Enrich STEP Models for Model-based Process Planning and Manufacturing

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Abstract. The use of the model-based definition (MBD) concept in manufacturing companies is important to streamline processes related to the design and control of finished products. However, there are no guidelines on how to take advantage of the opportunities offered by this approach in companies focused on the production of components with complex production processes. The conducted analysis showed that the information used in such production processes does not fit within the framework defined so far for MBD. To remedy the situation, the possibility of inserting additional information in a CAD model saved in a neutral STEP format was checked. A proprietary tool in the form of a workbench was also developed, which enables the use of the proposed solution in production environments and maximizes the benefits of its implementation. The results of the research can be used for future tests, changes in standards and definitions of CAD formats and the expansion of computer-aided design and process planning systems (CAD & CAPP).

Keywords: MBD, CAD & CAPP, process planning, manufacturing
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1 INTRODUCTION

Model-based definition (MBD) is a completely new approach to precisely defining (assigning attributes) of a product. Depending on the domain in which a given model operates, different product definitions are adopted. For example, for computer aided design (CAD), it is a set of geometric units and their relations. From a computer-aided process planning (CAPP) point of view, a product is the result of a series of successive processes. [4]

At the current level of knowledge, the model-based definition is strongly focused on the geometry of the designed product. It can also contain a number of additional information, such as dimensions, geometric dimensions and tolerances (GD&T), a bill of materials (BOM) and annotations. As shown in the article [7], it is possible to link material information using dynamic links to local zones on the model. The presented solution does not add additional information to the CAD model, but combines its features with information stored in an external source. Despite clear definitions and a long history of technology, there is still no standardized framework for presenting information [3]. Information about instruments, measuring gauges, and tools used during production are not stored in the models. Depending on the organization and infrastructure, they can be stored in dedicated database systems, work instructions or manufacturing operation sheets (MOS).

There is a research gap when you want to use a model-based definition for production and manufacturing. It will be discussed in this article and the data exchange framework for the technical preparation of production in the form of extended 3D models will be presented.

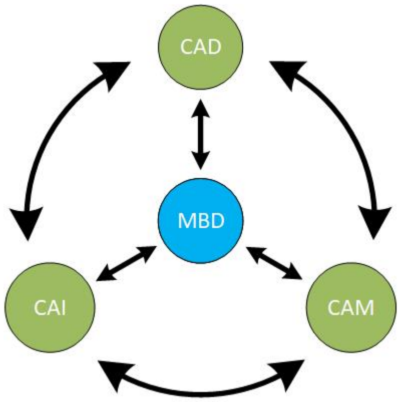
1.1 Model-based Definition

In rapidly changing environments, the essence of operating or project activities is the speed of responding to new requirements. This, in combination with the increasing complexity of products and the increasingly higher requirements, means that a new approach is needed that will accelerate the introduction of new products to the market.

A model-based definition is a concept that uses a 3D model as the main and complete source of information about a product. Information that has been placed and communicated using 2D drawings so far are stored as product manufacturing information (PMI), which includes: [2, 9]

- Dimensions
- Geometric Dimensions and Tolerances (GD&T)
- Surface finish
- Metadata
- Welding symbols
- Material specifications
- History of engineering changes
- Other digital information
- Annotations

This information may be displayed on the 3D model in human-readable or semantic computer-readable form. Linking this information with solid models allows for digital processing and connection of the areas of design (CAD), production (CAM) and control (CAI) and the exchange of information between them (Fig. 1). Each of these areas focuses on different tasks and may require specific information, but the basis remains the same as the geometric representation of the model.
While ASME (The American Society of Mechanical Engineers) and ISO (International Organization for Standardization) have developed standards for how parts drawings should look and how to interpret the annotations in these drawings, they are only sets of general good practices. Designers, or drafters in some larger teams, may use specific notations depending on the industry in which they work, or add additional information to the drawings, which do not meet the generally accepted recommendations. As a result, the full implementation of the MBD concept in manufacturing companies is associated with a number of technical problems that they encounter on their way. They are mentioned in article [17]. Depending on what kind of parts they refer to, the drawings may differ from each other. These can be drawings of individual machining parts, castings and forgings, weldments, general assemblies, and more. Each of these types requires the storage of information specific to it. This results in an average transposition rate of 96% for information transferred from drawings to models. It is also incorrect to assume that the transfer of annotations to models will shorten the time needed to prepare documentation due to the elimination of drawing preparation. However, the time needed to annotate the models is close to the time needed to prepare 2D drawings so far. [17]



