



## COORDINATE METROLOGY DATA MANAGEMENT OF MACHINE PARTS MADE BY METAL ADDITIVE MANUFACTURING

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**Abstract:** *The rapid development of Additive Manufacturing (AM) technologies has further highlighted the importance of coordinate metrology in the entire production process. AM often equivalent with reverse engineering (RE) and rapid prototyping (RP) in which the role of coordinate metrology is crucial. All AM technologies require (more or less) machine finishing operations, so coordinate metrology play key-role to production quality management. The paper will present two cases from practice: The first example is RE of the individual machine part that requires a higher scope of machining after production on 3D\_Print machines. The results of coordinate metrology are a key starting point of machining of complex spatial shape. Another example is the fast processing of the results of the optical (contactless) coordinate metrology of points cloud of mass production of turbine blades. The mathematical model was tested on the optical measurement results of the turbine blades produced by PBF-LB/M (Powder Bed Fusion - Laser Beam/Metal). The developed mathematical method is easily applicable to the serial production of aircraft turbine blades made with precise casting or forging.*

**Keywords:** *coordinate metrology, additive manufacturing, complex spatial forms, production quality.*

### 1. INTRODUCTION

The place and role of metrology, including coordinate metrology, is best illustrated by the words of William Thomson, better known as Lord Kelvin, spoken at the end of the 19<sup>th</sup> century: „I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.“[1]

The increasingly frequent application of additive manufacturing technologies in combination with classical machining technologies has put coordinate metrology in the foreground. In reverse engineering cases this is quite obvious but also in engineering "forward" coordinate metrology is a key factor in managing the quality of production.

The increasing use of contact and contactless measuring systems in production processes has greatly shortened the time delays between machining operations. If we add to this that complex spatial forms cannot be measured by linear measuring instruments (Vernier instruments), coordinate metrology has been given a role in the production process just as Lord Kelvin defined it.

In this paper, two case studies from the practice of applied coordinate metrology on machine parts made by AM

(Additive Manufacturing) laser fusion of metal powder in the build chamber (PBF-LB/M) will be presented.

Both machine parts are defined by complex spatial shapes; the first is an example is a rounded cycle of reverse engineering of the impeller (diffuser), after production on 3D\_Print in metal, must be finalized by milling machining.

Another example is the turbine blade of an aircraft engine, made 3D\_print in metal, for which it is necessary to quickly answer the question of whether it is in the required tolerances or not taking into account the mass production of these blades.

### 2. DESIGN FOR AM

The last decade has led to the full maturation of additive manufacturing. AM has experienced serious improvements and has become equal to classical technological procedures. This is the reason why it is increasingly being used in a diverse range of industries such as automotive, consumer goods, medical devices, aerospace, defense, etc.

Generally speaking, each machine part can be produced by applying different technological procedures, subtracting or adding materials. This is absolutely true if we ignore the time and cost of production. The role and task of the production mechanical engineer is to manufacture the machine part in the required quality in

the shortest possible time and at the minimum price. In the phase of designing mechanical parts, it is necessary to consider the planned technological process. It is clear that the design of sand cast parts is different from that of mechanical parts that are made by forging. This feature is called Manufacturability.

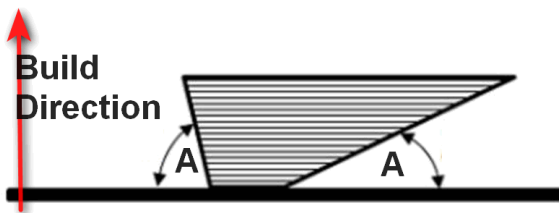
When we talk about the methods of adding and subtracting materials, different design features present completely different challenges in both production methods [2]. There are several factors that need to be considered in the design phase to efficiently produce parts using additive manufacturing. The basic characteristics of designing for classic manufacturing technologies in contrast to designing for additive manufacturing are shown in Table 1.

