the manufacturing process simulation based on the predefined parameters.
- The implementation and analysis of the simulation process. In order to obtain the most optimal solutions, it is possible to carry out several iterations.
- Manufacturing stage: the author suggests using an "in-process" monitoring system with the possibility of analyzing collected data and detecting some defects. Corrective actions could be sent back via a feed-back loop all the way to the planning or even design phase.

The presented paper further specifically analyzed the planning process for build orientation due to the significance of build orientation on the quality of the end-use part. The author emphasizes that before choosing the orientation of the part on the working plate, it is necessary to perform functional analysis and topological optimization.

Another interesting deduction about the planning process is given in [19]. Based on the preliminary analysis of several scientific papers, the authors, in their technical report, conclude that the additive manufacturing planning process consists of a set of standard operations (repairing, orientation, supports, slicing, and tool path generation), whereby in the continuation of their conclusions, they state the following:

- There are some common things/problems for all of the printing technologies (mesh repair, shape orientation, slicing, tool path planning, and external supports). But how these blocks are related to each other "is still considered as an open problem".
- These blocks cannot be treated separately—3D printing would be more predictable if the mutual relationship among these blocks could be better understood.
- Shape orientation is a strategic choice "spanning form the building time to surface quality".

According to [19], the term process planning (PP) refers to the definition of a set of individual production operations required for the production of a defined part on a specific machine.

The paper [20] offers a framework for formalizing the additive manufacturing planning problem at the operational level and can be used as a reference for focusing and solving problems related to the efficient planning of this production. The idea arose from the fact that additive manufacturing introduces a set of problems specific to this technology, such as the correct orientation of parts or placing several heterogeneous parts in the same build cycle, which are not solved by traditional approaches to planning and production scheduling. The review of the literature by the author revealed that there is no uniformity in the identification and solution of the mentioned problems in the application of additive technologies.

In [21], the focus is on two phases (product design and production for L-PBF technology) with the aim of their optimization. Product design is based on the integration of topological optimization and process simulation tools in order to redesign the initial product. The production process is based on the systematic use of simulations in order to prevent errors in production due to possible temperature variations in metal parts, as well as the occurrence of residual stress and deformations. The whole approach is based on the application of an integrated project-production PLM platform that enables the digital flow of information (digital process chain).

Based on the above presented analysis, as well as practical experience, a new framework for AM planning is proposed. The new framework is conceived with the idea of being cost effective, and providing as much information as possible, available in the planning phase, for decision-makers. Also, the framework should enable the use of modern optimization and decision-making tools, in order to facilitate these processes based on relevant data. The proposed framework for the AM planning process consists of two phases (Figure 1):

- The first phase (product design)—input in this phase is the CAD model, and the phase includes the application of different simulation tools for obtaining relevant data for part design exploration and validation. It contains the selection of parts and the implementation of FE analysis and topological optimization (TO). FE analysis is performed before and after topology optimization due to the fact that structural response before and after TO are not the same. The outcome of the product phase is a topology-optimized part, which is also the input element to the second phase.
- The second phase (process design)—this phase includes the activities of initial build preparation through the generation of ABOs, estimation/calculation of the optional optimization objectives (for the case study in this paper, these include build cost, support volume, and support surface), and the selection of the OBOs as well as the virtual machine setup to obtain appropriate data for the decision matrix (for example, build time, as is the case in this paper). The outcome of this phase is the optimal build (OB) orientation for the TO part.

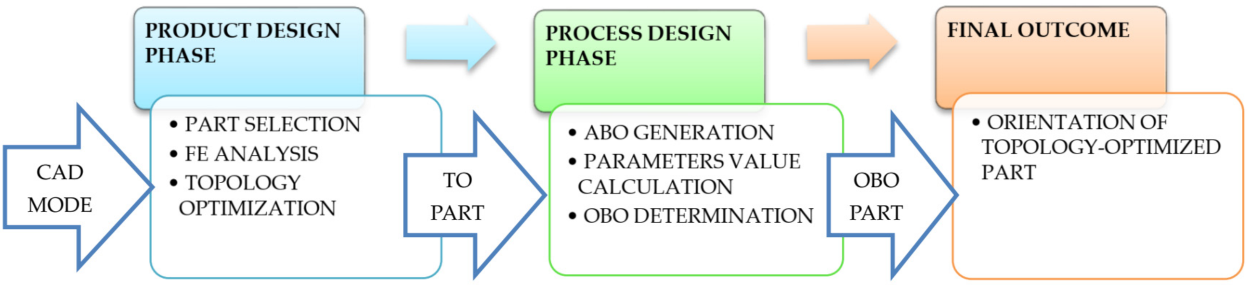


Figure 1. The overview of the new framework for the AM planning phase.

In the following sections, theoretical explanations and benefits of the proposed optimization and decision tools in the AM planning phase are given.

Part and Process Parameters Affected by Additive Technology During the Planning Process

In the process of planning additive manufacturing, it is important to know the relationships and determine how individual elements of the additive process (design, build orientation determination, etc.) affected part and process parameters.

The most important parameters, presented in [10], within the additive manufacturing process planning are shown in Table 1.

A comprehensive analysis of the set of parameters affected by the L-PBF technology was performed in [22,23]. In [22], some of the main parameters affected by build orientation were grouped as follows:

- Mechanical characteristics of the part (strength, hardness, elongation, residual stress, and material fatigue).
- Finished product accuracy (GDT and volumetric errors): Due to the possible phenomenon (shrinkage, curling, and distortion), GDT arise. Volumetric errors occur as

a consequence of the construction of the part in layers, that is, due to the phenomenon known as the "staircases effect".

Table 1. Process planning stages with main parameters.

Design for AM	Function analysis
	Topology optimization
Build orientation determination	Cost
	Mechanical properties
	Geometry properties
Support structure generation	Building process
Slicing strategy	Layer thickness
Scanning path generation	Filling pattern
	Feed rate planning

In [23], the criteria affected by the build orientation are also analyzed and divided into three categories (within which there are several subcategories): (1) technical criteria (surface properties, geometrical properties, mechanical properties, thermal and electrical properties), (2) economic criteria (cost and time), and (3) indirect criteria (resources status and logistics).

This paper analyzes topology optimization and build orientation effects on the total build cost, total build time, and support volume and surface. The reason for this is that in the planning phase it is hard to define mechanical and GDT properties of the part unless historical data about these properties is available in advance, or we have at our disposal some mathematical model or prediction algorithm that has already been developed. Also, another constraint is the fact that the OEM (original equipment manufacturer) has already proposed optimal process parameters and suggested they should not be changed during printing time. Anyway, these constraints should not in any way affect final results.

3. Optimization Elements in a New Framework for L-PBF Design and Production Process Planning

This section is dedicated to the theoretical assumptions and the importance of applying topological optimization and finite element (FE) analysis in L-PBF design and production process planning. The build orientation problem based on the feature recognition method, which is used when choosing ABOs, is explained too.

3.1. Topology Optimization

Topology optimization is a structural design technique that optimizes the shape and material component of a detailed part using the finite element analysis technique and various optimization techniques [16]. Bearing in mind that each final element of the structure is defined as a variable, this method enables a flexible approach and obtains a very complex final geometry.

There are several algorithms based on mass distribution optimization. The most common, and at the same time the most effective, are the solid isotropic material with penalization (SIMP) and bi-directional evolutionary structural optimization (BESO) algorithms, according to [16]. In addition to the optimization algorithm based on the mass distribution (density-based method), there are other optimization algorithms: the evolutionary structural optimization (ESO) and the level set method (LSM), as well as moving morphable components (MMC), and moving morphable voids (MMV) [24].

Topological optimization consists of the following steps, shown in Figure 2 and based on [3,25]:

- Three-dimensional modeling using appropriate CAD softwares.

- Topology optimization: Based on the results of a structural analysis of the stress distribution, the optimization algorithm removes the material from the area where the load distribution is less.
- The remodeling of the initial CAD model based on the results of the optimization results.
- Design verification using the FEM (finite element method) or in some cases prototype testing.

Figure 2. Steps in the topology optimization process.

There are several advantages and application areas of structural/topological optimization, according to [25], which are as follows:

- Great freedom in design because it pushes the boundaries of flexibility, and ensures improved efficiency.
- Topological optimization can generate several design variations allowing for different applications.
- Topological optimization focuses on elements of stiffness, weight, material distribution, and lightweight construction (a lighter component of equal or greater strength).
- It contributes to less wastage of materials (due to optimal material distribution).
- It shortens the time to market.

Recently, multidisciplinary optimization is also applied, meaning that the designed structure must meet multiple goals and certain limitations such as complex loads, resistance to thermal effects, limited stresses, displacements/movements, etc. [25]. The integration of materials, structures, processes, and their performance is very important and necessary in order to achieve high-performance products, multifunctional characteristics, and a light structure [26].

