ANÁLISE DOS FATORES QUE DETERMINAM A CAPACIDADE DE AUTOMATIZAÇÃO DE ALISAMENTO DO MODELO ELETRÔNICO DO PRODUTO RESULTANTE DE OTIMIZAÇÃO TOPOLÓGICA PARA USO NO PROCESSO DE MANUFATURA ADITIVA

ANALYSIS OF FACTORS THAT DETERMINE THE POSSIBILITY FOR AUTOMATION OF SMOOTHING OF PRODUCT ELECTRONIC MODEL, OBTAINED THROUGH TOPOLOGICAL OPTIMIZATION FOR THE PURPOSE OF ITS USE IN THE TECHNOLOGICAL PREPARATION OF ADDITIVE MANUFACTURING

АНАЛИЗ ФАКТОРОВ, ОПРЕДЕЛЯЮЩИХ ВОЗМОЖНОСТЬ АВТОМАТИЗАЦИИ СГЛАЖИВАНИЯ ЭЛЕКТРОННОЙ МОДЕЛИ ИЗДЕЛИЯ, ПОЛУЧЕННОЙ В РЕЗУЛЬТАТЕ ТОПОЛОГИЧЕСКОЙ ОПТИМИЗАЦИИ ДЛЯ ИСПОЛЬЗОВАНИЯ В ТЕХНОЛОГИЧЕСКОЙ ПОДГОТОВКЕ АДДИТИВНОГО ПРОИЗВОДСТВА

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RESUMO

Na maioria dos casos, é aconselhável realizar a geometria do produto, depois a otimização topológica e em caso se a produção for planejada em uma pequena série, usando as capacidades das tecnologias aditivas. As características tecnológicas da síntese de camada por camada formam os requisitos para a geometria do modelo eletrônico do produto e a conformidade com certos padrões. Um desses atributos necessários é o formato de arquivo STL, para que a geometria do produto seja carregada em um sistema CAM especial e para que seja possível prosseguir para a preparação tecnológica da produção. Como a geometria do modelo eletrônico do produto (densidade de malha poligonal, erros de grade) é essencial e deve levar em conta as características da tecnologia de impressão 3D selecionada. Um dos fatores importantes é a análise dos processos associados à automação do processamento de uma malha poligonal para o seu alisamento. O artigo analisa os fatores que determinam a possibilidade de automatização do alisamento de uma malha poligonal resultante da otimização topológica resultante para uso na produção de aditivos.

Palavras-chave: *tecnologias aditivas, modelo eletrônico, malha de elementos finitos, otimização topológica, alisamento.*

ABSTRACT

In most cases, it is advisable to develop product geometry, being subject to topological optimization and planned for small-scale manufacture, using the capabilities of additive technologies. Technological features of layer-by-layer synthesis determine requirements to geometry of the electronic model of the product and compliance with certain standards. One of these necessary attributes is the STL file format that allows loading product geometry into a special CAM system and technological preparation of production. Since the geometry of the electronic model of the product (density of polygonal mesh and mesh errors) is critical and should consider features of the selected 3D printing technology. One of the important factors is the analysis of the processes associated with the automation of processing a polygonal mesh for its smoothing. The article analyzes the factors that determine the possibility for automation of smoothing of a polygonal mesh obtained due to topological optimization for its use in additive manufacturing.

Keywords: *additive technologies, electronic model, finite-element mesh, topological optimization, smoothing.*

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АННОТАЦИЯ

В большинстве случаев, геометрия изделия, прошедшая топологическую оптимизацию, и планируемая к производству мелкой серией, целесообразно производить используя возможности аддитивных технологий. Технологические особенности послойного синтеза формируют требования к геометрии электронной модели изделия и соответствие определенным стандартам. Одним из таких необходимых атрибутов является формат файла STL, для того чтобы геометрию изделия можно было загрузить в специальную CAM систему и приступить к технологической подготовке производства. Поскольку геометрия электронной модели изделия (плотность полигональной сетки, ошибки сетки) критически важна и должна важных учитывать особенности выбранной технологии 3D-печати. Одним из важных факторов является анализ процессов связанных с автоматизацией обработки полигональной сетки для ее сглаживания. В статье проведен анализ факторов, определяющих возможность автоматизации сглаживания полигональной сетки полученной в результате топологической оптимизации для использования в аддитивном производстве.

