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Determining the Assumptions for the Selection of Measurement Methods for Products Manufactured with Incremental Methods

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Abstract: The article presents the method of determining the assumptions for the selection of measurement methods for products manufactured with the use of incremental processes. In the research area, an analysis of 3D printing methods was carried out in terms of the specificity of the additive process, the materials used, the possibility of process deformations, and the accuracy of technological machines. With regard to the measurement methods, the analysis covered the accuracy of the method, the speed of the measurements, the costs of the measurements and the applicability to additive manufactured products. As a result of the analysis, assumptions were made for the criteria for selecting measurement methods for incrementally manufactured objects. The accuracy of prototyping in incremental processes largely depends on the accuracy of their numerical models. Taking this into account, simulations and studies of program processing of data were also carried out, starting from the development of a 3D-CAD model, through the export of numerical models and the preparation of data for manufacturing and control-measurement processes.

Keywords: additive manufacturing; coordinate measurements method; data processing; quality control; 3D printing

1 INTRODUCTION

Additive technologies allow for the production of models, prototypes, semi-finished products and finished products with various geometrical accuracy, which depends on many technological factors. The geometric accuracy is influenced, among others, by program processing of data in the 3D-CAD modelling process, the process of exporting numerical models, positioning the model in relation to the 3D printer coordinate system, implementation and type of the incremental process itself and the material from which the object is produced [1, 2]. The analysis of geometric accuracy should be carried out at the key stages of the incremental process with the use of measuring devices and software for the analysis of geometric data [3, 4]. The selection of measurement methods and the method of data processing is important from the point of view of determining the quality of products [5], but also the time and costs of quality control. For this reason, it is advisable to carry out an analysis of the selection of measurement methods for additive technologies from the point of view of the intended use of products manufactured with specific 3D printing methods [6].

1.1 Analysis of 3D Printing Methods

The analysis of the accuracy of products manufactured with the use of 3D printing methods is subject to the standardization process in accordance with ISO standards [7-9]. The standards define the types of additive processes, guidelines for product design, materials used in 3D printing, numerical data processing, industrial applications and quality control. According to the information presented in the standards, as of today, there are seven basic incremental processes, which include:

- VPP – Vat Photopolymerization – a process consisting in layered photopolymerization of the resin carried out in a specific volume with the use of a concentrated beam of UV light or light emission from a UV projector, which source is located above or below the manufactured object,
- MJT – Material Jetting consists in layered printing of a liquid material in the form of a resin, from a print head, which applies successive layers of a specific thickness based on the program cross-sections of the model. The change from liquid to solid-state most often occurs because of photo-polymerization or solidification,
- BJT – Binder Jettingin volves bonding a powdered material with a liquid adhesive. In this process, the base material in the form of powder is bonded by printing the liquid adhesive from the head, which applies successive layers based on the cross-sections of the three-dimensional model,
- PBF – Powder Bed Fusion consists in selective sintering or melting of the material from the original powder form into a 3D model. In this process, concentrated thermal energy is delivered within the volume of the powder bed and binds successive layers of the model until the physical model is ready,
- MEX – Material Extrusion consists in layer extrusion of the material - the process is based on the extrusion of a thermoplastic material from the original form of fiber or granulate and layering according to given sections according to numerically defined paths,
- DED – Directed Energy Deposition consists in the targeted melting of the material, usually delivered in the form of a powder. In this process, concentrated energy melts the material in layers as it is deposited. Concentrated thermal energy can be emitted as a laser beam, an electron beam or a plasma or electric arc,
- SHL – Sheet Lamination is a process consisting in layered lamination of material sheets of a predetermined thickness. In this process, successive sections of the model are cut from the sheets of the processed material glued to each other.

2 FACTORS AFFECTING MODEL ACCURACY

In the process of additive manufacturing, two basic groups of factors influencing the accuracy of models can be distinguished: factors resulting from numerical processing of data and factors resulting directly from the incremental process. These factors, depending on the technology used, are directly or indirectly related to each other, they are often related to the technological capabilities of the 3D printer and the course of the additive process itself, or the materials used. The analysis of these factors is important from the point of view of selecting a measurement method to analyse the accuracy of incrementally manufactured products.