Topology optimization finds an increasingly intensive application in the design of parts. The latest adaptation of this method within the DfAM concept refers to the inclusion and limitations of support structures and internal structures, i.e., in the design of cellular structures, structures with internal channels, and in medicine for the production of supports for various tissues. The integration of topology optimization and additive manufacturing achieves most of their advantages and potential, and the approach as such finds more and more applications in modern production for special purposes.

3.2. Finite Element Analysis

FE analysis has an important role in the design phase of the product because it can highlight structural and strength problems and detect their location. It is used to check CAD models that have already been designed, and which could be modified in case any problems arise. Simulation analysis early in the design phase (instead of performing experiment after part is produced) could be of great help for the definition of correct orientations of the part in order to achieve the best possible mechanical and structural performances. The color coding system is applied by the FE software in order to better understand the outcomes of the analysis (the results of a von Mises stress analysis). Cold colors represent the part volume with low stress and warm colors represent the part volume with high stress, while the red color represents the maximum stress field [27].

3.3. Alternative and Optimal Build Orientation

The orientation of parts has a strong influence on many characteristics of the parts' production, and in this sense, certain rules, procedures, and design frameworks are necessary [28]. In the terminological sense, it is the process of orienting parts around the coordinate axes within the working space of the machine itself. This terminology does not refer to the translation of parts around the coordinate axes of the machine.

A key fact in considering the orientation is that the orientation of the parts is directly related to the achievement of certain quality characteristics in the final product. Some of them are dimensional accuracy, surface quality, shape accuracy, manufacturing costs, manufacturing time, the bending of components, stability, the volume of the supporting structure, the utilization of working space, the reduction in post processing, and the possibility of removing the supporting structure.

All of these quality characteristics depend on the geometry of the parts. The orientation of the parts of certain geometry in the working space allows for reaching the optimal values of these characteristics, and it is basically a process of multi-criteria optimization in order to achieve a compromise.

According to [29], there are two methods for choosing alternative orientations of parts on the machine working plate:

- Computation-based methods or direct search method: based on the direct application of nonlinear optimization-based methods and population-based optimization algorithms.
- Evaluation methods: first, a set of ABOs is defined and then an OBO is generated from this set. The generation of ABOs is realized by the following techniques: feature recognition [30], convex hull generation [31], quaternion rotation [32], and facet clustering [33].

For supporting the decision-makers and solving planning problems which include multiple (usually conflicting) criteria, one of the most appropriate solutions is the MCDM model. There are two types of MCDM models: multi attribute decision-making (MADM) models for ranking alternatives and multi objective decision-making (MODM) models [34]. According to [32], there are several differences between the decision-making methods and optimization methods:

- In decision-making methods, the alternatives are pre-selected, meaning that the space for decision-making is limited. On the contrary, for optimization methods, the decision space is not limited but is actually infinite.
- Optimization methods provide better quality output results because the objective function reaches the maximum value, but it is not suggested to use too many evaluation criteria due to the convergence problem.
- The decision-making methods do not have the convergence problem, and can take into account as many criteria as needed. This means that decision-making methods can treat part orientation more systematically.

3.4. Feature Recognition Method

In this section, the feature recognition method for choosing alternative orientations has been explained in more detail, based on the analysis of several key works.

The geometry of the part is a key carrier of information. In additive manufacturing, the "key" geometries are influenced by the whole set of parameters (the orientation of the part, overhangs that require an additional support structure, process parameters, scanning strategy, etc.) and thus form the desired mechanical and geometrical and dimensional tolerances (GDT) characteristics in the final product. This clearly indicates the importance of the selection of "key" surfaces and alternative/optimal orientations in additive manufacturing. Key explanations and a case study related to the generation of alternatives and selection of optimal orientations is provided in [35].

The selection of key geometries based on the method of feature-based recognition (the recognition of "key" shapes) is used in this paper. In this sense, for the generation of the final number of alternative orientations, a concept based on the recognition of the geometry of the part and the available knowledge base (lessons learned) regarding the orientation of the part on the working plate is applied, and the choice of the optimal orientation is completed by the application of the MADM method.

One of the first authors who defined the orientation of critical surfaces was [30]. In [33], it is suggested that it is important to define the coordinate system towards which parts are oriented, and that the z-axis points in the building direction. Also, in [30], the orientation for some specific surfaces/features like cuts, protrusions, and shells is proposed. In addition to the above mentioned, the defined rules for orientation are given in [36], along with other critical features (overhangs orientation, features with two planes, features with holes, and features with an inclined plane).

Based on the foregoing it can be concluded that the best GDT values of the parts can be obtained through the maximization and minimization of the following characteristics (in the phase of choosing alternative orientations):

- Maximize the horizontal and perpendicular faces in the z-axis (build direction).
- Maximize the cylindrical feature (hole, cone, etc.) axis in line with the z-axis.
- Maximize the total number of curved surfaces in the horizontal plane.
- Maximize the base surface area.
- Minimize angular/inclined surfaces.
- Minimize the overhanging area.
- Minimize the trapped volume.

The influence of the orientation of the parts on the working plate on the production costs (for the L-BPF process) was discussed in [37] and the following three important facts were stated:

- The orientation influences the amount of supporting structures;
- The orientation influences the height of the component in the building space;
- The orientation of the component influences the number of parts that can be manufactured simultaneously.

Based on the conducted experiment, which includes two different orientations of the same components on the working plate, it is concluded that it is necessary to first calculate the production costs of the relevant parts (based on the selected orientations) and then choose the most favorable solution. Based on this conclusion, the cost parameter has been chosen for further analysis in this paper.

4. Symmetry Operations and Symmetry Elements

Symmetry is often used to describe the balance in proportion and objects, to better understand the geometry, or to create balance. The symmetry operation is related to symmetrical transformation, and as a consequence, creates one object at the end of that movement [38]. The geometrical representation of one or more symmetry operations involves the symmetry elements. Symmetry operations and symmetry elements are presented in Table 2. The combination of these elements produces complex symmetry elements like roto-inversion axes, screw axes, and glide planes.

Table 2. Symmetry operations and their corresponding symmetry elements.

Symmetry Operation	Symmetry Element	Geometrical Entity
Rotation	Rotation axis	Axis
Inversion	Center of inversion	Center or point
Reflection	Mirror plane	Plane
Translation	Translation vector	Vector

Symmetry elements can be spotted in other objects too. Further implications and the connection of the symmetry principle to additive technology are given below.

4.1. Symmetry in ADDITIVE Technology

The subject of the research in [39] is the application of symmetry elements in other additive technologies like wire arc additive manufacturing, WAAM (sub-categories of the directed energy deposition, DED, technology). The basis for the research is the fact that material deposition techniques, combined with different process parameters, have a negative impact on the mechanical properties and dimensional and structural accuracy of the part. A comparison of the shape and physical characteristics of the weld bead for two techniques (overlapping and oscillating) is performed through the symmetry coefficient including the calculation of a symmetry coefficient for both techniques. The ultimate goal is to understand the impact of symmetry on the quality and performance of DED fabricated parts. The conclusion is that the industrial application of this approach can contribute to the improvement of quality in DED technology, as well as the acquisition of data (part geometry, symmetry, and process parameters) in real time and their implementation in the control loop will significantly improve process adjustment and its optimization.

The work in [40] proposes the simultaneous or parallel application of multiple printers (the focus is on FFM 3D technology) with the objective of reducing printing time. The proposed algorithm enables the uniform division of a large part (exploits reflective symmetry to partition models) as well as optimum balanced use of multiple printers in parallel so that there is no idle work. Although the parallel printing of divided parts is insisted on, considering the price of the printer, as well as the effort that should be invested in the preparation and monitoring of parallel printing, the presented application of symmetry for parallelization remains at the laboratory level for now.

The study in [41] is based on the fact that mechanical performance of 3D printed ceramic materials depends on both the part orientation and printing angle with respect to the loading direction. The influence of symmetry in the structure of the material (under tensile loading) is considered at the filament scale. On the basis of the tests conducted (SEM micrographs of fractured patterns), it is concluded that orientation and loading direction have a positive influence on the structure of the material.

The work in [42] presented a practical application of the generative method in creating complex and materially heterogeneous geometry, which can be manufactured as such by additive techniques. The generative method implied that, on the basis of the initially generated user-guided input mesh and the defined set of planes (as a framework for all subsequent operations), a symmetrical mesh is formed, which is then recursively re-applied for a certain number of iterations until obtaining the final product. Complex geometries are driven by the symmetry principle. The additive technology that was considered is photo polymerization.

In [43], the relationships between symmetry and additive manufacturing workflow (design/redesign process, manufacturing stage, and post processing—final part geometry and microstructure) were analyzed in detail and a connection was established. The use of symmetry in additive technologies is recognized with the aim of optimization. As for the additive technologies focus was on the analysis of properties and process control.

4.2. Interaction of Symmetry Elements as a Potential Solution for Part Orientation

In order to explain the application of symmetry elements as a potential solution to the part orientation at the working plate, the model from [39] will be used to explain how objects can be oriented in different directions.

Since symmetry elements and operations interacting with each other (simultaneously or consecutively) produce new symmetry elements and symmetry operations, this phenomena can be used for part orientation.