mbd - cad cam cai.jpg

Figure 1: Information flow diagram

The primary industry standard for the presentation of geometric dimensions and tolerances (GD&T) on a 3D model is ASME Y14.41-2019 [2]. It has also served as the basis of the international standard ISO 16792 [9] Computer-aided design (CAD) software vendors use their own dedicated formats that are optimized for the software. However, neutral CAD formats such as STEP allow information to be transferred between different programs and the same file used in different processes. In the STEP format, the management of engineering data is governed by ISO STEP AP 242 [11]. There are other neutral CAD formats available for data exchange. The most popular are JT, QIF, 3D PDF. Each of these formats has an advantage in a particular situation.

3D PDF is a document exchange format, based on its PDF prototype, which has been perfectly accepted and continues to enjoy unflagging popularity of the document exchange format used all over the world. By using the Universal 3D (U3D) format, 3D PDF allows you to embed 3D graphics generated on the basis of a CAD model in your documents. Therefore, it is perfect for presenting the PMI. However, it has very limited possibilities of computer processing and use in other areas.

Quality Information Framework (QIF) is an integrated model for storing data related to product quality. The most recent of all formats was prepared for the needs of quality information processing in production processes. [12] In addition to the information on the model geometry and PMI data, the QIF format can also contain and store information about the measured actual values of the characteristics on the manufactured components, which can be used in processes such as Advanced Product Quality Planning (APQP), Production Part Approval Process (PPAP), Failure Mode and Effects Analysis (FMEA), Measurement Systems Analysis (MSA), Statistical Process Control (SPC) and First Article Inspection (FAI). Another major benefit of QIF is its ability to be extended via XML schemas. This makes it very attractive in the context of using it as a medium for data exchange between systems; however, the low support at the moment makes it impossible to use it in all systems.

Jupiter Tessellation (JT) is a lightweight format for exchanging CAD models. It is characterized by a small size (1-10% of CAD file size) compared to the same model saved in a different format. This feature makes it ideal for cooperation and data exchange via the Internet, and as a long-term archive option in Product Life Management (PLM) or Product Data Management (PDM) systems. Saving data in binary form (as opposed to other formats) makes it extremely efficiently processed by systems, even if it contains assemblies consisting of tens of thousands of elements, but it prevents its extension and adding additional information beyond the definition referred to in the specification.

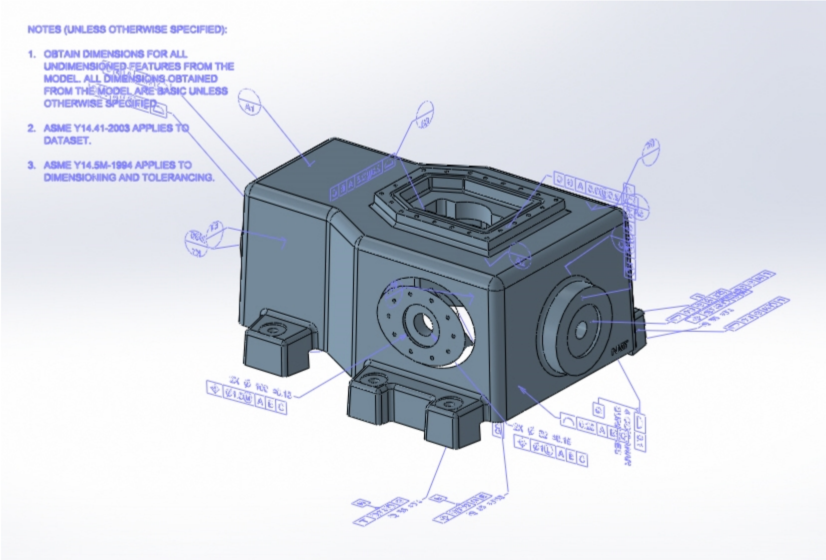


Figure 2: 3D model with a graphical representation of the PMI

1.2 Computer-Aided Process Planning

Computer-aided process planning is a class of systems supporting technological process design as well as production planning and control. Chlebus aptly described this in his study as a combination of "what and how" with "where and when"[5].