2.1 Data Numerical Processing

The first steps in the additive manufacturing process include mainly numerical processes, starting from 3D-CAD modelling, through converting the CAD model to a software format dedicated to a 3D printer (e.g. STL format), up to the division of the model into layers and preparation of numerical data directly for the incremental process. The 3D-CAD modelling stage is important from the point of view of the correct solid model, which will be further processed numerically [10]. Generally, the CAD model must be a uniform solid that allows it to be converted to the intermediate 3D-AM format. One of the most common 3D-AM intermediate formats is the STL format, in which, because of the triangulation of a solid model, its representation is created in the form of a triangle mesh spanning the entire surface of the model. Most 3D-CAD modelling programs have modules for transforming a solid model into an STL model, which can be a base model for analysing the dimensional accuracy of products [11, 12]. The influence of numerical data processing on the accuracy of mapping the 3D-AM model and ultimately the product is most noticeable for objects with shapes composed of curvilinear surfaces. In the case of objects consisting of flat surfaces, in most cases the triangulation parameters do not affect the number of triangles describing the model (Fig. 1).

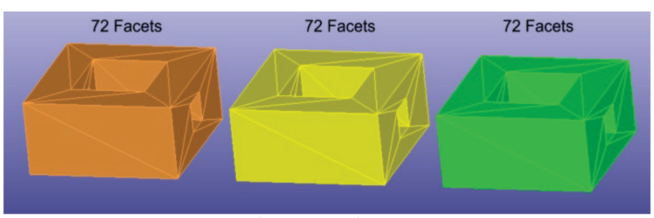

Figure 1 STL model of the test body

The model of the solid shown in Fig. 1 shows that the change of the tessellation parameters in CATIA (= 1 mm, SAG = 0.01 mm, SAG = 0.001 mm) in each case gave the number of 72 triangles describing the solid. The situation changes with the appearance of curvilinear surfaces. The model shown in Fig. 1 was rounded off all edges with a radius of 1 mm. This solid was also triangulated for which the change of the tessellation parameters in the CATIA program (SAG = 1 mm, SAG = 0.01 mm, SAG = 0.001 mm) in each case increased the number of triangles describing the solid successively from the value of 744 triangles to 3369 triangles and 22616 triangles (Fig. 2). Additionally, Fig. 2 shows a close-up of the edge rounding detail for specific mesh densities.

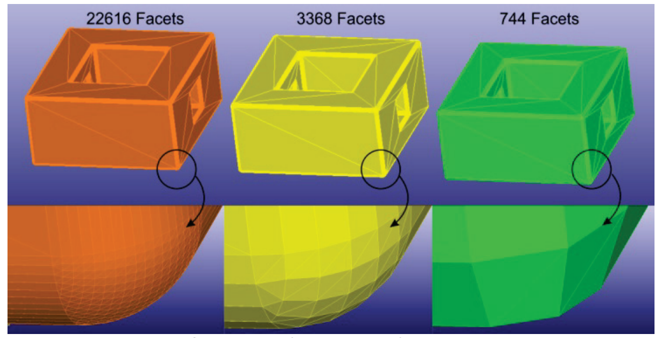

Figure 2 STL model of a test solid after edge rounding

Many coordinate measurement methods are based on the transformation of sets of points obtained because of measurements to the form of a triangle mesh saved in the STL format. This applies to both non-contact measurement methods based on laser scanning or structural light emission, where the triangle mesh is built on a set of points from the scanning of the object's surface, as well as volumetric measurement methods in which the triangle mesh is built programmatically on the basis of cross-section images as well as this is the case with computed tomography. In addition, the production of products based on the STL model can be carried out both using the STL model obtained because of the software transformation of the 3D-CAD model as well as the STL model obtained in the process of program processing of data from 3D scanning.