The application of a twofold rotation axis and an inversion (a center of inversion located on the axis) on the selected object is presented in Figure 3.

An explanation and conclusion of the presented interaction is as follows:

- Starting object (A) is performing twofold rotation (180 degrees Celsius) around axis (1) to obtain object (B), then object (B) performs inversion and is converted to object (C). If we applied the inversion operation to object (A) we would obtain object (D).

- It can be noticed that objects (C and D) are reflected images of objects (A and B), respectively. This means that, as a result of two symmetry elements, a new one (mirror plane perpendicular to the axis) emerges.

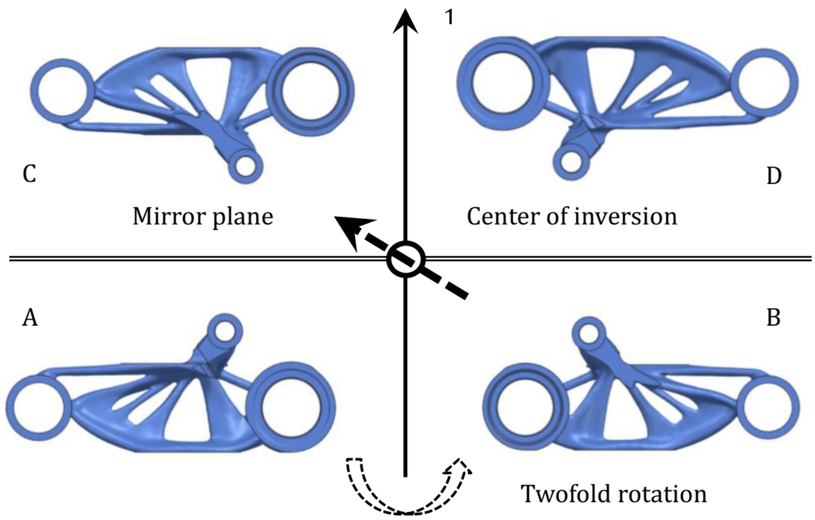


Figure 3. Scheme of twofold orientation and an inversion: position **A**—original position, position **B**—rotation of object A for 180 degrees of Celsius (mark twofold rotation in the direction of the curved dotted arrow), position **C** inversion of object B (in the direction of straight dotted arrow), position **D**—reflection of object B as well as inversion operation of object A.

If the order of symmetry elements is replaced (inversion of object A to obtain object D, and then a twofold operation: from abject A to get object B and from object D to get object C), at the end, the same results will emerge.

This brings us to the conclusions mentioned in [39], "any two symmetry operations applied in sequence to the same object create a third symmetry operation, which applies to all symmetrically equivalent objects".

5. Application of Multi-Criteria Decision-Making Process in Selecting the OBO

Based on the research available in [44], it was concluded that orientation problems (including the set of criteria) can be solved by quantitative methods and techniques, but these methods and techniques still do not have full application in advanced production technologies such as additive manufacturing. The authors suggest the improvement of quantitative and qualitative methods in such a way as to include the perspective of the decision-maker, which has been done in this paper.

Based on the research conducted in [45], the author concluded that the identification of the right MCDM techniques from the list of potential candidates is a difficult task. They conducted some research and assessment on different MCDM approaches in the selection of the manufacturing process. In the final conclusions, for the selection of the manufacturing process, they pointed to the VIKOR and TOPSIS methods as adequate methods because of the number of alternatives and parameters to be processed, adequacy in supporting a group decision, and agility during the process of decision-making.

In [46], it is emphasized that single MCDM techniques cannot yield the best solution for a designated problem, so they proposed a hybrid model which can improve "the weakness and amplify the effect and reliability of solutions acquired through single models". For their problem (prioritize risks in self-driving vehicles), the author proposes the application of hybrid multi-criteria decision-making methods employing the AHP, TOPSIS, and VIKOR.

A methodical review of the application of MCDM methods in material selection is presented in [47]. It was concluded that the combination of two or more MCDM methods is the best possible approach in the material selection process.

The MCDM helps a decision-maker to select or rank alternatives, but the first step is to quantitatively or qualitatively evaluate a group of selected criteria. The MCDM framework features four elements: alternatives (choices), criteria (attributes), weights of criteria (comparative significance), and ranking of alternative's against criteria [48]. MCDM methods were classified according to the following three criteria:

- Methods of ranking by the closeness score.
- Methods of ranking by the original score.
- Methods of ranking by the positive score.

The distinctive characteristic of methods from the first group (VIKOR and TOPSIS belong to this group) is the calculation of negative and positive ideal solutions, and then the calculation of the distances between alternatives and calculated solutions. The ranking is achieved based on the proximity to the ideal solution [48].

In [49], it is confirmed that, for situations characterized by multiple alternatives and conflicting criteria, the best solution is to use multi-attribute decision-making (MADM) techniques instead of MCDM. The authors especially mentioned the use of the AHP method for determining objective weights.

In [50] it is suggested possibility to use other available MCDM techniques, instead of TOPSIS and VIKOR, since ideal or anti-ideal solution may not exist in real case scenario.

In [51], it is emphasized the importance of the process of generating attribute weights directly from the decision-makers through interview, discussion, or questionnaire. They also classified weight assignment methods into three categories: subjective, objective, and hybrid.

Based on the above analyzed literature, it was concluded that the optimal solution to be applied for problem resolution in this paper is a hybrid MCDM approach in which the following three methods are used:

- The analytic hierarchy process (AHP) for defining the weight of attributes, and for the ranking of the ABO.
- The technique for order of preference by similarity to ideal solution (TOPSIS).
- VIKOR (multi-criteria compromise ranking).

The complete flow of the MCDM process for choosing the OBO that will be applied in this paper is shown in Figure 4.

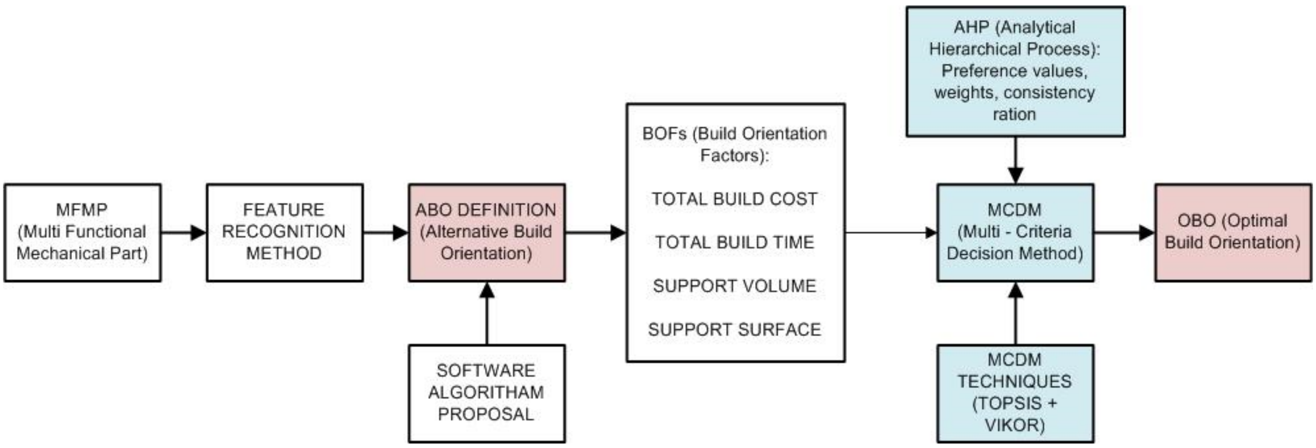


Figure 4. Scheme of the proposed MCDM process.

5.1. Analytical Hierarchy Process (AHP) Method

When it comes to the analytical hierarchy process (AHP) method, [51] explains that the majority of analyzed authors chose this method because of its ability to take into consideration, in a simple way, both quantitative and qualitative data in the decision-making process, as well as the consistency measurement for the pairwise comparison of the alternatives/parameters, which helps to minimize the inconsistency of decision-makers.

With the ability to use a multi-level hierarchical structure of objectives, criteria, and alternatives, the AHP is a structured technique and decision support tool which can be used to solve complex decision problems. In the calculation process, AHP considers the priorities of each criterion [52]. In a hybrid approach, this method is predominantly used for defining the weight of attributes (parameters or build orientation factors in additive manufacturing).

For the mutual comparison of criteria, and the construction of a pairwise comparison matrix, the Saati scale is used, defined on the interval (9, 1/9). In order to check the consistency of weights and priorities, the AHP method calculates the consistency rate, which should be less than 0.1 if consistency exists; otherwise, the preference value needs an additional check [53].

5.2. Technique for Order of Preference by Similarity to Ideal Solution—TOPSIS

This method is based on the concept that the optimal alternative has the least Euclidean distance from the positive ideal solution and the greatest distance from the negative ideal solution. Both solutions (positive and negative) are hypothetical solutions for which attribute values have the most desirable or least desirable values in relation to other criteria. The best ranked solution maximizes the benefit criteria and minimizes the cost criteria, according to [54–56].