Ключевые слова: *аддитивные технологии, электронная модель, конечно-элементная сетка, топологическая оптимизация, сглаживание.*

INTRODUCTION

Modern requirements to development of rocket and space equipment, such as: the maximum delivered payload; costs for launching launch vehicle; cost for developing LV; quality; reliability; time for development and preparation of manufacture of the launch vehicle; minimum mass of LV; fulfillment of the task on delivery of payload by LV, etc. demand from modern design engineer to find optimal decision for these or that technical solutions so that such decision satisfies to a certain extent one of the requirements and contradicts the other one as little as possible.

The use of modern computing systems at all stages of the product life cycle has a positive effect on reducing the time and cost of development, preparation for manufacturing, commissioning, and also allows optimizing and modifying products, thereby increasing the competitiveness of the enterprise in the market for this kind of services. This will result in completely new characteristics and operational capabilities of manufactured products.

Modern computers allow to solve the problem of topological optimization in automatic mode with the use of special software. The most popular approach to determination of optimal design is to minimize compliance function or the potential energy of deformation under limited volume of construction. The formulation of a construction optimization problem has the following mathematical form:

Find $min \boldsymbol{f}^{\boldsymbol{T}}\boldsymbol{U}$

Under the following limit

$$\int_{\Omega} \rho x \, d\Omega \leq M_0 \quad (1)$$

where **f** is the external load vector; **U** is the displacement vector; ρ is the material density in the considered project area; *Ω* is the set of elements of the project area; M_0 is a value limiting the mass of the power material.

The solution of the optimization problem (Promising areas…; Development prospects…, 2010; Shevtsov, 2010; Bryukhov and Maksimov, 2016; Kozik *et al.*, 2017) is based on the introduction of design variable x, which links Young modulus to density of each final structural element in each final element of the project using the following relations: $\rho x = \rho_0 x^p$, $Ex = E_0 x^p$, where ρ_0 and E_0 are the initial density and the Young's modulus of the material, *p* is the penalty indicator for highlighting necessary and unnecessary structural elements (Sysoeva and Chedrik, 2011; Shevtsova and Shevtsova, 2013).

There are also topological optimization methods that allow building up material on the original product, taking into account the stiffness and strength characteristics (Vasilkov, 2013; Vasilkov and Markin, 2002; Vasilkov, 2003). In general, the process of topological optimization consists of separate stages of design optimization, designed for search of optimal structural and power representation of the product under certain effective loads. Then results of topological optimization need to be formalized in order to obtain the concept of the topology of this product, as well as to create the final product ready for manufacturing (Borovikov and Tenenbaum, 2016).

RESEARCH METHODOLOGY

To consider the possibilities for using topological optimization tools in modern rocket manufacturing enterprise as well as evaluating the positive and negative factors that affects product life cycle and the final product itself, first of all it is necessary to analyze t conventional methods and stages of development of .rocket and space equipment. In enlarged version, the stages of manufacture of finished products are as follows:

- Design;
- Calculation;
- Release of design documentation;
- Preparation to manufacture;
- Manufacture,

where product design stage includes the development of product appearance, certifying calculations, preparation and release of the design documentation, development of manufacture methods and direct manufacture.

The above-mentioned enlarged structure of the organizational sequences of the stages of the product life cycle is considered to be 'conventional'. The use of = topological optimization tools in this conventional structure will result in new structural solutions:

Stages of design, calculation and issue of design documentation will be combined into a single whole, where the design engineer will conduct studies on the topological optimization of developed products based on data with respect to load, tests and properties of tested materials provided by structural analysts and manufacturing methods specified by production engineers.

Preparation to manufacture and manufacturing processes will be also combined, since electronic models of product are not suitable for manufacturing by removing material from work piece and manual manufacture of products in most studied cases of topological optimization. This results in the need for the use of additive manufacturing methods, where process engineer is the operator of a 3D printer, which make such person responsible for preparing operators to 3D-printing based on electronic model of product and supervision over additive manufacturing process.

