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# Digital Transformation - Implementation of Drawingless Manufacturing: A Case Study

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**Abstract**

The typical procedure in the product development process is based on the fact that 3D CAD models of the product are created at great expense with great effort. Such a 3D model contains all geometric information about the product, and this information is available in machine-readable, digital shape. In practice, it is still common today to create only 2D technical drawings for manufacturing and quality inspection from this wealth of information. Leading software systems offer the option of adding 3D annotations directly to the part instead of 2D drawings, so that product and manufacturing-relevant information is also available in digital shape. However, many companies are deterred by the enormously costly and extensive transition to Model-Based Definition (MBD), as several factors, such as the elimination of technical drawing, data management, hardware, and software infrastructure, must also be considered in the supply chain. This paper describes a case study from conceptualization to full-scale implementation of drawingless product definition via the CAD-CAM-CAQ chain in a leading large enterprise in Austria. As a result of the centralized machine- and human-readable information provision, not only the creation and maintenance of data has decreased, but also processes downstream of construction, in particular the control program generation for machine tools and coordinate measuring machines, can be automated to a high degree with the two key technologies Feature Technology (FT) and MBD. Automation of control program generation has the advantage of significantly reducing costs and applying best practice manufacturing processes. In addition, it enables to calculate the precise manufacturing costs already at the construction stage.



*Keywords:* Drawingless Manufacturing; Model-Based Definition (MBD); Product and Manufacturing Information (PMI); Feature-Technology (FT); 3D-Master

## 1. Introduction

Even after half a century of digitization and amid the age of Industry 4.0, there still exist methods and processes in manufacturing that, from today's perspective, are outdated. Such a process is the creation of technical drawings.

It is still common to create 3D Computer-Aided Design (CAD) models of the product with great effort and afterwards a 2D technical drawing from this wealth of geometric 3D data. The technical drawing, which usually contains orthogonal projections of the object and manufacturing-relevant dimensions, tolerances, surface finishes, and other metadata, serves as one of the main information carriers throughout the entire Product Development Process (PDP). The fundamental problem of the data and information contained in the technical drawing is that the data located in the drawing cannot be processed by machine for important and expensive subsequent processes. On the other hand, the 3D CAD model, from which the technical drawing is obtained, already contains all the geometric information about the product, and this information is available in machine-readable, digital form. Leading software systems offer the possibility of providing 3D annotations directly on the part instead of the 2D drawing so that the Product and Manufacturing Information (PMI) are also available in digital form. Nevertheless, the practical conversion from drawing to MBD seems to be a significant hurdle for many companies, even though the transformation would bring significant benefits.

This article highlights the challenges of implementing MBD with Siemens NX. The focus is on the advantages as well as the software limitations and the downstream use of machine-readable data in Computer-Aided Manufacturing (CAM) and Computer-Aided Quality (CAQ). The applied approach and the experience gained in this article are based on a case study in which a large company in Austria realized the implementation of MBD with Siemens NX.


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## 2. Related work

MBD and the machine-readable data obtained from it enable the automation of downstream processes. The following subsections discuss areas and critical technologies required for this.

### *2.1. Model-Based Definition (MBD)*

Driven by the aerospace and automotive industries, the American Society and Mechanical Engineers (ASME) came up with the concept of MBD and the standard ASME Y14.41 [3] in response to the need to use 3D data for manufacturing and quality inspection as well.

MBD means that PMI, such as dimensions, tolerances, and surface finishes, are attached directly to the 3D CAD model as 3D annotations. With this approach, no 2D derivation is performed for the preparation of drawings. The PMI are directly associated with the 3D CAD model and can serve as machine- and human-readable information carriers for subsequent processes. The ISO 16792 [7] standard was drafted based on the ASME Y14.41 standard. Both standards describe the correct handling of PMI to the designer from the user's point of view. In a broader sense, the two standards also specify which functionalities should be covered by the application system. One such core function is the bidirectional association between the machining feature and the PMI. Only this function allows the PMI to be assigned to the machining feature in a machine-readable way. The International Organization for Standardization (ISO) 1101 standard [6] refers to the preparation of 2D drawings as well as to the attachment of PMI to the 3D model.