The simplicity of the method as well as the ability to solve problems regardless of the number of criteria and alternatives is a main benefit of the TOPSIS [52].

The TOPSIS method tends towards universality in the selection of attributes for all AM methods, and it connects the evaluation of attributes with their characteristics and benefits [57].

5.3. Multi-Criteria Compromise Ranking—VIKOR

The name of the method multi-criteria compromised ranking is a Serbian name, but in English this method can be called criteria optimization and compromised solutions. VIKOR ranks alternatives and determines the optimal solution by comparing alternatives with respect to the measure of closeness to the ideal alternative. The VIKOR method is suitable for decision-making problems where attributes of a quantitative nature prevail, according to [50–52]. Further, in [52], it is said that what makes VIKOR one of the popular methods in the MCDM concept is the simplicity of the algorithm and ability to give almost accurate results.

In [58], it is emphasized that this method is suitable for use because it is a less complex method for application than others, the method is stable to changes in certain parameters, and similar results are obtained by applying more complex methods (in their case, the ELECTRE method).

6. Case Study

The case study is performed based on the proposed framework for the AM planning process (Figure 1) and an explanation is given in [21]. Each proposed step is executed in detail, including the use of adequate software with an explanation of the results.

6.1. Case Study—Phase One: Part Selection

Regarding the selection of the part for production, the selection rule related to the metal AM defined by [59] is applied. The basis for selecting a part for optimization (and subsequent production) can be an existing CAD model or a new part is designed. In the first case, the focus is on its redesign for additive manufacturing and the possibility of applying topological optimization, Figure 5.

In addition to the above, it can also be noted that the generally accepted rule among manufacturers is that if a part can be economically produced using a conventional production process, that part should probably not be produced using AM technology.

A necessary condition regarding the selected part is that it is required to have certain information related to function, loading conditions, constraints, frequency requirements, etc. The above information is necessary in order to carry out the following steps: FE analysis and topological optimization.

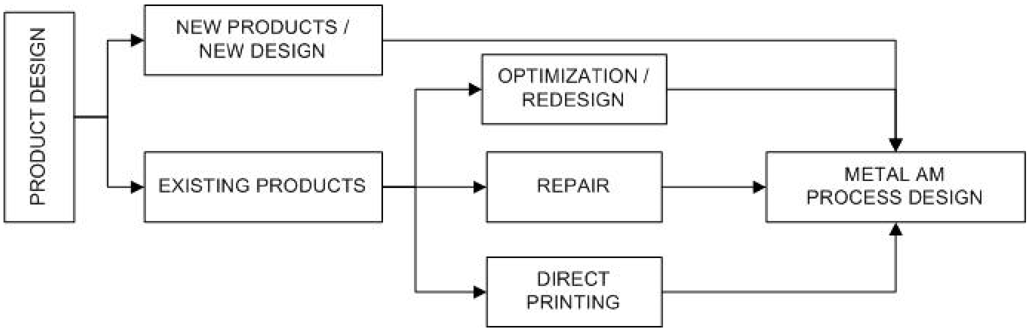
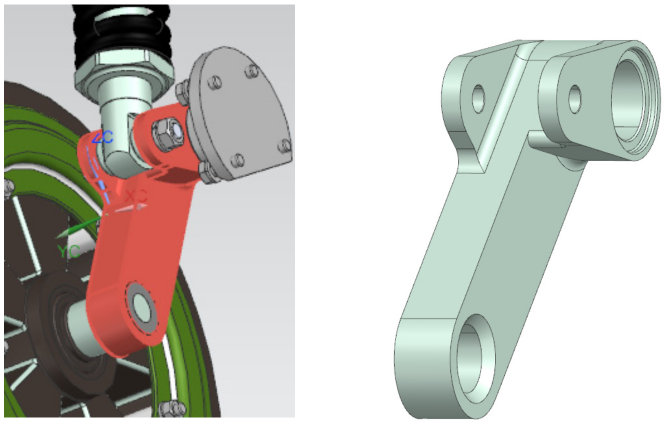


Figure 5. Procedure for the selection of the AM part for optimization/production.

In this case study, a part that is an element of the suspension system of an unmanned vehicle is considered, which serves to connect the fixed and moving parts of the suspension system and carries certain loads shown in Figure 6.



(**a**) (**b**)

Figure 6. MFMP display: (**a**) as part of suspension system and (**b**) individually.

It is a multi-functional mechanical part (MFMP), and in that sense, it consists of a certain number of planes as well as cylindrical surfaces whose axes are parallel to each other. The part is originally designed for fabrication using traditional production technologies and now it is planned to be produced using additive technology (L-PBF).

6.2. Case Study—Phase One: Perform Finite Element Analysis

The FE analysis is necessary to define the actual loads and possible displacements of the considered part, caused by the defined loads. To carry out FE analysis, it is important to define several initial parameters and then perform the simulation. The following parameters are defined in the FE analysis module (the solver is the Siemens NX NASTRAN add-on module):

- The type of load (the analysis type is structural, and the solution type is static 101 and single constraint).
- Network parameters (3D Tetrahedral Mesh).
- The definition of load characteristics (fixed and variable load was selected) as well as the magnitude and direction of action (constraint type: fixed constraint and rotation, and load type: Force 1250 N).

After defining the actual loads and forces and executing the simulation, the obtained solution was analyzed through the analysis of the load distribution and displacement of the structure. The FE analysis was performed for metal alloy steel with the following characteristics: ultimate tensile strength: 276 MPa, yield strength: 138 MPa, density: 7.829 g/c^3, and Poisson's ratio: 0.288.

Von Mises criteria are among the most commonly used criteria for checking yield conditions in different engineering fields. Figures 7 and 8 below show the results from the FE analysis for the following:

- A minimum and maximum displacement of 0.059 mm.
- Stress analysis (calculated stress is 79.15 MPa), which indicates that the part has an FOS (factor of safety) higher than 1.5.

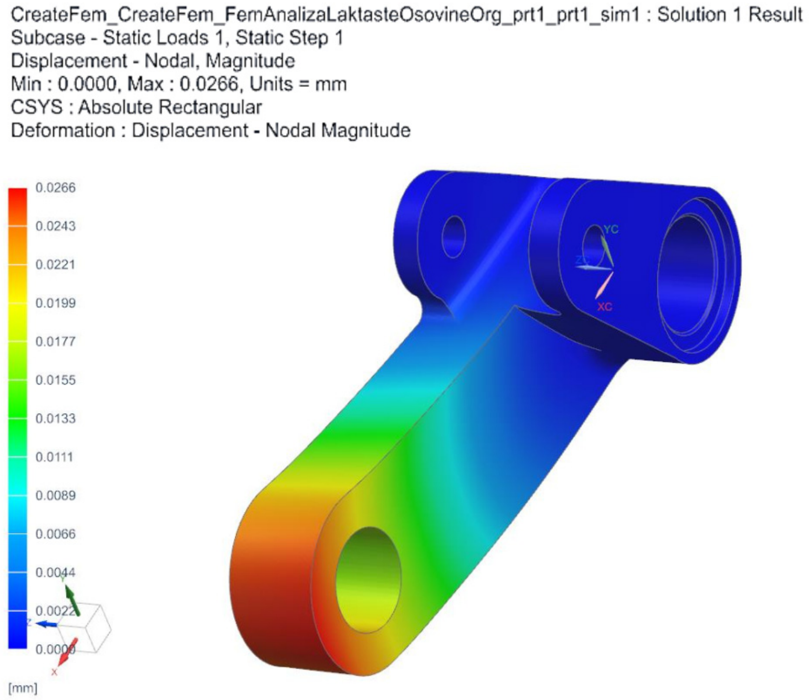


Figure 7. Color distribution of the displacement on the model.

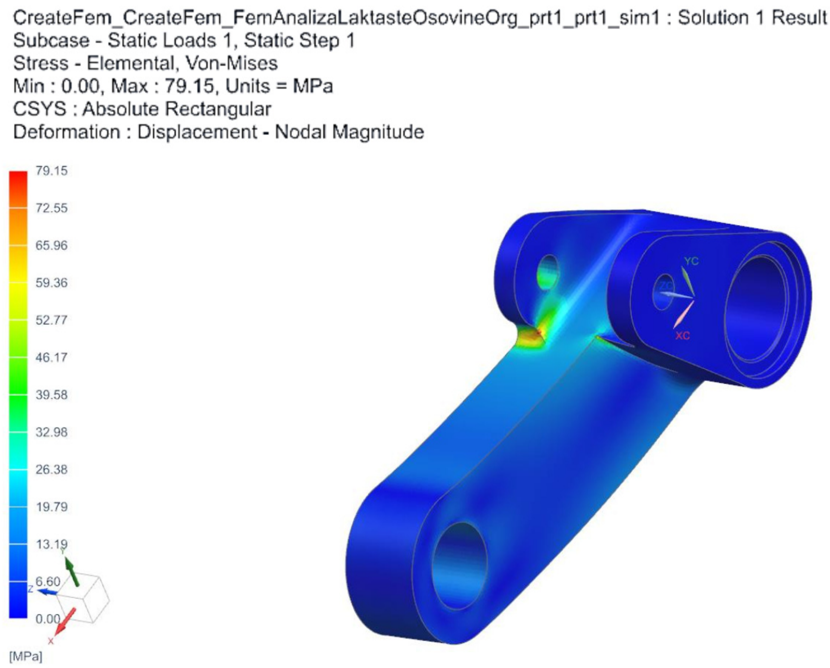


Figure 8. Von Mises equivalent stress field before optimization.