Such innovation significantly reduces the number of stages and iterations in product life cycle, which reduces the time and cost for development and manufacture of the product. The use of topological optimization tools allows developing and manufacturing competitive products that meet set tasks and operational requirements, and the use of additive technologies in small-scale or piece production of rocket and space equipment is the best options for the methods of manufacturing these products, ensuring reproducibility of manufacturing results, defect minimization, the possibility for flexible production for a wide range of tasks.

RESULTS AND DISCUSSION:

Additive technology. Manufacture of products with a large number of curved surfaces requires careful evaluation of the technological approach. Some products that have been subject to topological optimization can be manufactured on CNC machines, but this type of manufacturing is not suitable for complex 'mesh' designs or requires large-scale production for economic reasons. Additive technologies are suitable for products of complex shape. Additive production (Additive technologies…; Technosphere) allows creating products of various shapes within the accuracy of several microns.

Quick development of technological base and increase of production scale suggest the need in introduction of preparatory technological measures aimed at validation of entire technological chain of layer-by-layer synthesis of products to ensure reproducibility and validity of values. Technological preparation to production. For a comprehensive consideration of the problems of layer-by-layer synthesis, it is necessary to have an idea of the full production cycle of the part (Figure 1), software and data formats used at each stage.

Thus, there is a need in smoothing of obtained geometry at the stage of technological preparation of topologically optimized products for additive manufacture. This is conditioned by the fact that obtained electronic model of the product has a “saw-like” surface (Figure 2), which is unacceptable for the manufacture of supporting structures due to the multitude of randomly arranged stress concentrators (Maksimov and Fetisov, 2016; Ripetskiy *et al.*, 2016; Freilehman, 2017).

Analysis of stages of preparation to layer-by-layer synthesis suggests that this defect associated with the poor-quality surface of the electronic model of the product can be affected only at the design stage. Considering this fact, we have determined effective methods for solution of this problem:

1) Import of obtained geometry from the optimizer into CAD, where the engineer, using available tools, recreates the optimized geometry. For this purpose, he needs CAD tools that can convert finite element mesh of optimizer into file format that can be read by CAD programs. It is also necessary to have professional skills in CAD operation to ensure maximum reproducibility of geometry obtained by the optimizer. This method requires a lot of effort and time to prepare the geometry for printing and can significantly distort initial contours of the optimized electronic model of the product (Maksimov and Fetisov, 2016).

2) Calculation of the product in the optimizer using FE mesh, the dimensions of the elements of which will be less than the technological accuracy of the 3D printer, so that the resulting 'saw-like' surface does not adversely affect the strength properties of the product. This method is one of the actual solutions but it is not technically feasible due to significant increase in the number of FE mesh, which leads to a significant increase in the time spent for calculations subject to the implementation of this hardware and software products (Oganesyan and Shevtsov, 2014).

3) Construction of NURBS-surfaces that partially follow the contour of the optimized product. This method provides for the availability of CAD tools that allow you to build NURBS-surfaces, as well as the skills necessary to carry out this operation. The product geometry obtained in this way will differ from the original optimized model, which again leads to a distortion of topological optimization results (Altair Inspire…).

Analysis of the surface roughness of the product. Before making final conclusions about the considered methods for solving the problem of smoothing the optimized geometry by applying topological optimization tools, let us analyze the degree of influence of surface roughness on its mechanical properties. According to the considered sources (Oganesyan and Shevtsov, 2015; Glotov, 2015; Kolesnik *et al.*, 2015; Formalev and Kolesnik, 2017; Rosa *et al.*, 2017), the surfaces roughness of the part directly affects its performance.

Analysis of printing fidelity of 3D printer. Considering previous results of the analysis, we make the following assumptions: that the smaller the roughness of the product, the higher its mechanical characteristics. Thus, it is possible to determine the following correlation: the smaller surfaces roughness of the electronic model of the product, the more accurate the product can be obtained after the additive manufacture. But this assumption is not unambiguously true: the quality of the product depends on the quality of the electronic model, but the quality of the printed part will differ from the electronic version for worse due to the presence of errors in the process of layer-by-layer synthesis.