**Table 1.** DfMA vs DfAM [3]

<b>DfMA</b> (Design for Manufacture & Assembly)	<b>DfAM</b> (Design for Additive Manufacturing)
Focus on keeping the geometry as simple as possible	The complexity of the geometry increases the demand for AM
Segmentation of parts for easier production and assembly	Consolidation of the total number of parts / functions, increases the demand for AM
Designing within production constraints	The design goal is functionality, not limitation (bionic shapes and honeycomb/lattice structures are encouraged)

**2.1. Designing Rules for AM**

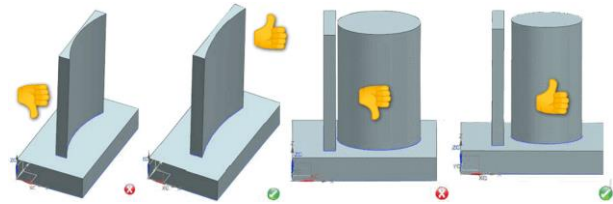
Although many scientific papers [2][3][4] and specialized journals articles have been written on the topic of design rules for AM, not a small number of engineers still do not understand the essence and reasons for these rules. This clearly indicates that the key is the education.



**Figure 1.** Faces requiring support

The rule that stands out everywhere as the first is illustrated in Figure 2: faces with an angle greater than 45 degrees in relation to the build direction must have support, Figure 1. The consequence of this rule is that machining (mainly milling) of the faces with the support is necessary. Additional machining increases the total manufacturing time and thus the total price of the final product [5].

Another important rule is shown in Figure 2. The minimum faces distances are generally constrained by the additive manufacturing method.



**Figure 2.** Minimum distance btw Faces [2]

The minimum thickness or minimum distance of faces directly depends on the AM method and the resolution of the machine itself. If it is not possible to avoid it, for various reasons, it is quite possible that post processing is necessary. Specifically speaking, any AM production requires post-processing, more or less. Minimally, it is necessary to treat it with sand or pellet and removing the auxiliary supports [7].

If at the design stage the geometry had to be thickened or widened due to AM technological limitations, the scope of additional machining will not be so small. In a case study, one such example will be explained in detail here.

The third follows from the previous two rules: minimum feature size (Pocket/Island/Text) or minimum hole diameter [2]. It should not be forgotten that during AM production, a large amount of heat is introduced, which can lead to unwanted deformations of the work piece. It follows from the previous that the relationship between the diameter and the height of the boss has its own limitations, which are an integral part of the AM design rules [6].

If we know AM is just another production technology, how an average designer can know all the design rules for AM but also for all classic technologies (turning, milling, casting, forging, bending, punching, molding...)?

How to apply all these rules quickly and immediately to a truck assembly with 10,000 components? Large ships, of course, have a million components! The solution of this task is the automation of the entire process. It is necessary for the designer to have at his disposal a service that, after activation, immediately gives an answer to the applying appropriate manufacturing technology of the all parts in the assembly.

**2.1. Automation of DfMA & DfAM Principles**

'Design for Manufacturability' or 'Design for Manufacturing' (DfM) is a methodology involves designing with intent to minimize the cost of production and time-to-market, without compromising on the quality of the product. In 1958 ASME (American Society of Mechanical Engineers) published a book it is explains the principles of *DfM*, although not used this term.

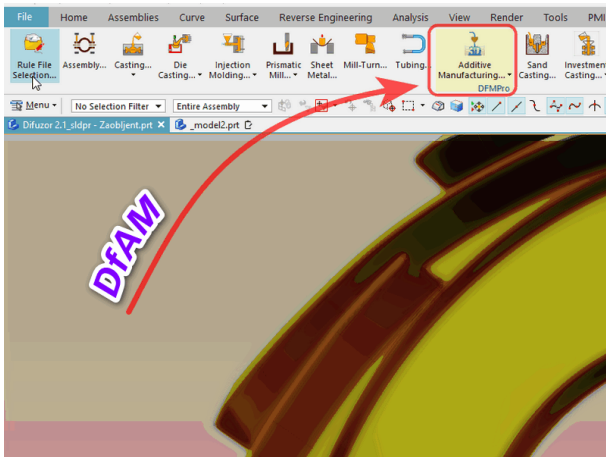
Manufacturability is not a new term, but automation of the application of this principle is necessary in the 21<sup>st</sup> century. DfM is a tool for designers, added to CAD, that facilitates upstream manufacturability validation and identification of areas of a design that are difficult, expensive or otherwise impossible to manufacture.

Rule Manager allows to manufacturing engineer to specify the rules which designer must to use. Rules are

saved by category which allows manufacturing engineer to customize the type of rules that are used for analysis.