Regarding the values of yield stress (138 MPa) and maximal calculated yield stress (79.15 MPa) it can be concluded that the initial CAD design satisfies all stress constraints. This is the starting point for our optimization procedure. The current results of displacements (0.0266 mm) show that this part movement is not of great significance to the selected part and can be accepted.

6.3. Case Study—Phase One: Performing the Topology Optimization

Topology optimization is a powerful tool for obtaining the optimal design based on a finite element model of the design space and loading conditions. Topological optimization is carried out in several iterations until the optimal result is obtained. For performing the topology optimization, the NX Topology Optimizer (Siemens, Minhen, Germany) add-on module is used.

The first step is to define the design space. We started with the part body (main body in Figure 9) that will be used to define the functional requirements and our design space. Then the construction bodies are defined (shafts in Figure 9). These bodies represent areas where we want to keep a certain material around them while at the other areas of the part material are removed or optimized.

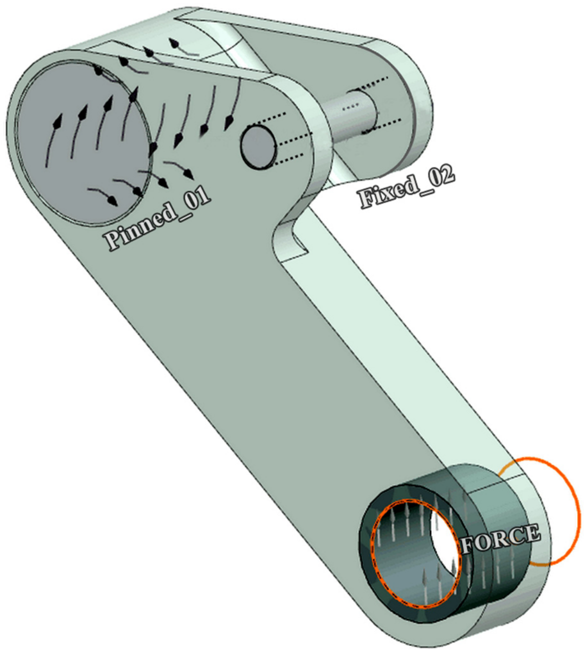


Figure 9. Initial design (main and construction bodies) for topology optimization.

The next step in performing topology optimization is to define displacement constraints and load cases (Figure 10). In this situation, the real case scenario is transferred to the software for further analysis and simulation. There are two pinning constraints (places where the part is fixed to the other suspension components—in this case, the shock absorber) and one load force positioned on the lower hole of the part where the shaft from the wheel is connected. During the movement force from the ground is pointed upward onto the shock absorber.

After all parameters are set, we can start topology optimization, and see final results (Figure 11). Topology-optimized parts are 70% lighter in weight then the initial parts (0.21 g compared to 0.698 g). This is almost max mass reduction. Since the topological optimization software could affect the geometry, the weight, and the strength of the final designs, this needs to be taken into account.

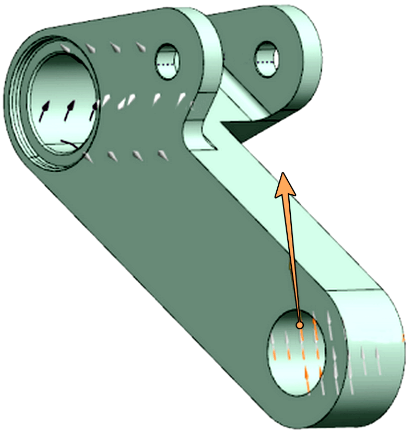


Figure 10. Fixed constraints and load force (arrow): load force is pointed upward transferring ground movement up to the next support were shock absorber is attached.

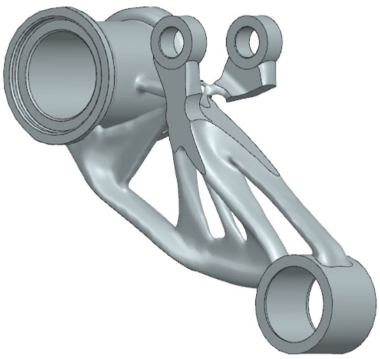


Figure 11. Final optimized part.

After performing FE analysis on the optimized geometry, Figures 12 and 13 show the displacements and stress results, as well as how the optimized part fits into the assembly (Figure 14). The results from Figures 8 and 13 are compared with initial data for the metal alloy (the optimized part form Figure 13 has a max stress of 61.16 MPa and the original part from Figure 8 has a max stress of 79.15 MPa).

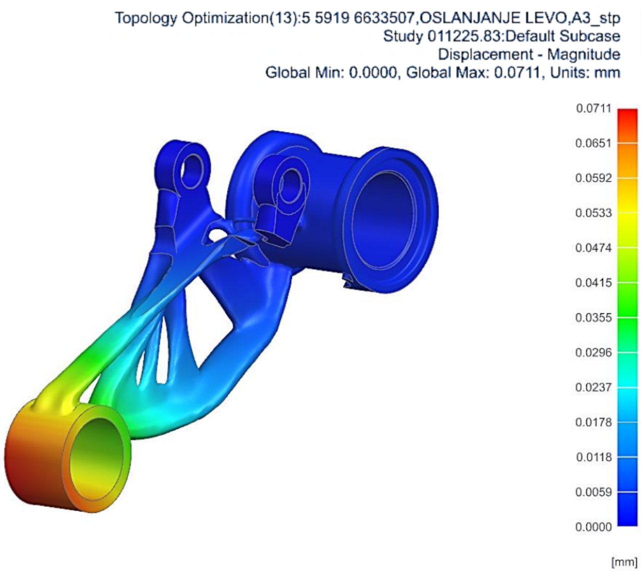


Figure 12. Displacement on the optimized part.

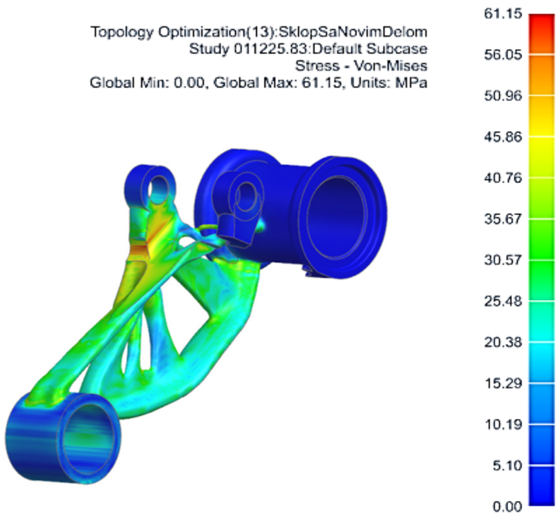


Figure 13. Von Mises equivalent stress after optimization.

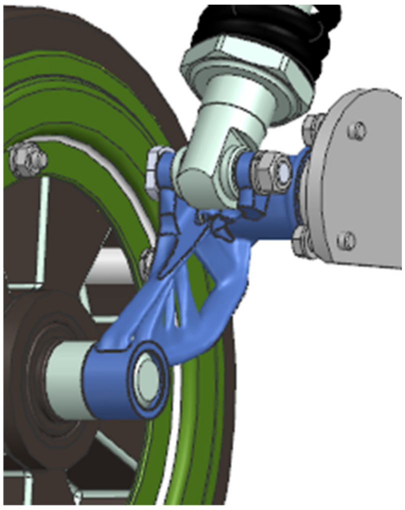


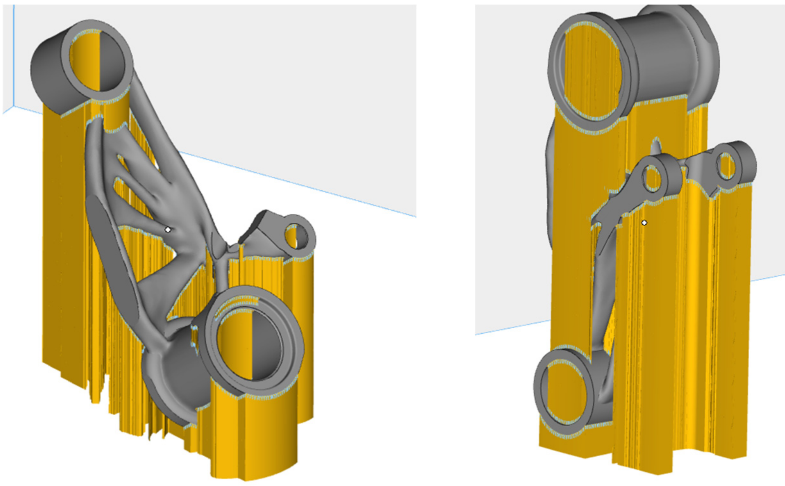
Figure 14. Optimized part mounted into the assembly.