To determine the causes of these errors, it is necessary to analyze the printing process itself. Lets consider the SLM (Selective Laser Melting) technology of 3D printing, Figure 3. SLM 3D printing technology is an additive manufacturing method based on high power fiber-optic laser. The main consumable is a powder metal alloy.

As shown on Figure 3, this technology of layer-by-layer synthesis of products includes two main working bodies, which, while moving, set the contours of the future product. They are working platform that moves along the OZ axis and is responsible for the “height” of the product and the laser, along with scanning and laser beam redirection system, which ensures the formation of a cross section of the model in a specific XOY working plane. Each of these product formation bodies has its own technological limitations and errors.

The working platform is moved along the OZ axis by a step servo drive, a set of two or more servo drives or other means. This information suggests that the technical limitation of product creation accuracy along the OZ axis is the sensitivity of the listed control mechanisms. The analyzing of 3D printing process and the resulting products suggests that there is a distortion of information about the product, i.e. deviation from the original electronic model of the product, along OZ axis.

This can be explained by the specifics of technology of layer-by-layer synthesis. The analysis of these data suggests that the distortion of data about the product in over OZ axis cannot be avoided. However, it is possible to change the degree of this error, by changing the pitch between the layers within the technical characteristics of control bodies.

The laser beam is moved along the working surface by means of system designed for scanning of working surface in XOY plane. Movement accuracy of the laser beam determines the quality of product formation along OX and OY coordinates. The accuracy of the flat section of the future product depends on the following factors: positioning accuracy of laser beam on the working plane, the dimensions of the laser "point" on working surface. Other factors affecting the accuracy of cross section formation are also properties of the powder used, namely the size of the fraction of powder grains.

Methods for layer-by-layer anti-aliasing of the geometry of product electronic model. Considering above-mentioned factors affecting the accuracy of 3D printing, we can assume the following hypothesis: there is no need to create a "perfectly" smooth electronic product model for additive manufacturing due to the presence of errors in the 3D printing process itself conditioned by technical limitations of working and control bodies.

This hypothesis suggests the conclusion that the geometry of the electronic model of the product after topological optimization needs to be smoothed out to the level of technological error of the 3D printer itself. More accurate smoothing is not reasonable due to the future loss in quality of 3D printing process. The areas of the product that do not require high precision processing, straight surfaces and other areas can be excluded from the area to be smoothed by the proposed algorithm at discretion of machine operator.

Based on the above analysis of the process of technological preparation for 3D printing and causes of deviation of original electronic model from the final product, it is proposed to change the sequence and content of the stages of technological preparation to additive manufacture (Figure 1):

•"Generation of layer-by-layer presentation' can be placed after 'layout of the desktop' stage

• It is necessary to analyze roughness of section contour (Ra) and compare it with set printer error (ξ) along the OX and OY axes at 'generation of layer-by-layer representation' stage.

• If Ra ≤ ξ, then proceed to the subsequent stages 'tooling design' and 'generation of layer-by-layer presentation' of the product and supporting structures in their original presentation and other remaining stages up to the finished product.

• If Ra ≥ ξ, this geometry needs to be smoothed out. Geometry smoothing process is a layered approximation of each section of the original electronic model of the product. After completion of smoothing process, it is necessary to perform all subsequent stages of technological preparation for production, as with Ra ≤ ξ.

Implementation of layer-by-layer smoothing method. The process flow diagram for preparing an optimized product for additive production using the above hypothesis has the following view (Figure 4):

Considering this scheme, it is clear that the input data to the system for preparing printing technology is the electronic model of the product in the STL file format. This electronic model is the result of topological optimization. The output data from the technological preparation system for production are G-code, i.e. a set of control commands that will be executed by the control bodies of 3D printer in the process of 3D printing of a new product.