*DfM* is CAD/CAM add-in, is shipped with the rule modules for Milling, Turning, Sheet Metal fabrication, Injection molding, Casting, Die casting, Welding, Additive Manufacturing and Assembly, Figure 3.

This add-on is available for all well-known *CAD/CAM* systems: CATIA V5, SOLIDWORKS, PTC Creo Parametric, Siemens PLM NX, SolidEdge, Autodesk Inventor. This add-in is applicable in very wide areas of mechanical engineering: Medical device, Aerospace and defense, Automotive, High-Tech Industry (smart devices) & Industrial Manufacturing.



**Figure 3.** *DfAM* Add-In for CAD/CAM [3]

The rules manager allows you to set the rules and parameters for a very wide range of different 3D printing technologies: Fused Deposition Modeling (FDM), Stereolithography (SLA), Poly-Jet (3DP), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Metal Powder Bed Fusion (MPBF). Similar to conventional machine tools, AM machines with different resolution and accuracy exist for the same technology.

Rule Manager allows to manufacturing engineer to specify the rules which designer have to use. Rules are saved by category which allows manufacturing engineer to customize the type of rules that are used for analysis [8]. Importance of the Rules are noted with following letters:

- {I} = Insignificant
- {L} = Low
- {M} = Medium
- {H} = High
- {C} = Critical

From all of the above, it is obvious that each production plant has its own rules that are specific and different from similar production plants. These differences may refer to the accuracy class, the size of the working space of machine tools, the number of degrees of freedom of simultaneous control, conventional and unconventional machining methods. These differences can be very large in cases where a factory does not have a technological process, e.g., sand casting. All this does not have to be known to the designer; the production facility can be

dislocated, in another city or even a continent.

The importance of designing for manufacturing is underlined by the fact that about 70% of manufacturing costs of a product (cost of materials, processing, and assembly) are determined by design decisions, with production decisions (such as process planning or machine tool selection) responsible for only 20% [8].

### 3. CASE STUDY – DIFFUSER

The first example is the manufacture of four diffusers, different geometries but very similar complexity. It is a classic example of *RE*; it has not any documentation, neither electronic nor paper. Diffusers are spare parts because they wear out during exploitation. Originally these parts made by sand casting and post processed by turning and milling.



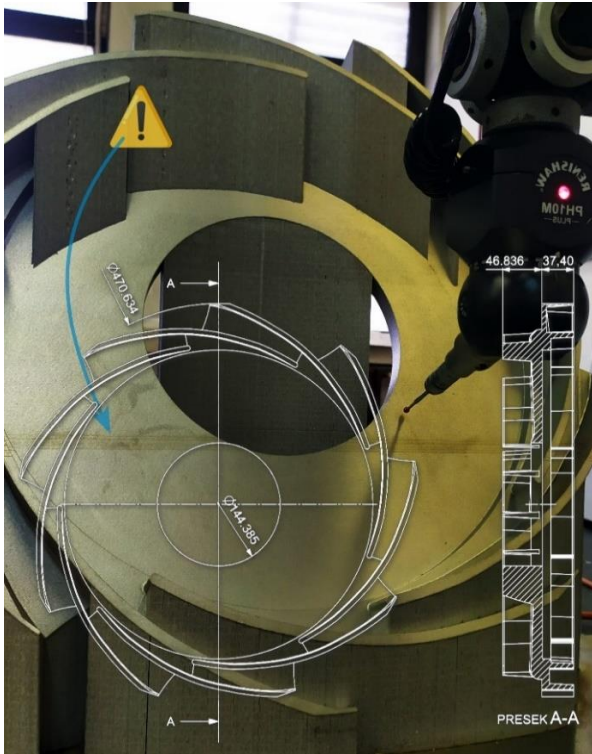
**Figure 4.** Diffuser N°3 on the CMM & touch trigger probe measuring path

The contracting authority requested a geometry redesign based on the submitted (damaged) sample and its manufacture from stainless steel. Considering that the working space of the AM machine in MTI is the largest in Serbia and amounts to 450x450x500 [mm], the maximum diameter of the diffuser (472mm) required building of parts inclined in the working space of the AM machine. This means that the build vector is not coincident with the axis of rotation of the diffuser. This required additional analysis after the redesign, Figure 3. Such an analysis cannot be carried out without a specialized *DfAM* module.