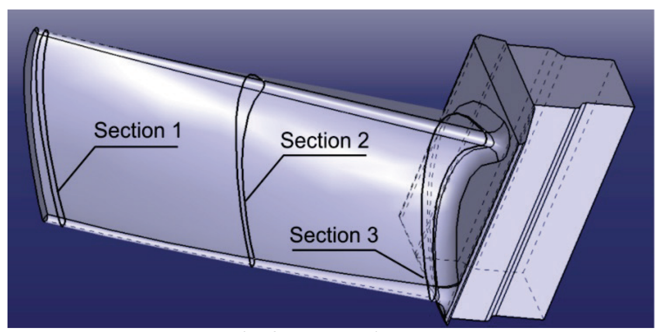

Figure 3 3D-CAD model of the test blade

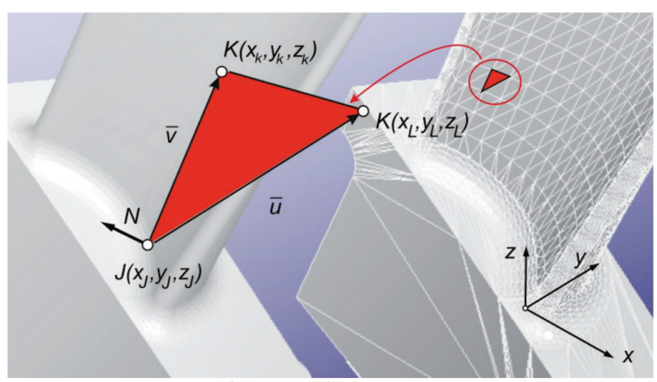

Figure 4 Parameters of the mesh of triangles describing the STL model

A good example for considering the accuracy of incremental methods and their dimensional analysis can be a blade of a fluid flow machine, with a pen described by curvilinear surfaces described in guide curves, the 3D-CAD model of which is shown in Fig. 3. The surfaces of the paddle blade must be transformed into a solid model, which, together with the lock, forms the basis for the transformation into an STL model. The correct STL model is completely covered with a mesh of triangles with normal points outside the model (Fig. 4).

The paddle model was subjected to a tessellation process using standard software settings (Fig. 5). Trials should be carried out for various values of the mesh describing the surface in order to optimize the accuracy of the mapping, the results of the analysis are presented in Fig. 6.

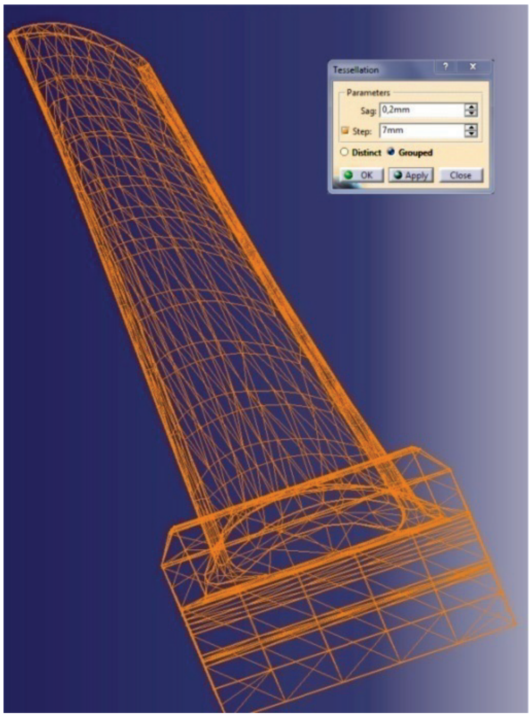

Figure 5 Test blade tessellation process

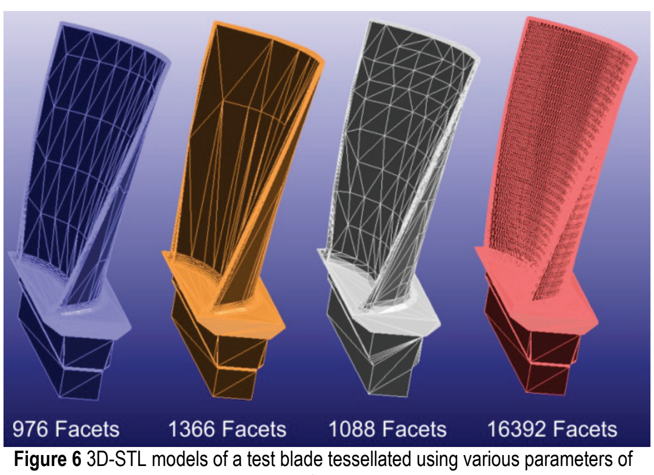

Figure 6 3D-STL models of a test blade tessellated using various parameters of the solid surface description

The 3D-STL model obtained as a result of exporting data from a 3D-CAD file should be of such accuracy that it can be used as a base model for the accuracy analysis of objects, the measurements of which will be carried out with the use of 3D scanning, as a result of which the STL model is also obtained (Fig. 7).