Thus, it can be assumed that the production process is a series of consecutive steps commonly called "operations", the number of which is due to the complexity of the finished product. Each of these steps requires certain data (elements) at the input and on their basis, as part of processing or performing specific tasks, the output meets the assumed requirements. The steps are also closely related to each other. For example: a fragment of the input data will be the result of the previous step, and the result will be part of the input data of the following step.

Modern CAPP systems use a number of advanced computer techniques, including: neural networks, optimization, fuzzy logic, artificial intelligence and others. [14]. Despite the use of these techniques, the role of CAPP systems is very limited due to the lack of complete information on the requirements defined in the CAD model. Planning of the process takes place only on the basis of the identified features extracted from the model body and to the extent required by CAM systems.

1.3 Industry 4.0

Although Industry 4.0 affects many areas and fields, it is based on six main principles: [8]

- interoperability
- virtualization
- real-time capability
- decentralization
- service orientation

- modularity

From the point of view of the research problem discussed, the following are important: interoperability, decentralization and modularity. Interoperability means that, depending on the scale considered, elements of systems or even entire systems are compatible with each other and are able to cooperate and exchange data with other existing elements or those to be created in the future without limiting their possibilities. Decentralization, in turn, is a change in the concept of systems architecture. Instead of the current supervisor who supervised the proper allocation and implementation of tasks, we have a number of smaller ones, but which are characterized by a certain autonomy in the operation of cells that continue to perform tasks. They do not send the results to the supervisor, but exchange data with each other. The last principle, or in this context a feature of the systems, is their modularity, i.e. defining system functions in such a way that they can be easily combined with other functions (modules).

The intense growth and rapid shift towards model-based design (MBD) and model-based enterprise (MBE) may suggest that some kind of revolution is taking place. CAD, CAE, PDM and PLM systems are aging, and their existing definitions and capabilities no longer meet the expectations of modern engineers. Industry 4.0 defines the product life cycle and the way it is managed in a completely new way, and the MBD strategy is its important element and plays a key role. The benefits of moving to a model-based definition and the challenges and risks are described by the authors [6, 1, 16, 15]. The advantages undoubtedly include simplifying data management and ensuring better communication, eliminating unnecessary documents and drawings from processes, and improving data consistency, improving processes and supporting computer-aided technologies. In addition to the benefits mentioned above, implementing MBD throughout the product lifecycle will also be challenging. A cultural shift will be needed to use annotated models instead of 2D prints. It is also very important to fully understand the semantics of the product information hidden in the drawings and fully transfer to the form of the 3D model and make sure that no information relevant to the manufacture of the products has been lost during this transition.

1.4 Research Goals

The primary research goal is to develop a runtime environment that will allow the development of complete production processes based on the MBD concept. The currently available CAD-model saving formats, in accordance with their specifications, do not allow for the storage of data necessary for production planning and technological preparation of production. The article also presents the framework for data exchange and archiving in CAD models. This framework was created in the form of extending the existing possibilities of recording and storing information provided for by the STEP AP242 standard by means of comprehensive description structures of digital twins. The main purpose of this article is to describe the framework for the extended CAD model structure and to illustrate the implementation with an example use case.

2 APPROACH

In order to correctly identify what data CAx systems exchange, it is worth referring to the diagram that the author of [5] presented in his study. It shows a network of connections between the systems and an exemplary percentage share in the information provided. It is therefore a classic example of a many-to-many relationship. Thus, each of these systems will require information from the others, and, at the same time, will share its information with them. Such a solution is possible to implement when building a complete environment from scratch. However, if one or several systems already exist in the environment, the implementation of a new one or modification of the existing ones is difficult and the expected benefits resulting from the implementation of the change are reduced by the limitations of the existing environment. The new approach presented in this article allows to overcome these limitations and improve the exchange of information between systems.

According to the principles of Industry 4.0, a modern CAE environment must be interoperable, decentralized and modular. This can be done if the CAD model is the element that will hold the individual systems in the environment together. For this purpose, the STEP AP 242 format will be used, which has been extended with the possibility of storing additional information. The choice of this format is not accidental, because it is characterized by elements important from the point of view of the described solution:

- standardization
- standardization
- geometry representation as boundaries
- stored as a plain text
- susceptibility to modification
- possibility of adding additional content

According to the international standard ISO 10303-21 [10] STEP format is written in plain text using the characters of the alphabet encoded according to the UTF-8 scheme, defined in the ISO 10646 standard [13]. It therefore means that the STEP format is readable by both humans and machines. Depending on the area of use in the STEP format, different STEP application protocols (AP) are distinguished. The most popular of them are:

- Part 203: Configuration controlled 3D designs of mechanical parts and assemblies
- Part 210: Electronic assembly, interconnect and packaging design
- Part 214: Core data for automotive mechanical design processes
- Part 238: STEP-NC Application interpreted model for computerized numerical controllers
- Part 242: Managed model-based 3D engineering

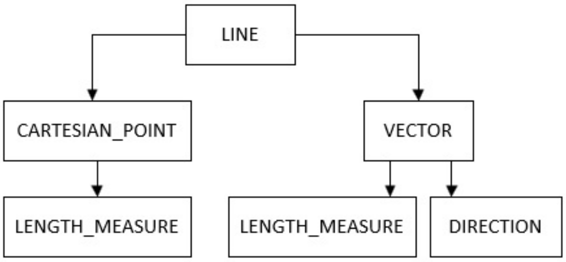
Some APs can be related to each other through the same set of integrated resources (IR), meaning they use the same definitions to describe the same information, e.g. 3D geometry. [18] The structure of the STEP format content is described in unambiguous templates defined using the EXPRESS language. For example, the template "AP242 managed model based 3d engineering - EXPRESS MIM Long form" in version 1.101 consists of 29 constants, 449 types, 2,118 entities, 316 functions and 55 rules. Entities are the basic elements that describe the contents of a CAD model and can contain such properties as references to constants, types, or other entities. Entities can also be related to each other on the basis of the SUBTYPE (child) and SUPERTYPE (parent) relationships, where they inherit their properties from a parent entity (SUBTYPE OF), or transfer their properties to a child entity (SUPERTYPE OF). An example of the definition of entities in the EXPRESS scheme and the scheme of connections are shown in Fig. 3. The EXPRESS scheme for STEP AP242 referred to above defines only the elements for storing 3D geometry and PMI characteristics in the CAD model. For different APs, there are different schemas in which different entities can occur. This property was used to develop a new EXPRESS scheme that allows to store information used during the technological preparation of production and to collect data from the course of the production process. When defining new entities or other components, however, the existing convention should be adhered to in order to comply with existing standards, which will allow the implementation of the new schema in existing CAD systems. The second research problem was finding a method to place and store new information in a CAD model file saved in the STEP format. Initial analysis of the documentation and review of sample 3D models provided by the National Institute of Standards and Technology (NIST) found that each 3D model saved in STEP format consists of the opening keyword "ISO-10303-21" and five optional sections for various purposes:

- HEADER - is a header that matches and stores information about the description, name, and schema of the file

```
ENTITY line
  SUBTYPE OF (curve);
  pnt : cartesian_point;
  dir : vector;
WHERE
  WR1: dir.dim = pnt.dim;
END_ENTITY;

ENTITY cartesian_point
  SUPERTYPE OF (ONEOF(cylindrical_point,
                      polar_point,
                      spherical_point))
  SUBTYPE OF (point);
  coordinates : LIST [1 : 3] OF length_measure;
END_ENTITY;

ENTITY vector
  SUBTYPE OF (geometric_representation_item);
  orientation : direction;
  magnitude   : length_measure;
WHERE
  WR1: magnitude >= 0.0;
END_ENTITY;
```



schema.jpg

Figure 3: An exemplary definition of a subject in the EXPRESS schema (left) and a diagram of connections (right)

- ANCHOR - is the section where the names of external instances are located
- REFERENCE - this section references external documents or specifications
- DATA - stores information about geometry and annotations
- SIGNATURE - signatures confirming or guaranteeing the compliance of the file and protecting it against unauthorized modification can be stored here

Each of the listed sections must always be terminated with the keyword "ENDSEC;".

The test steps are presented in Fig. 4. In the first part of the tests, specially created files with 3D models were prepared. The change consisted in adding individual elements to the existing sections in the code of the file. From the point of view of the data types to be added to the STEP file, only two sections are suitable for this: HEADER and DATA. According to the documentation of the ISO 10303-21 standard, both sections allow the storage of user-defined entities; however, they must be marked accordingly. This means that all entries not falling within the standard and appropriately marked should be ignored and omitted at the stage of loading the STEP file content by the CAD program. [10] A new entity, undefined in the EXPRESS schema,