After optimization, the stress level should be at the same level or higher than in the initial design, due to the material removal in some areas of the part. In the presented case, the stress level is smaller and this requires an additional analysis of the following elements: the shape of the mesh (for example, use of hexagonal instead of tetrahedron mesh), the direction and the size of the load force, the nature of internal deformation, etc. The resulting stress after topological optimization is lower than the yield strength of the chosen metal alloy (61.16 MPa compared to 138 MPa).

6.4. Case Study—Phase Two: Process Design

The first step is the generation of ABOs. The following approach was used to select an adequate orientation on the working plate:

- Accepting the proposal generated by the software program (Materialize Magic) and selecting two options (orientations 1 and 2 in Figures 15a and 15b, respectively).
- Other orientations were proposed by the experienced operator by applying the concept of feature recognition (Figure 16) and symmetry operation to the selected part (orientations from 3 to 7 in Figure 17 from (a) to (e), respectively).



(**a**) (**b**)

Figure 15. Part orientation on the working plate chosen from the software solution: (**a**) orientation that provide minimum support surface (**b**) orientation that minimize XY projection.

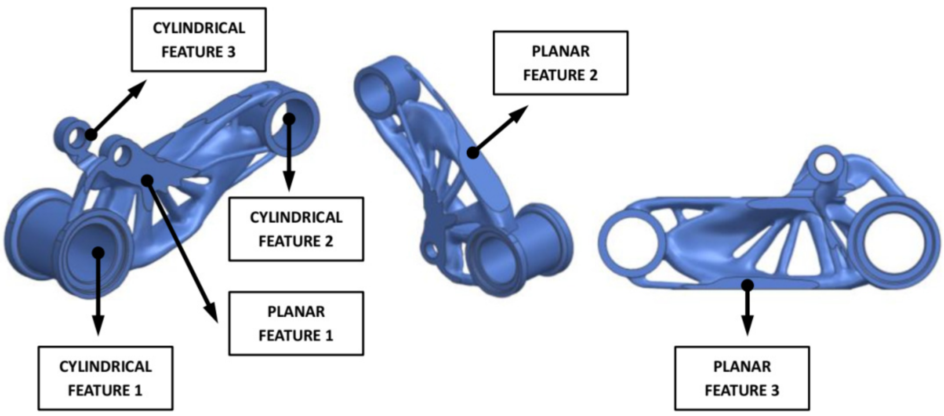


Figure 16. Feature recognition on the optimized part.

6.4.1. Generation of ABOs: Selection of Software-Defined Orientations

Together with the possibility of fine-tuning part orientation using the adequate rotation tool, software Materialize Magics also provides some advanced options (through the use of the orientation comparator) where three orientations can be calculated (the shortest Z height, the smallest support surface, and the smallest maximum XY section orientation from the original CAD file). Two software solutions have been chosen for further comparison: (1) minimum support surface (orientation 1 in Figure 15a) and (2) minimize XY projection (orientation 2 in Figure 15b), and data related to these orientations were inserted into the decision matrices. Associated data and positions of these two chosen orientations on the working plate are shown in Figure 15. The other two parameters (total build cost and time) were extracted from printing machine software (virtual print preparation) and mathematical calculation, respectively.

6.4.2. Generation of ABOs: Selection of Orientations Defined on the Basis of Feature Recognition

In the feature recognition method, the features of the input model for the topology-optimized model are recognized (Figure 16).

Based on the recognition process, the following five possible positions were considered (Figure 17 from (a) to (e)):

- Planar feature 3 parallel with the working plate (orientation 3 in Figure 17a).

- Planar feature 3 rotated 180 degrees (orientation 4 in Figure 17b).
- Cylindrical features 1 and 2 have parallel axes with the build direction (orientation 5 in Figure 17c).
- Planar planes and the working plate are under some degree (orientation 6 in Figure 17d).
- Parallel axes of the main cylindrical feature with the build direction (this orientation corresponds to the minimum Z-height orientation from the software) (orientation 7 in Figure 17e).

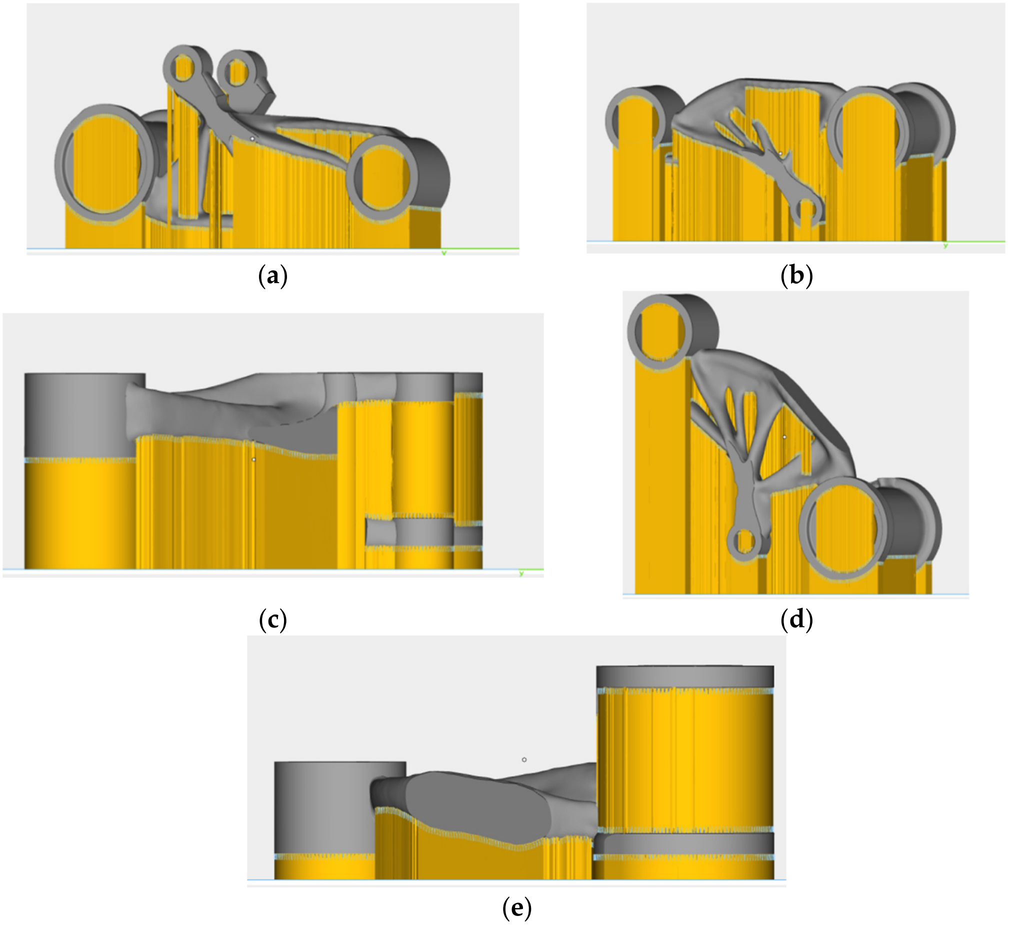


Figure 17. Part orientation on the working plate defined by the operator: (**a**) planar feature 3 parallel with working plate (orientation 3), (**b**) planar feature 3 rotated 180 degrees (orientation 4), (**c**) cylindrical features 1 and 2 have parallel axes with build direction (orientation 5), (**d**) planar planes and working plate are under some degree (orientation 6), (**e**) parallel axes of main cylindrical feature with build direction (this orientation corresponds to the minimum Z-height orientation from the software) (orientation 7).

6.5. Case Study—Phase Two: Application of Symmetry Operations and Elements

The analytical approach, presented in [39], will serve as the basis for the analysis of the application of symmetry in this paper.

When selecting ABOs using the feature recognition method, symmetry elements are found in the position (a, c) shown in Figure 18. These positions are defined as an asymmetric unit—meaning that the next positions (b, e) will be established from these asymmetric units and symmetrical operations to be performed, as follows:

- The original object (asymmetric unit—a) is immediately inverted from its original position through the center of inversion. These operations result in a symmetrical new object (b) which is positioned 180 degrees opposite to the original one, Figure 18a.

- The same symmetry operation (inversion) is applied to the asymmetric unit (c) in order to obtain symmetry part (e), Figure 18b.
- Other positions on the working plate do not have elements of symmetry.