In the first step, CMM was used to generate the initial CAD model based on the sample. After, remodeling and customizing the design for AM making in metal powder was started. The submitted sample was designed for casting in sand and therefore had inclined faces for easier removal from the mold. The AM process has different

technological requirements and remodeling has been carried out so that the part does not lose its functionality.

After AM building of diffuser, before separating from the building plate, the diffuser is measured at CMM. Figure 5. shows the measurement of diffuser geometry N°2. on CMM; measurement results are shown in the same figure. All diffusers are made inclined, auxiliary supports are added to basic geometry. In Figure 4, auxiliary supports are highlighted. The same figure shows the trajectory of the measuring probe during the measurement of the primary datum plane.



**Figure 5.** Diffuser N°2 on the CMM & measured results

The task of measuring on the CMM is double: the first is to check if the designed geometry is in the required tolerances; Second, to precisely and accurately determine the datum features for the positioning on the milling machine for necessary post processing. Figure 4 shows the measurement path for determining the datum plane for the purpose of placing on the working table of the milling machine. The diffuser has no rectangular elements, and therefore angular positioning is critical and very tricky. The data obtained on the CMM must be clearly and unambiguously transferred to the operator on the milling machine.

In Figure 5, an arrow and an exclamation mark {! →} pointed an anomaly on the built diffuser. In one zone (strip) it can be observed that the color of the built diffuser is different. During the building of the diffuser, there was a disruption-interruption in the power supply. It is known for MPBF technology that interruptions in work due to very different reasons, are undesirable because it requires re-preparation of the working chamber as well as reheating of the working part. It was suspected that there were unwanted hollows inside the built diffuser, and for this reason the machine part was recorded with X-rays.

All the X-rays photographs showed that the unwanted hollows did not include the internal structure of the diffuser.

#### 4. CASE STUDY – TURBINE BLADE

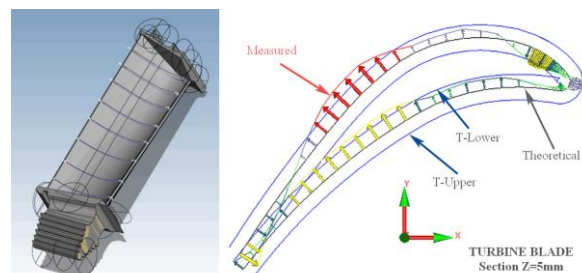
Another case study is an aircraft engine turbine blade, shown in Figure 6. The blade is small, much smaller than the diffuser from the first case study. It is built in metal powder by PBF-LB/M technology.

Aircraft engine turbine blades are made by precision casting or forging. The blades root is subsequently finished by grinding with a profiled grinder. The whole process is expensive because it requires using of complicated and very expensive molds. This is acceptable for serial and mass manufacturing processes. For the development phase as well as for small series, using the PBF-LB/M manufacturing process is cost-effective.



**Figure 6.** Turbine Blade built on an AM machine

All cases, single, small-series or large-series manufacturing necessarily require geometric inspection of the definition airfoils. A typical geometric inspection report of the airfoil of a selected section of a turbine blade is shown in Figure 7. The theoretical airfoil is shown undeformed, everything else is shown enlarged to make it easier to see: measured airfoil, upper tolerance limit and lower tolerance limit. The direction of deviation is shown by arrows. Deviations out of tolerance limits are marked with red arrows. The turbine blade was measured in 8 sections, shown on the left side of Figure 9. Each section was measured in 60 points (30 upper side + 30 lower side); that amount is a total of 480 measurement points.



**Figure 7.** Turbine Blade: geometric inspection [9]

The report in Figure 7 was made after measuring on a CMM with a contact probe. The whole process is not so fast, and its application on all manufactured blades of serial and large-scale production is economically unprofitable.

A new request was made to speed up the entire process but to keep the reliability of the conclusion high. Figure 9 shows the same turbine blade scanned on a CMM with a

laser measuring head. In the same picture it is indicated that the total number of scanned points is over a million.

More than a million measured points is much better than half thousand measured points only if it is possible to infer something from these results. If you have no conclusion then it is completely irrelevant whether you have measured a thousand, a million, a billion or a trillion points! A new approach necessarily requires the development of new mathematical models. This is one such case.