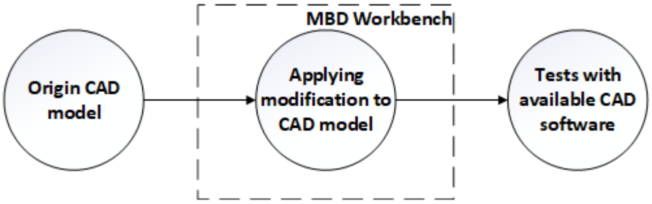


Figure 4: Preparing and testing process of enriched models

was placed in sample I. In sample II, the same entity was placed in the same place, but marked as user-defined, in accordance with the provisions of ISO 10303-21. The method of assessing the correctness of modifications and introduced changes was the opening of a modified file in the most popular CAD systems currently available on the market, enabling the opening of 3D CAD models saved in the STEP AP 242 format: Catia V5R30, SolidWorks 2020, Siemens NX 1911, Inventor, MBDVidia. The test results are presented in the table 1.

Table 1: Test results for specially prepared files with 3D models.

CAD program	Change in HEADER I	Change in HEADER II	Change in DATA I	Change in DATA II
Catia V5R30	no error	no error	no error	no error
SolidWorks 2020	no error	no error	no error	no error
Siemens NX 1911	error	error	error	error
Inventor 2021	no error	no error	no error	no error
MBDVidia	no error	no error	no error	no error

In the second part of the tests, it was established that the data prepared for inclusion in the file with the 3D model will be previously grouped according to their type and nature. Thus, three groups of data were created:

- TOOLS
- PROCESSES
- RESULTS

and additional sections have been placed in files. Again, attempts were made to open files in the most popular CAD programs. The test results are presented in the table 2. It can be seen that some of the tested programs were unable to open the modified file. This in no way limits the ability to define subsequent groups according to the identified data types, but reduces the group of programs that allow working with modified models.

Table 2: Test results for adding specific sections to the STEP file.

Program CAD	Add section TOOLS	Add section PROCESSES	Add section RESULT
Catia V5R30	error	error	error
SolidWorks 2020	no error	no error	no error
Siemens NX 1911	error	error	error
Inventor 2021	no error	no error	no error
MBDVidia	error	error	error

3 WORKBENCH

The new approach to adding annotations to 3D models presented in the article goes beyond the framework defined in the standard for the STEP AP 242 format. Therefore, it is impossible to use this solution in CAD systems currently available on the market. However, it is possible to develop a dedicated system that will complement the previously prepared 3D model with the information entered by the technologist. Based on the proposed framework, a prototype workbench has been prepared, which enables the loading of a 3D CAD model saved in the STEP AP242 format and then processing it in accordance with the adopted rules. An example of the use of the program and the user interface are presented in the figure 5.

Figure 5: An example of using the program. A - module responsible for displaying the graphic representation of the model, B - preview module of the STEP file source code

The program consists of many modules that correspond to specific functions. The basic function of the program is importing 3D models; the program enables the presentation of visualization of the geometry of the saved model and graphic representations of PMI annotations, as well as its manipulation and rotation in space. Other functionality available in the program is the ability to preview the source of the STEP file and modify it. The following modules constitute the core of the program as they enable the implementation of the assumptions and approach presented in this article. These include reading the semantic representations of PMI annotations and the ability to define and add new entities to the model and logically link them to the PMI and geometry features of the 3D model. The last and no-less-important function is the module for managing the actual values of the characteristics defined in the 3D model.

4 IN-USE CASE

The diagram of using the framework in production conditions is presented in the figure 6. The 3D model of the product is prepared in one of the available CAD programs. From the point of view of the functionality of the entire framework, the necessary condition for choosing the right CAD program is the ability to export the model to the STEP AP242 format, thanks to which it will be possible to store PMI annotations and constitute the basic requirements of the MBD concept. The 3D model prepared in this way is imported to the workbench, where it is supplemented with information used in the production process or production preparation, and then placed in the PDM system, which is responsible for its management, storage and distribution to the target places of use. The model can be used in CAM software to prepare a control program for a CNC machine tool (Computerized Numerical Control). Thanks to the PMI annotation on the model, it can be successfully used to prepare a complete measurement plan on CMM (Coordinate Measuring Machine) machines. The software controlling CMM machines are already mature enough to allow automatic generation of measurement plans based on models prepared in accordance with the MBD concept. Other important places to use enriched 3D models are integrated and automated manufacturing stations. Such positions are most often prepared especially for the clients' requirements, and because that they are built of automatic lines or robots, they require a supervisor to control them. The implementation of the extended CAD format proposed in the article in the service supervisor will enable the process to be controlled depending on the parameters set in the model.