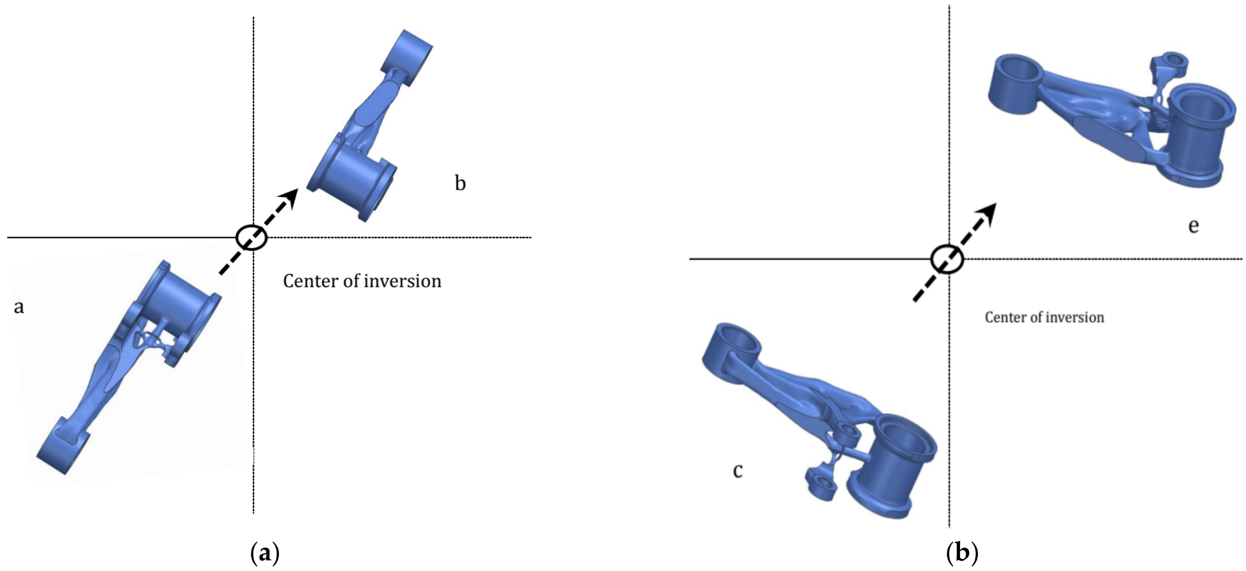


Figure 18. Use of symmetry operation in part orientation for the presented case study: (**a**) Object a inversion to obtain symmetrical new object b which is positioned 180 degrees opposite to the original one (in the direction of the dotted arrow). (**b**) The same symmetry operation (inversion) is applied to the asymmetric unit c in order to obtain symmetry part e (in the direction of the dotted arrow).

Furthermore, it is also important to cover the application of symmetry in post processing since decisions made in the previous planning stage have big influences on several aspects of the final part. So the application of symmetry can be viewed as a control activity for the following:

- Performing an analysis of GDT parameters of the final part through a comparison with the initial CAD model in order to obtain information about the occurrence of defective parts.
- Checking the existence of symmetrical formation (symmetry pattern) in the crystalline structure changes.

6.6. Case Study—Phase Two: Estimation of the Build Orientation Factors

In defining the OBOs, the first step is to determine parameters (BOFs—build orientation factors) influenced by the orientation of the part, and calculate them through mathematical calculation or extracting data from applied software.

In connection with the selection of adequate parameters, the most common parameters that are characteristic for additive manufacturing have been analyzed and refer to the state of the parts and some process parameters.

For the purposes of the case study, four parameters were chosen (print time, print cost, support volume, and support surface) on which the orientation has the greatest influence. Unlike mechanical parameters, the selected parameters are available in the planning phase, which makes the decision-making process easier. Other parameters listed above, which are not analyzed for the purposes of this paper, and which relate to GDT and mechanical characteristics, can be obtained in the planning phase through mathematical estimations or at the end of the printing process by measuring their values in the final product.

The amount of material for the supports is obtained from the Materialize Magics (Materialise, Leuven, Belgium) software for build preparation. Total build time was extracted directly from software that supports the printing machine, therefore, directly representing manufacturing/printing time. Materialize Magics provides automatic support generation and provide option for support to be later upgraded due to the design changes. Also, this software provides flexibility to adjust support geometry. For this case study, in order to provide part stability and to obtain better part quality, the support structure is generated by the combination of three support types: cones, contours, and blocks.

6.7. Case Study—Phase Two: Cost Calculation

Based on the analysis of the cost model given in [60–63] as well as data obtained from experienced operators on the machine, values were obtained for calculating the criteria of printing costs. Total printing costs are the sum of pre-processing costs, process (build) costs and post-processing costs. More explanations can be found in [63] and reference literature. For the purposes of this paper, only the costs in the process/build phase of the selected part were calculated. The total build costs of an individual part (consisting of machine, material, inert gas, and energy costs) are calculated according to the following formula:

$$C_{build}(P_i) = T_{build}(P_i) \times (C_{machine} + C_{inertgas}) + \rho \times V(P_i) \times C_{material} \times 1.1 + C_e \quad (1)$$

where

C_{build}—the cost of the building part with ith geometry (€/part);
P_i—ith geometry;
T_{build}—total build time (hour);
$C_{machine}$—machine cost per hour (€/hour);
$C_{inertgas}$—the cost of inert gas (euro/m^3);
V—part volume + support volume (mm^3);
ρ—the density of metal powder;
$C_{material}$—material cost (€/kg);
C_e—the cost of the energy consumed by the machine (euro).
Value 1.1—increase in material consumption by 10% of the non-recyclable powder.

The formula for printing costs also includes energy and machine operating costs. These costs are calculated as follows. Energy consumption costs are as follows:

$$C_e = E \times T_b \times E_R \quad (2)$$

where

C_e—the cost of the energy consumed by the machine (euro);
E—energy consumed by the machine (Kw);
T_b—total build time (hour);
E_R—energy cost rate (euro/Kw).

Total machine cost per hour $C_{machine}$ (€/part):

$$C_{machine} = \frac{\text{Machine purchase cost}}{h \times upt} + \frac{\text{Maintenance cost per year}}{upt} \quad (3)$$

where

Machine purchase cost (euro/part);
Maintenance cost per year (euro);
h—machine depreciation period (years);
upt—machine uptime (hours/year).

The data required for the calculation are partly obtained from publicly available data and part of the data was obtained by competent persons (operators and process engineers) from the laboratory where the simulation was carried out. The obtained data are entered into the decision matrices (Table 3—total build cost column).

Table 3. Decision matrices with measured values of defined BOFs.

Weights of Parameters	0.39	0.44	0.1	0.07
BOFs	**Total Build Time (Hour)**	**Total Build Cost (Euro)**	**Support Volume (mm^3)**	**Support Surface (mm^2)**
Orientation 1	12.18	488.10	55,773.19	2478.39
Orientation 2	13.42	539.77	68,668.50	2996.63
Orientation 3	7.48	305.26	36,808.62	4349.03
Orientation 4	8.47	314.10	57,164.96	4359.99
Orientation 5	6.57	273.10	40,606.09	2906.05
Orientation 6	10.43	419.50	47,515.68	3527.98
Orientation 7	5.49	224.37	20,799.81	2986.16

6.8. Case Study—Phase Two: Application of the MCDM Process in the Selection of the Optimal Build Orientation

The OBO is selected from the set of ABOs that are generated by the orientation of the part in the machine's working space (seven orientations are defined). For each selected orientation, the values for the four selected criteria (total build time, total build cost, support volume, and support surface) were either calculated or extracted from the adequate software applied in the planning phase, and hence, the decision matrices presented in Table 3 were obtained.

Each criterion has its own weighting factor that represents the aggregated values of the decision-makers. In the process of defining the weights of the selected criteria, six experts dealing with additive manufacturing (decision-makers—managers, engineers, and operators) were included in the survey. The AHP method was used for the mutual comparison of parameters and the results are shown in Table 3 (weights of parameters).

For the selection of the optimal orientation, a hybrid approach was applied using well-known multi-criteria optimization methods: TOPSIS and VIKOR, as described in [47,48].

With the TOPSIS method, the ranking of alternatives is performed based on the relative proximity of the alternative to the ideal solution, the best alternative having the biggest value. With the VIKOR method, the compromise solution is the one that is closest to the ideal solution, and in this regard, the alternative with the smallest value (distance) is also the best alternative.

All selected criteria (four in total) are of the cost type, bearing in mind that they all generate certain costs that affect the total cost of printing with the L-PBF method. This is significant due to the execution of the normalization process in both selected methods.

The obtained ranks of alternatives (Table 4 columns Rank) using two methods (TOPSIS and VIKOR) indicate that there is a maximum matching of results, which indicates consistency. On the other hand, the results obtained with the VIKOR method, for the first and last alternative (Table 4, values 0 and 1 in the Value VIKOR column), match with the negative ideal and positively ideal solution, respectively.

Table 4. Final results and ranking of alternatives.