Optical scans have many advantages compared to contact methods, but also some disadvantages. The point cloud obtained by optical scanning often has false overlaps, dislocated zones and a unwanted noise. It is necessary to remove all observed irregularities and then reorganize the point cloud according to the desired structure. Figure 8 shows this step. Only the zones of interest for the required analysis were selected. Every cross-section, was represented via the same number of uniformly spaced parametric samples of the corresponding B-spline, enabling characterization of each airfoil using same dimension vectors [10].

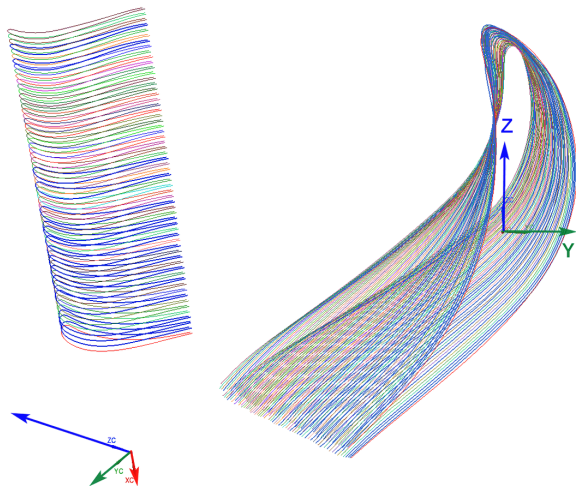


Figure 8. Turbine Blade: Reorganized points cloud

It is noticeable that the number of airfoils selected from the point cloud is much higher than the number of sections from Figure 9, but they will not be analyzed in the same way.

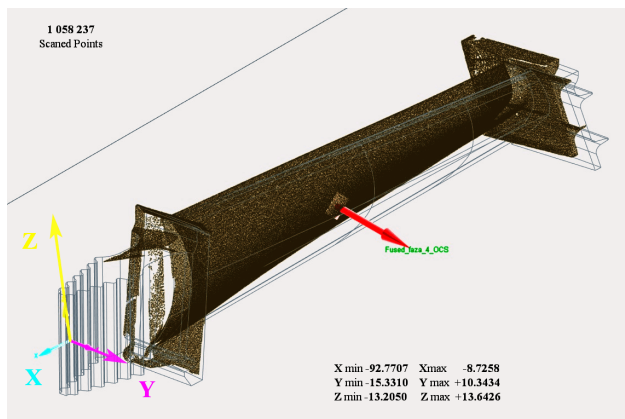


Figure 9. Turbine Blade scanned using CMM with laser

First, one of the sets of manufactured turbine blades is selected to represent the etalon piece. The selected blade is carefully and very precisely measured and analyzed, identically shown in Figure 7. This step is critical and must be done carefully and without rush. All other turbine blades will be optically scanned and that image will be compared with the image of the selected reference piece. This approach will give us a very quick answer to the question of whether the turbine blade is good or not, i.e., is its geometric image close to the reference turbine blade.

This approach is fully in line with the principles of the *Industry 4.0* concept, i.e. creating a digital twin. The approach combines production and metrological information so that they have their own digital twins for each stage of the production process, is called CPM<sup>3</sup> (Cyber-Physical Manufacturing Metrology Model), fig 10. This original concept was presented in a series of scientific papers at conferences organized by the International Academy of Production Engineering CIRP<sup>1</sup> [9]

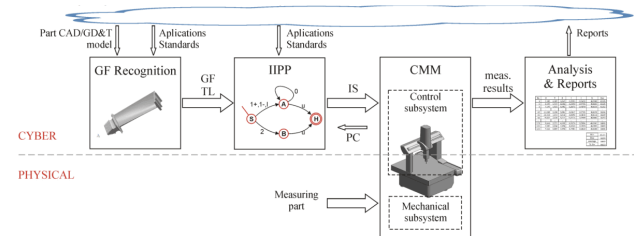


Figure 10. Structure of the CPM<sup>3</sup> concept [9].

Optical scanning generates a very large amount of data. If we add that it is multiplied with a large number of pieces, such as serial and mass production of turbine blades, it is clear that searching and processing large databases can take a lot of time even on fast computers. The described deficiency was overcome by the development of a special approach in the search of large databases [10].