The software for dimensional analysis allows loading the base model and the model obtained from measurements into one file, and perform deviation analysis in the global system or in specific sections (Fig. 8).

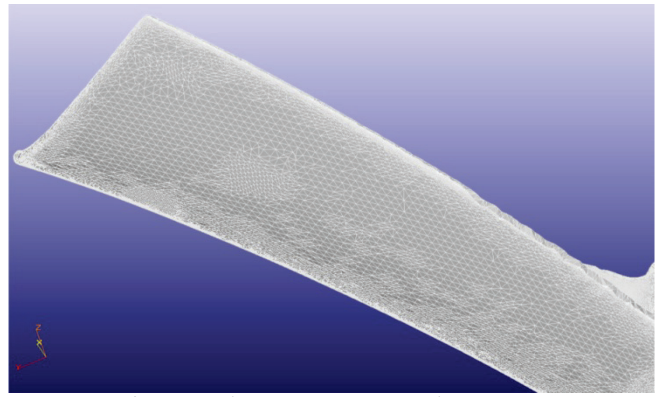

Figure 7 STL model of the blade obtained in the 3D scanning process

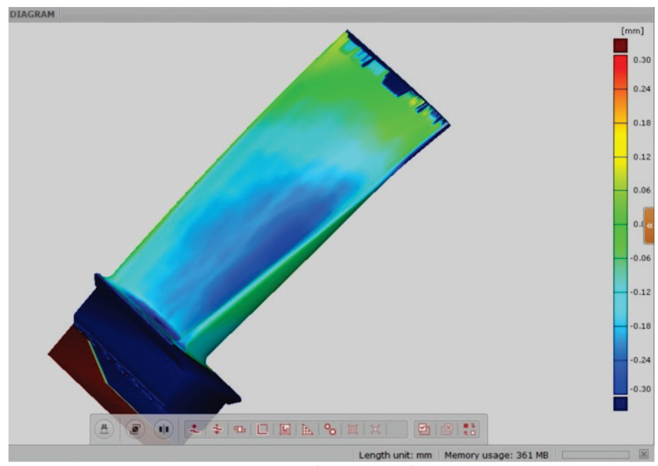

Figure 8 Analysis of accuracy of test blade

2.2 Preparation of Data for the Manufacturing Process

Preparation of data for the manufacturing process has a significant impact on the dimensional accuracy of additive manufactured products. In the first stage, the position of the model in relation to the coordinate system of the 3D printer should be determined. The next stage is the division of the model into layers of a certain thickness (Fig. 9) and preparation of possible transition paths in a given layer (if it is assumed by a given incremental process).

Algorithms controlling a 3D printer can differently determine the structure of the physical model in relation to the 3D-CAD model. For this reason, the model can be made with a negative tolerance (Fig. 10a), a mixed tolerance (Fig. 7b) and a positive tolerance (Fig. 7c). The reason for this is in most cases the inability to clearly map the model dimensions resulting from the nominal values converted to the 3D-AM format (e.g. STL) and the dimension values resulting from the division of the model into layers for a given additive technology.

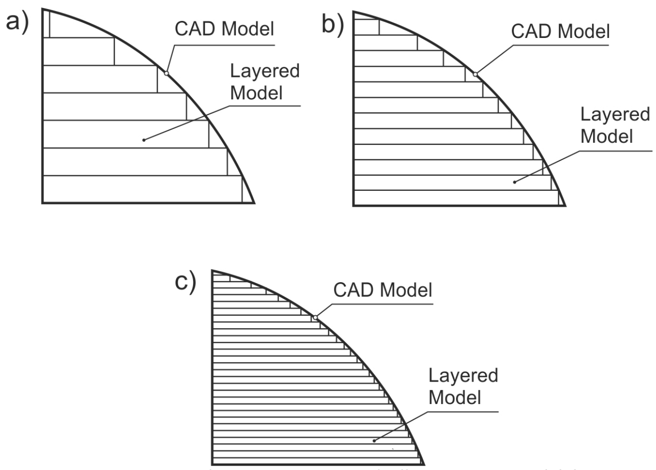

Figure 9 The process of dividing into layers of different thickness: a) 0.05 mm, b) 0.1 mm, c) 0.15 mm