### *2.2. 3D-Master*

With the elimination of the information carrier in the form of the technical drawing, the data management and structure in dealing with MBD data must also be reconsidered. In the traditional approach, several documents are usually scattered throughout a company, e.g., technical drawings, work plans, and inspection plans. With the omission of the technical drawing and digitization across the entire PDP, the term 3D master has become established. The term 3D master refers to the central provision of a leading information carrier so that everyone accesses only this one data carrier, which is the so-called Single Point of Truth (SPOT). In case of a change or revision of a part, everything is up-to-date throughout the entire value chain utilizing the 3D master [10, 9]. In addition, the concept of front-loading is significantly supported via the 3D master. Front-loading considers product development as a bundle of problem-solving cycles, so that faster product development can be achieved by generating earlier problem- and solution-related information. Faster problem solving is realized by using advanced technologies such as Computer-aided Technologies (CAx) [14].

In addition to the 3D master, the Verband der Automobilindustrie (VDA) recommends a data management concept using Drawing-Free Process (DFP) containers by VDA 4953-1 [16] and VDA 4953-2 [17]. A DFP container consists of both alphanumeric, non-geometry-related metadata and geometry-related 3D data, including PMI, so that all product data is represented in a digital form. This primarily enables a more efficient, partly automated creation of data, simple maintenance, and further electronic processing. Another goal of data management, according to the DFP container principle, is that there should be no redundant information acquisition on various CAx and Product Data Management (PDM) systems.

### *2.3. Feature Technology (FT)*

Features are information technology elements that describe an area of particular technical interest [19]. In general, feature-based models are created in CAD. These features are prismatic 3D machining features and include the machining features such as slots, steps, pockets, and holes [1]. Usually, feature-based models established on feature recognition and feature-based design are used to integrate Computer-Aided Design and Manufacturing (CAD/CAM) [15]. A feature provides a specific view of the product description, which is related to particular property classes and certain phases of the product life cycle, and thus supports a wide variety of activities of the individual departments along with the product creation chain.

Feature technology switches from a part-related macro perspective to a feature-related micro perspective. With the focus on machining features and the approach that both geometric information and PMI are available from the shape feature, machining features can be improved throughout the PDP. This feature-related perspective allows following a Knowledge-Based Engineering (KBE) concept, where frequently occurring machining features are modeled via User-Defined Features (UDF), which provides all product, operation, and resource information necessary for product manufacturing [20]. This approach enables a modular principle in product development with those machining features that are already standardized, optimized, and (partially) automated in the company. In the case of automation, the most significant added value lies in the automatic control program generation of machine tools and coordinate measuring machines.

### *2.4. Automatic control program generation*

One of the most significant advantages of drawingless product definition and persistent model-based data continuity in the CAD-CAM-CAQ process chain is the ability to automatically create control programs for machine tools and coordinate measuring machines. Since the new Geometric Product Specification (GPS) standards are no longer example-based but rule-based, control program generation can be standardized, optimized, and automated. Regarding the drawingless manufacturing in Siemens NX, the study of Stanasel et al. have shown that the time required for the creation of Numerical Control (NC) programs is reduced. In addition, the standardization of the manufacturing processes contributes to the reduction of programming errors, and the automatism realizes the elimination of the programmer's repetitive work. [13].

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Hedberg et al. compared model-based with drawing-based processes. On average, the results of the study showed that a 74.8% shorter cycle time could be achieved via the model-based approaches in manufacturing and inspection [5].

### 2.5. Implementation of MBD

The following publications refer to the implementation of MBD, and show that a reasonable conversion can only be done step by step. The VDA describes two expansion stages of MBD: (1) VDA 4953-1 [16] describes a transitional phase in which the use of simplified drawings is envisaged. These now contain only the textual information required to understand the part and identification, while other textual information is managed in a master data list. (2) VDA 4953-2 [17] describes the use of MBD without technical drawings.

In aeronautics, step-by-step implementation of MBD has already been implemented. The case study of Saab Aeronautics shows that the individuals involved have different prerequisites and that solutions or problems must be viewed from different perspectives. In addition, the implementation also meant that the organizational structure had to be adopted by the company. Strategically, Saab Aeronautics has chosen a step-by-step transition with five development stages. One of the initial steps was to chose a project as a case study. At Saab Aeronautics, the Unmanned Combat Aerial Vehicle (UCAV) project was used as a case study [11]. The case study by Zhu et al. from Chinese Aeronautics shows that a step-by-step implementation is a prerequisite. In this case study, a specific part was explicitly taken from the portfolio, used to test the implementation with Siemens NX and Teamcenter. The fan of a motor was chosen as the part. The knowledge gained from the case study was used for further planning [21]. Another case study from Polish aeronautics demonstrates that verification and control of the software used are needed [2]. Verification of requirements was performed using Product Acceptance Software (PAS) Validation, which is defined in the Quality Assurance Standard for digital product definition at Boeing Suppliers [4]. All these case studies indicate that, on the one hand, a step-by-step implementation concept is needed. On the other hand, the software infrastructure requirements must be tested with feasibility studies.