The algorithm of the system of technological preparation of an electronic model to production consists of the following sequence:

1. Validation of model geometry. The processing of input data into the system.

2. The layout of the working chamber. The electronic model of the product is composed and positioned in the virtual workspace of a 3D printer. The process of product composition and positioning will not be considered in this work since this task requires a separate study.

3. Generation of layer-by-layer presentation. The electronic model of the product is divided into multiple layers parallel to the 3D printing plane with pitch that is equal to the height of one printed layer set by the machine operator.

4. Analysis of layer roughness. Each section formed by splitting the electronic model into layers is approximated, i.e. contours of a flat section are smoothed out by applying an

approximating function. Then smoothed contour is used as the middle line to determine the minimum and maximum roughness values.

5. Layer-by-layer smoothing of the model. If it was disclosed that the minimum roughness of the cross sections of product electronic model significantly exceeds the accuracy of the 3D printer ta previous stage, then it follows that the print quality of this model is affected by its geometric characteristics and needs to be smoothed out. The smoothing process is a replacement of the original external contour of the sections by the approximated curve obtained in the previous step to obtain smooth contours of the future printed layers of the model.

6. Tooling design. After optimization of the cross sections, the supporting structures necessary for 3D printing are constructed based on the obtained geometry of the electronic model. The features and aspects of this process will not be considered, since this requires a separate study.

7. Generation of layer-by-layer presentation. The model is re-divided into layers for 3D printing, considering the supporting structures. This division into layers is final and the set of control commands for the machine, i.e. G-code, will be formed on the basis of these layers.

8. Verification of hardware compatibility. The implementation of this algorithm saves time for preparation of the product to additive manufacture at the design stage by transferring this operation to the stage of technological preparation and automation of this process. The other advantage, if compared with presented methods for smoothing the geometry of an electronic model, is the presence of an express analysis of the roughness of the product, which allows the process operator to evaluate the properties of the surfaces of the product, the possibility of their 3D printing and the ability to predict the quality of the future product.

CONCLUSIONS:

The article analyzes the possible ways of upgrading high-tech products. This work describes method of topological optimization of the structure and determines problem in the implementation of topological optimization tools. It also shows existing methods for solving considered problems.

To assess the applicability of the solution proposed in the article, the influence of the quality of surfaces of product electronic model on the final product of the additive manufacture has been analyzed and the possible reasons for the influence of the technical characteristics of the machine (3D printer) on the quality of the final product has been shown.

Based on the results of performed analysis, it was propose to carry out smoothing and preparation of the geometry of the electronic model by layer-by-layer method at the stage of technological preparation to additive manufacturing, and a method for analyzing the roughness of the optimized geometry of product electronic model was developed to determine the need for a smoothing operation.

The method has been developed for layer-by-layer smoothing of geometry at the stage of technological preparation of a product model to manufacture by introducing polynomial approximant to smooth out external contours of cross sections of product electronic model.

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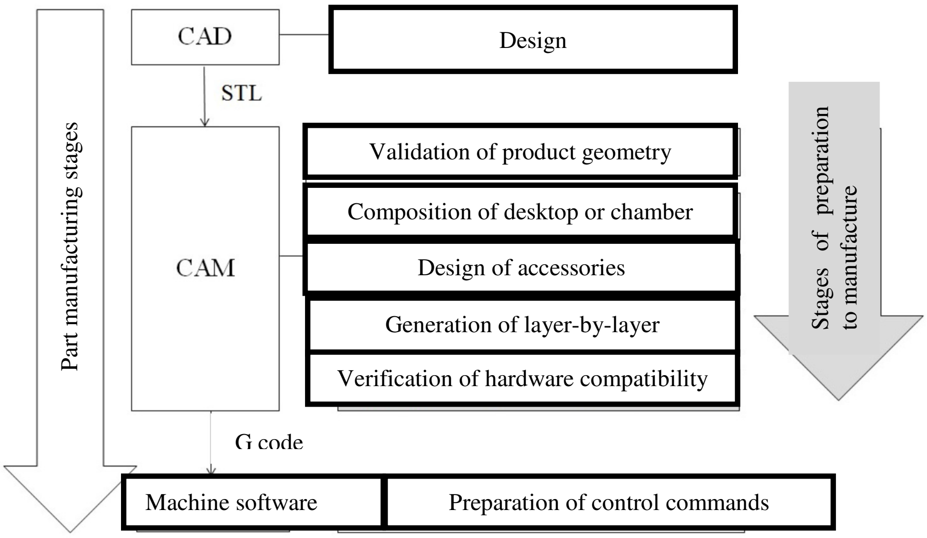