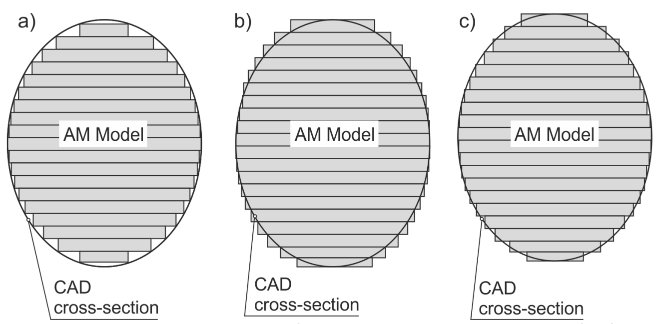

Figure 10 Determining the position of the layered model in relation to the 3D-CAD model: a) negative tolerance, b) mixed tolerance, c) positive tolerance

2.3 Incremental Manufacturing Process

The incremental manufacturing process is also a source of dimensional errors in the physical model. The accuracy of the products in this case is influenced by many factors, including they include: the progress of the incremental process, the kinematic accuracy of the mechanical system of the 3D printer, materials used for 3D printing, compensation procedures, environmental conditions, operating parameters and the condition of the devices. The issue of the accuracy of incremental processes is very broad and it should be analysed in detail for each incremental process, therefore it goes beyond the volume and content-related framework of this article.

3 MEASUREMENT METHODS USED TO ANALYSE THE ACCURACY OF PRODUCTS MANUFACTURING IN INCREMENTAL PROCESS

The accuracy of additive manufactured products can be checked using a variety of measurement methods, depending on the intended use of the product and the complexity of its shape. In the case of products with simple shapes and products with regular shapes, e.g. circular or rectilinear, where length or diameter measurements can be made, it is possible to use basic workshop tools, i.e. calliper type-measuring tools (Fig. 11). It is also possible to use gauges that allow, for example, verifying threads (Fig. 12). Products with higher accuracy can also be measured relatively quickly using micrometric measuring tools (Fig. 13).

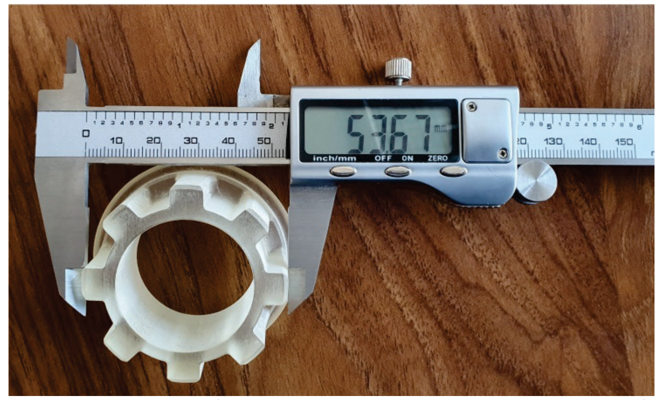

Figure 11 Measurement of the model made by the PolyJet method with the use of a calliper

Figure 12 Checking the correctness of the thread geometry of the cap model made using the PolyJet method with the use of a gauge

Figure 13 Measurement of the gear model made by the FFF method using a micrometer

The analysis of the dimensional and shape accuracy of products with complex shapes should be carried out using computer-aided coordinate measurement methods based on various methods of data acquisition and processing. These methods include contact coordinate measuring techniques, laser scanning with the use of scanning heads and handheld scanners, scanning with the use of structured light and computed tomography. An example of measuring a blade model using a coordinate measuring machine is shown in Fig. 14.

Models used in medical engineering are obtained based on images obtained in the process of computed tomography. An example of this is a model of the skull with a bone defect, for which a prototype of the defect restoration was developed, and the accuracy of the fit was based on the analysis of measurements made with an optical scanner (Fig. 15) or a computed tomograph [13].