ABO	Value TOPSIS	Rank TOPSIS	Value VIKOR	Rank VIKOR
Orientation 1	0.194636443	6	0.815373669	6
Orientation 2	0.078339882	7	1	7
Orientation 3	0.72514405	3	0.281743461	3
Orientation 4	0.64579099	4	0.38159598	4
Orientation 5	0.83972765	2	0.150856111	2
Orientation 6	0.382107763	5	0.622690496	5
Orientation 7	0.969407647	1	0	1

6.9. Sensitivity Analysis

The MCDM methods are tools for reducing subjectivity in the decision-making process. Each MDCM method characterizes a different mathematical approach, and in some cases, the application of different methods to the same problem can give different solutions, meaning that alternative choices do not depend solely on the chosen criteria but also on the chosen MCDM method. Although the results largely depend on the applied methods and analyzed problems, it is also necessary to conduct a sensitivity analysis (an analysis of the final results on the change in the value of certain parameters).

The sensitivity test can be carried out in the following ways: changing the weight value of the criterion and by the analysis of the final results obtained from the two MCDM methods. Given that the VIKOR method gives compromise solutions, the result obtained in Table 4 was checked against two conditions: (1) the condition of sufficient advantage and (2) the condition of sufficient stability.

The optimal alternative does not fulfill the condition of sufficient advantage in relation to the second alternative (the value difference 0.151 is less than the condition 0.33 = 1/(number of alternatives − 1)), but it fulfills the additional conditions from point 2.

Namely, the best alternative should meet the following conditions:

- That it is the best according to two metrics (S—overall benefit and R—individual deviation). Table 5 indicates that the optimal solution has the best scores for S and R values, hence this condition is fulfilled.
- That it ranks as first for values (υ = 0.25, υ = 0.25, and υ = 0.75, where "υ" represents the balancing factor between the overall benefit—S and maximum individual deviation—R). Table 6 shows that the optimal solution maintains the first place for different "υ" values.

Table 5. Ranking of alternatives according to S, R, and Q metrics.

	S Rank		R Rank	υ = 0.625	Q Rank
0.7700	6	0.3679	6	0.815373669	6
0.9493	7	0.4400	7	1	7
0.3138	3	0.1128	3	0.281743461	3
0.4177	4	0.1466	4	0.38159598	4
0.1784	2	0.0680	2	0.150856111	2
0.6100	5	0.2722	5	0.622690496	5
0.0189	1	0.0189	1	0	1

Table 6. Ranking of alternatives according different balancing factor (υ) values.

	υ = 0.25	υ = 0.50	υ = 0.75	Rank
OR-1	0.823445935	0.818064424	0.812682913	6
OR-2	1	1	1	7
OR-3	0.246566062	0.270017661	0.293469261	3
OR-4	0.334539392	0.365910451	0.397281509	4
OR-5	0.130287266	0.143999829	0.157712392	2
OR-6	0.610017676	0.618466222	0.626914769	5
OR-7	0	0	0	1

Since there are zero changes in the ranking of alternatives, with different values for the balancing factor—"υ", the results are stable and without sensitivity to the changes in the balancing factor "υ".

7. Discussion of the Results

The selection of adequate parameters and implementation of hybrid MCDM approaches in the AM decision process poses significant challenges.

The analysis of the weighting coefficients indicates the importance of the first two parameters (costs and time), while the remaining two parameters have no significant importance, according to experts. Regardless of the obtained results of the expert assessment, these two parameters still significantly contribute to the increase in costs (through the increased consumption of materials for the construction of the supporting structure).

All of the selected parameters are of the cost type and their value should be as low as possible, which is certainly a matter of compromise, and this is indicated by the best alternative, which has the lowest values for each parameter.

The values of the selected parameters can be obtained (either through software or calculations), even in the production planning phase, so it is not necessary to carry out the experimental phase, which shortens the preparation time and costs and provides enough information for quality decision-making.

The choice of parameters does not have to be limited to the proposed four parameters, and depends on several factors: the choice of additive technology, the choice of software for production preparation, the needs of the decision-maker, the operator's experience, etc.

The results showed that the best chosen alternative (orientation 7) is the choice of an experienced operator who based his attitude on the basis of the feature recognition approach and symmetry operations. From a more detailed analysis of the proposed software solution, that was not selected as an option in the case study (orientation solution that require minimum Z height); it can be concluded that it also matches the operator's proposal (as an orientation option). However, it is important to point out that the ranking positions from 2 to 5 (Table 3) are related to the orientations chosen by the operator, which points to the conclusion that we cannot fully rely on the software's suggestions, i.e., that it is necessary to know the basic settings of additive manufacturing planning as well as the geometry of complex parts in order to choose an adequate orientation.

The results show that there are no deviations in the rankings of the alternatives using both chosen methods, so there is a maximum correlation.

The analysis from the aspect of the printing cost parameter indicates that in the selected formula there are no costs of supporting equipment (for example, a gas generator), but only the cost of the machine is included. On the other hand, the costs as well as the operating parameters of the machine can vary, which affects the final price, so the obtained production price does not always have to be a correct reference.

8. Conclusions

This paper is focused on the planning process of the design and production of metal parts by additive manufacturing (PBF-L technology). Despite certain disputable facts (about cost and time), it was determined that this technology offers certain advantages compared to traditional production technologies, which were also explained in the introductory part of the paper.

It is proposed that the planning process be carried out in two phases (product and process design), within which the sub-phases must be carried out in the manner and in the order as specified. The limitation of the proposed framework is that its complete application requires knowledge of several areas (topology optimization and FE analysis, mathematical solutions for build parameters calculation, etc.) and that requires teamwork. The simulation of process planning and production is time consuming, requiring the implementation of very expensive software tools as well as expert knowledge in L-PBF additive technology. Speaking about L-PBF technology operators, users or experts in this field need to be familiar with machine technology, feedstock powder materials, post-processing activities, etc. In practice, this process is still labor intensive. The proposed framework is targeted towards application in L-PBF technology, but with minor changes (mainly depending on the chosen additive technology) it is applicable for the product and process planning of other available additive technologies.

Also, the paper emphasizes the importance of simultaneous topological optimization and the optimization of the orientation of the part on the working plate, with the aim of achieving an optimal solution (obtaining the final product of reduced mass that satisfies the initially set structural loads, in a cost-acceptable range).

The benefits of using simulation tools in the earliest stage of conceptual design are in providing a set of data which can help in the systematic exploration and analysis of product design (can reduce redesign in later stages and reveal systematic flaws) as well as in the analysis of process parameters in order to avoid any build cycle failures.

Based on the analysis of the literature in the field of planning, design, and production with additive technologies, it has been concluded that there is a lack of work in which the orientation of the parts on the working plate (proposed by an implemented software solution) is compared to that of an experienced operator.

Four parameters (total build time, total build cost, support volume, and support surface) were chosen as parameters for comparing the proposed orientations (seven in total), which clearly and explicitly represent the characteristics of PBF-L additive technology. The list of parameters is not final and can be arranged according to expectations and the final goal.

Although not considered in this paper, since we suppose that process parameters are constant, special attention should be paid to the concept of uncertainty, different sources of uncertainty, and uncertainty propagation in the additive manufacturing processes. Uncertainties (in process parameters, printing conditions, etc.) affect the consistency in the quality of the final product and the repeatability of the additive process. Uncertainty can be modeled by applying certain uncertainty quantification techniques in order to find optimal process parameters and increase the resilience of the whole additive process.

Related to the applied MCDM methods (TOPSIS and VIKOR), and since these methods are based on a computation of ideal or anti-ideal solutions that may not exist in a real case scenario, this should provoke researchers to look for the implementation of other MCDM methods like ANP, PROMETHEE, COPRAS, MABAC, etc. Nevertheless, the hybrid approach in the application of the MCDM method, with the inclusion of the expert opinions and the implementation of sensitivity analysis, is a suitable and valuable tool for obtaining quality decision.

In addition to the clear promotion for the acceptance of additive technology for the production of metal parts, there are some other contributions that this paper brings to wider scientific community:

- A description of efficient and economically acceptable process planning for additive manufacturing production of metal parts.
- The paper points out the importance of applying simulation tools in the process of planning and designing products based on which additional information can be obtained for decision-making processes.
- The paper also points to the fact that parts designed for production using traditional production technologies could be good candidates for production through additive manufacturing.
- The paper emphasizes the importance of including the experienced operator in the design phase and selection of production parameters for additive production. This further means that available software solutions and algorithms can provide additional but not decisive help in the decision-making process to initiate production.
- There are spaces for the application of symmetry operations and associated elements in the part orientation problem. Symmetry operations (rotation, inversion, mirror, and transition) can provide a different orientation of parts on the working plate which can further contribute to the detailed understanding of the influence of the part orientation on the mechanical and geometrical characteristics of the produced parts. This work

pointed to some of the stages in the additive manufacturing workflow (product and process design) where symmetry can contribute significantly.

Further steps in the research should be directed to the analysis of the influence of the orientation of the part on the geometric, dimensional, and mechanical characteristics. In this sense, it is necessary to carry out a specific experiment in which these characteristics would be measured, and then, based on the obtained results, alternatives would be compared and the best one selected. With this approach, a full cycle of the additive production of metal parts would be reached.

The presented phases in the preparation and planning of the additive manufacturing process together with the hybrid MCDM approach as a decision-making tool present a good framework for implementation in other similar processes.

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