***Figure 1**. Stages of preparation to layer-by-layer synthesis*

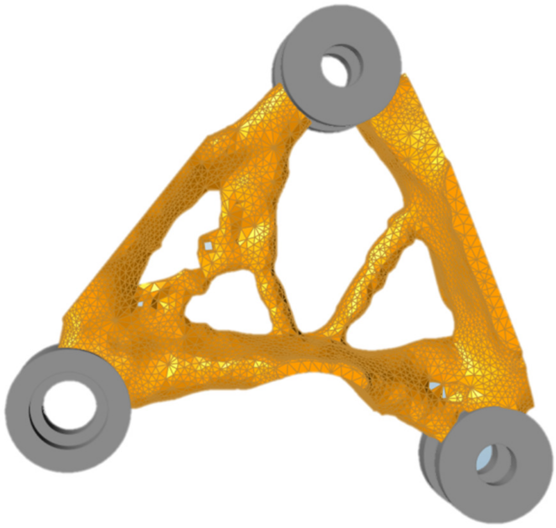

***Figure 2**. Example of optimized product*

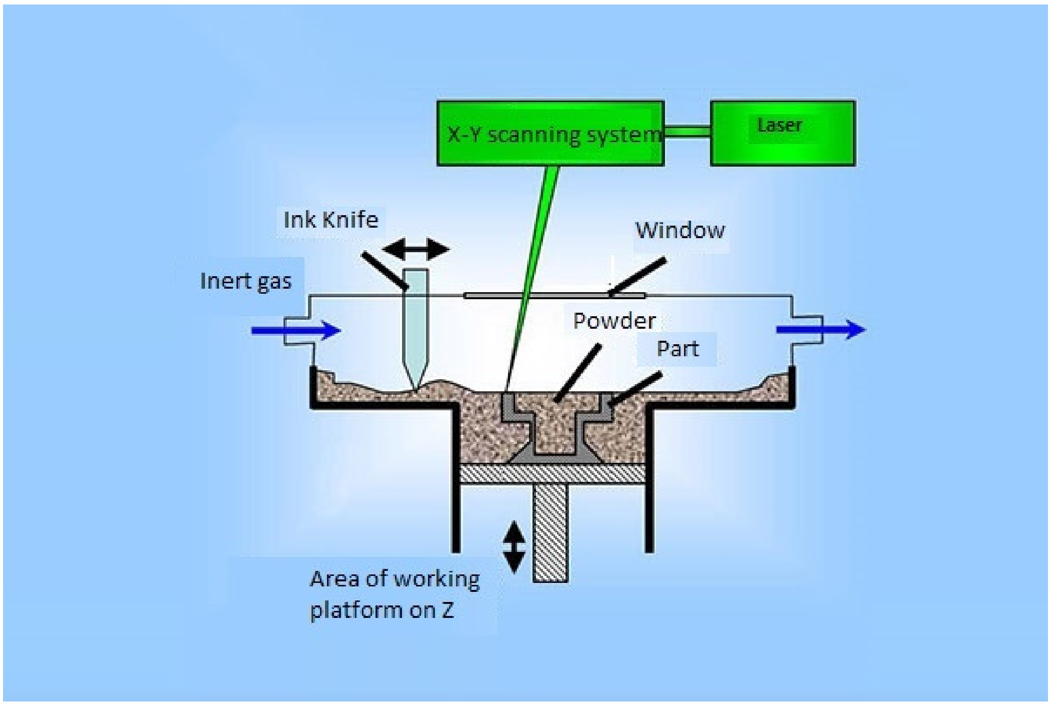