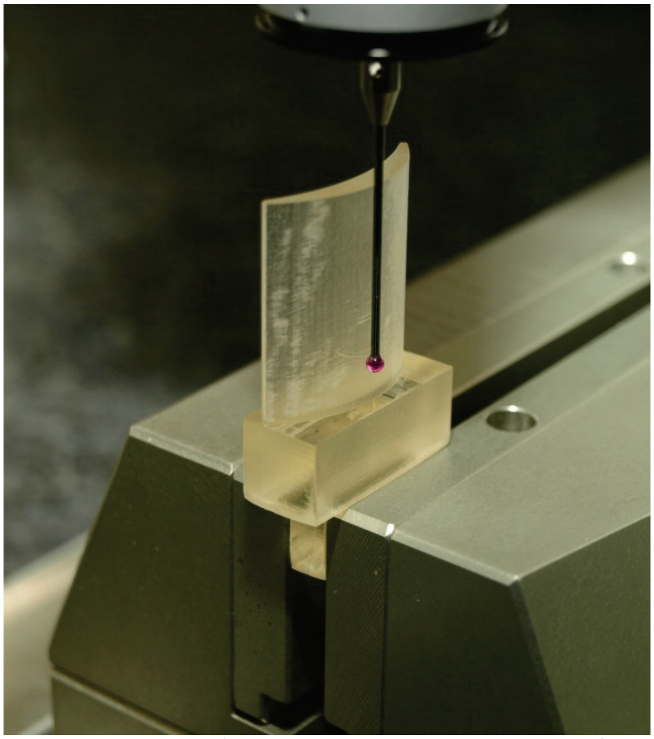

Figure 14 Measurement of the rotor machine blade model made using the SLA method with the use of a coordinate measuring machine

Figure 15 Optical measurement of the skull fragment model made with the 3DP incremental method with the bone defect

As can be seen from the analysis examples, additive manufactured products can be measured using various methods and tools. The selection of measurement methods should be dictated by both cost considerations and the time of measurements. Considering this, an attempt can be made to analyse the criteria for the application of measurement methods to assess the geometric accuracy of incrementally manufactured products, for example by adopting a three-level parameter evaluation scale: LOW – L, MEDIUM – M, HIGH – H.

Table 1 Characteristics of selected measurement methods

Characteristics	Workshop tools	Laser scanner	Optical scanner	CMM	CT
Accuracy measurement	M	M	H	H	H
Time of measurement	L	M	M	H	H
Data processing time	L	M	M	H	H
Measurement costs	L	M	M	H	H
Operator skills	L	M	M	H	H
Purchase costs	L	M	M	H	H

It should be noted, however, that the assessment included in Tab. 1 is relatively simplified and does not contain detailed data, but it gives a certain view on the possibility of using measurement methods at the initial selection stage. Product details and measurement methods can already be taken into account at a later stage. It is also possible to create a computer application that allows the selection of a measurement method for a given incrementally manufactured product, adopting specific criteria and input data. The application can function in this way both in the system of a production company, also as an application of companies offering measurement services and can be an element of a distributed system using modern network tools based on the Industry 4.0 structure.

4 CONCLUSIONS

The considerations presented in the article are preliminary with regard to the selection of measurement methods for products manufactured additively. It should be remembered that the processing of numerical data is particularly important and it should be taken into account already at the initial stage of designing the production process of a given product, for the production of which additive technologies will be used. The architecture of the quality control system in which IT tools from the Industry 4.0 area are used is also important. It is important to define access to data from measurement processes and to ensure the security of this data.

Based on the data collected in Tab. 1, it can be seen that coordinate measurement methods based on laser scanning or structured light emission work very well with the measurement of incrementally manufactured products. It is caused, among others, by in that these measuring dates are characterized by measurement accuracy higher than that of most additive technologies. These measurement methods use the same type of data as 3D printing methods, which greatly facilitates the processing of numerical data in the quality control process. In addition, the measurement time is relatively short, which is important from the point of view of the entire production process.

Coordinate measurement methods using contact measurements are rarely used for the evaluation of additive manufactured products due to the long measurement times.

Computed tomography is perfect for measuring products with complex shapes with closed spaces, as well as for analysing the internal structure of the product produced with incremental methods.

Notice

The paper will be presented at MOTSP 2022 – 13th International Conference Management of Technology – Step to Sustainable Production, which will take place in Primošten/Dalmatia (Croatia) on June 8–10, 2022. The paper will not be published anywhere else.

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