In [10], a new and original concept of data curation<sup>2</sup> of large databases was proposed. The proposed methodology decomposes metrological data into a tree structure by grouping them into distance-based clusters. This approach, in comparison with traditional search methods, enables a logarithmic acceleration of the search and thus brings significant advantages.

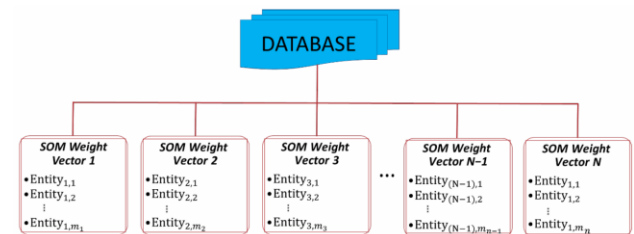


Figure 11. Database re-organization: Self-Organizing Map (SOM) [10].

<sup>1</sup> CIRP - French acronym of College International pour la Recherche en Productique

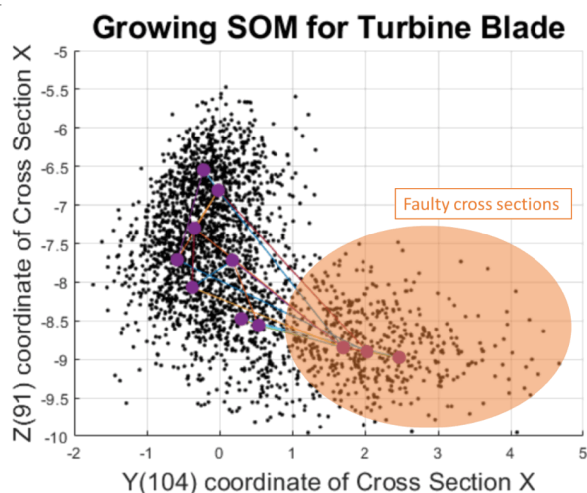
<sup>2</sup> Data curation is the process of transforming and enriching raw data into smaller, more accessible subsets.

In [10] is proposed using of growing Self-Organizing Map (SOM) based unsupervised clustering of metrology data to obtain clusters of database entries as Voronoi<sup>3</sup> sets.

For the purposes of testing the developed mathematical model, anomalies were artificially generated on the surface of the turbine blade in the zone between 2→3 [cm] from the coordinate origin, shown on Fig. 6.

Each black dot on Fig. 12 [10] corresponds to a turbine-blade cross-section, while each purple disk represents a cluster centroid in the tree-based database.

In Figure 12, it is clearly visible that the SOM centroids of the turbine blade with the faulty cross-section are displaced in relation to the centroids of the original reference turbine blade. The conclusion is clear and very reliable, this turbine blade must be rejected because its geometric characteristics do not meet the required geometric requirements.



**Figure 12.** A 2-dimensional projection of CMM data

The set goal was reached, we got a quick answer to the question: accept or reject the turbine blade. For large-scale and mass production, this approach is very useful. This approach is a supplement and not a substitute for a detailed geometric inspection of the turbine blade, Fig. 9.

## 5. CONCLUSION

The primary topic of the paper is a geometric inspection of machine parts complex spatial form. Both case studies showed a diverse application of coordinate metrology of complex spatial forms: parts of smaller and larger dimensions, contact and non-contact measuring methods, small and large number of measuring points, complete and partial geometric inspection. Both case studies were applied to machine parts manufactured by AM using PBF-LB/M technology process. Geometric inspection, in both case studies, had a double role: final geometric inspection and quality management of production process of subsequent necessary machining. Both case studies

clearly indicate the necessity of coordinate metrology in all stages of the production process taking into account all AM specificities.

Product quality management as well as the final quality of the product made of PBF-LB/M technology is very complex and multidimensional. The design phases should not be considered separately from the production process. Errors incurred in the design phase, as a consequence of non-compliance with the standards, affect the total price of the product. Previous chapters have been comprehensively processed the quality topic of machine parts made in PBF-LB/M technological procedure.

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<sup>3</sup> Voronoi partition is a geometric structure that divides a given space into the regions based on the distance to a set of the points called "seeds" or "sites".

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