***Figure 3**. Elements of working chamber of SLM 3D-printer*

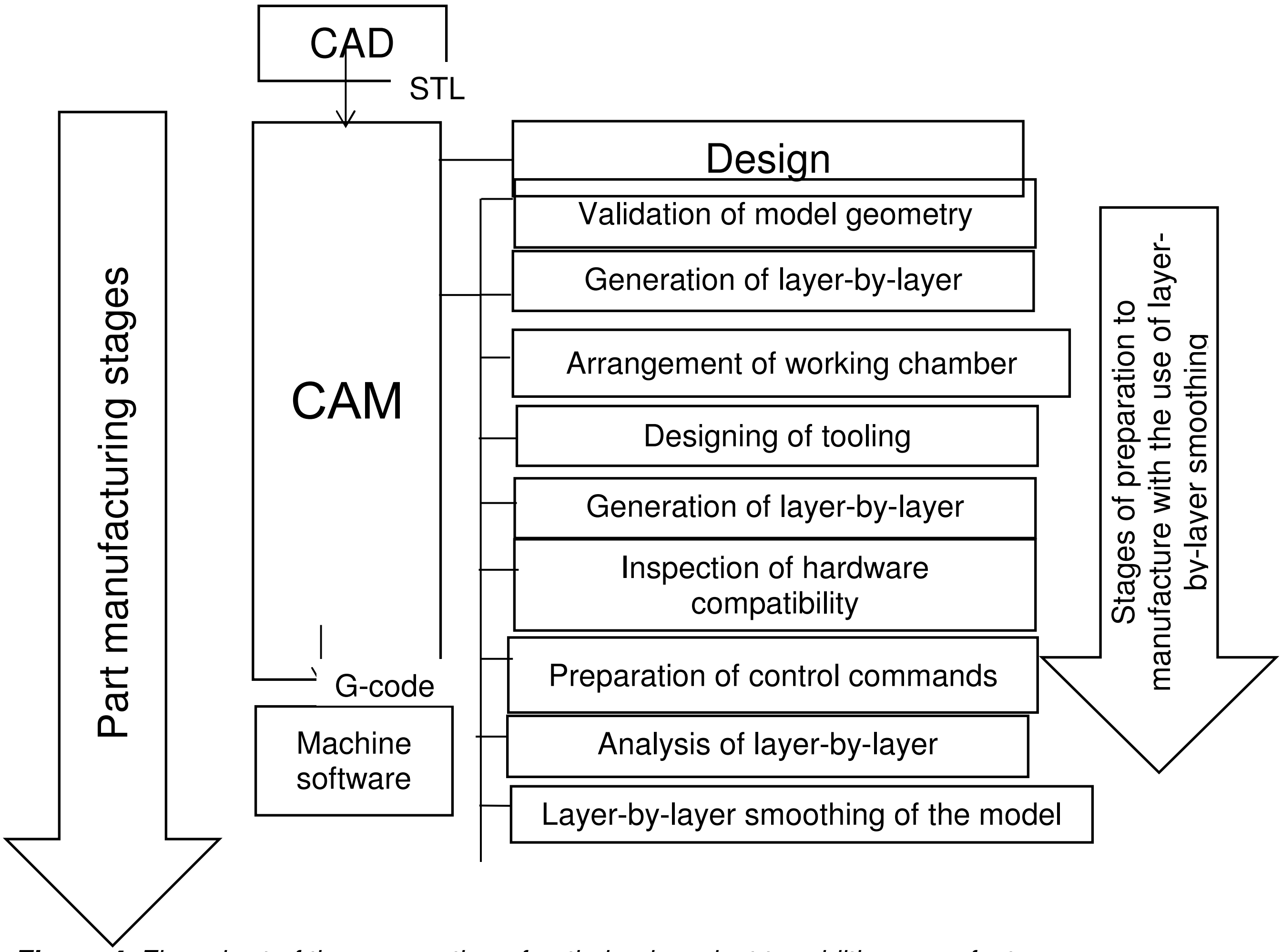

***Figure 4**. Flow chart of the preparation of optimized product to additive manufacture*