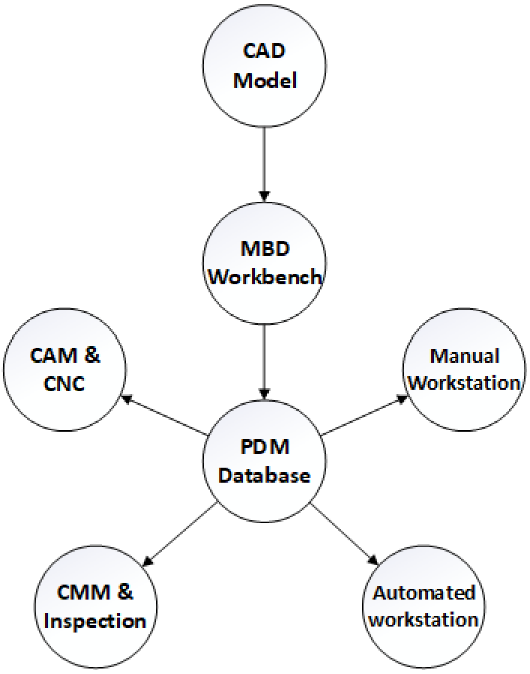


Figure 6: Workflow diagram.

An example can be an automatic line for performing heat treatment, where the supervisor, after reading the appropriate model, determines the process parameters (e.g. temperature and time of batch annealing) and the sequence of steps necessary to perform the operation in order to obtain the required properties. The last, but no-less-important, place to use the models are workstations, where the tasks are partially or completely performed by the operator. Its station is equipped with a digital desktop. It can download the appropriate model from the PDM system and then process it and display to the operator information relevant to the performance of his tasks, e.g. a list and sequence of activities to be performed, product properties to be achieved or a list of instruments to be prepared. The examples mentioned are only some of the possible areas and data that do not fully exhaust the possibilities of the approach presented in the article.

5 DISCUSSION

As presented in chapter 2, it is possible to add additional information from CAD models saved in the STEP AP242 format. Admittedly, not all of the tested computer aided design programs allow correct opening of modified files, even if the modification is within the ISO 10303-21 standard. Therefore, you can see a rather loose approach of software producers to meeting the requirements of the mentioned standard. Although the STEP AP242 format was used in the research referred to in the article, it is possible that similar results can be obtained using a different format.

A proprietary program has been prepared to present the results, which is an independent part of the presented framework and the entire system. From the point of view of ergonomics and work efficiency, it seems reasonable to integrate its functionality with existing CAD programs or CAPP systems.

Chapter 4 presents the practical use of the prepared approach. The examples, although simple, by no means fully exhaust its possibilities, which largely depend on the profile of the company's activity, using them as well as the scope and complexity of data used for the purposes of product definition, technological preparation of production, and the production itself.

6 CONCLUSIONS

The presented article presents a completely new approach to defining CAD models within the MBD concept. Industrial plants that are trying to implement this concept in their environments have so far faced difficulties such that not all information that was previously included in 2D drawings can be transferred to 3D models using currently available tools and methods. This required the development of an additional way to exchange missing information. In this case, we cannot talk about the implementation of the MBD concept, as the model is then not the only medium for information exchange. The solution to this problem are the results presented in the article. At the same time, they constitute the foundation for the construction of MBE systems.

The conducted tests and the obtained results allow to assume that a properly modified file that stores a 3D model saved in STEP format can store additional information and serve as a data exchange format for the technological preparation of production in accordance with the MBD concept. Information stored in such a model can be used to extend the existing CAPP systems with the possibility of planning complete production processes, including special processes such as heat treatment, applying protective coatings or finishing the surface condition.

The same information, thanks to its semantic form, can be processed by machines and used to prepare work in autonomous production centers. This approach is consistent with the idea of Industry 4.0 and its main principles mentioned in chapter 1. This solution may also contribute to reducing the time associated with implementing new products into production or introducing modifications to existing ones. Manufacturing companies using such a solution will be able to more efficiently respond to changing conditions.

The last important aspect is the possibility of storing the actual values, characteristics defined on the 3D model and data from process recorders. It also fits the current trend of collecting data and then analyzing the collected information in order to assess the capacity and maturity of production processes.

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