By moving the drawing elements from a 2D to a 3D environment, these elements have to go through a data adjustment and filtering process. Quintana et al. distinguishes which drawing elements are needed, not needed or need to be added.

In addition, the human factor respectively the acceptance must be taken into account.

### 2.6. Data consistency and data formats

In the context of drawingless product definition, the focus is on ensuring model-based data consistency between CAD, CAM and CAQ. One way to realize it is the native data exchange, which is only possible if the application system covers all three application areas. Neutral data formats such as Standard for the Exchange of Product model data (STEP) or Jupiter Tessellation (JT) also support MBD. Therefore, benchmarks such as the 8th JT Application Benchmark from prostep ivip and VDA exist. This benchmark deals with neutral formats for cross-process data exchange in shipbuilding. It shows that STEP and JT are suitable for PMI cross-process data exchange [18].

Another study by Stanasel et al. confirms that JT achieve the best results by comparing the different CAD interoperability formats.

There is also a possibility to create technical data packages in the form of 3D PDF and embed 3D files in the 3D PDF.

## 3. Feasibility study for the introduction of drawingless manufacturing

Based on current case studies from industry, a feasibility study was conducted regarding drawingless manufacturing in Siemens NX in the areas of *Scope of functions and missing spots in CAD (3.1)*, *Data formats, data structure, and data consistency (3.3)*, *CAM automation (3.4)* and *CMM automation (3.5)*. For this purpose, a team of experts in the areas of CAD, CAM and CAQ was assembled. Such a team must be familiar with the traditional process flows in the respective departments and interested in implementing new approaches. Since drawingless manufacturing is a cross-data, cross-departmental process, it is also essential that the team of experts regularly exchanges knowledge gained in their department and that a standard is realized across the entire PDP in the concepts developed. The following subsections describe the feasibility study process and its results.

### 3.1. Scope of functions and missing spots in CAD

It is crucial to determine whether there is appropriate robustness in model-based data design procedures and processes in CAD. Another criterion is the completeness of the data so that all functions such as symbols, views, etc., that are used and required in traditional drawing derivation are also available in MBD. It is also necessary to enable machine processing of PMI for CAM and CAQ. To test the robustness and the operating range of the software, several company-typical, simple and complex parts are provided with PMI. In the standards ISO 16792, ASME Y14.4, and ISO 1101, there are illustrations of 3D annotations for this purpose. However, some open questions remained for practical implementation in the company:

*What dimensions are needed?* Since computers, tablets, or smartphones with various viewers are required to display the 3D model with the PMI, the question arises whether adding and highlighting additional dimensions is still necessary since most viewers provide a measurement function. The question refers, for example, to those main dimensions that are subject to general tolerances or can be measured via geometry. The team of experts agreed to set all dimensions as in traditional technical drawings, despite the possibility to perform measurements on the part afterward, because over the entire PDP time is saved by avoiding the manual measurements in the viewers. However, this step is only planned for the transition phase since dimensions subject to general tolerance will no longer be needed in the long term. This only changes the way users work to a limited extent and ensures greater acceptance.

*How should the PMI be positioned in the model?* In the initial attempts to place PMI on the 3D model, it was found that a strategy for placing the PMI is needed so that some structure and clarity is enabled. For this purpose, it was decided to place PMI similarily to traditional technical drawings by creating a main view and placing the PMI on the three orthogonal projections. This increases readability and reduces user misinterpretation. In addition to the main view, several other views are created, which allow filtering of PMI, such as main dimensions, GD&T, or surface finish.

*Can PMI be referenced to edges, faces, or even auxiliary geometry?* In a traditional technical drawing, only dimensions on edges or auxiliary geometries can be specified. In three-dimensional space, however, it is possible to reference PMI bidirectionally associatively on edges, faces, auxiliary geometries such as a centerline, or a machining feature, and even on the entire part. Here, downstream processes subsequent to the construction, such as CAM and Coordinate Measuring Machine (CMM) programming, have shown that dimensioning over auxiliary geometries or from edges should be avoided since the bidirectional association with an edge is useless for further machine information processing. PMI should be associated with machining features or surfaces.

*Is a title block still needed? If so, where should the title block be located?* The title block is an important information carrier in the product definition, which can contain geometry-related information in addition to essential metadata such as part name, part number, material, or weight. Geometry-related information can be revisions or general tolerances. Therefore, it was decided for the time being not to deliminate the title block as an information carrier. For this purpose, a table is created in the graphics area and additionally provided with attributes in Siemens NX so that it is filled automatically. The main view is created as the position, and the table is placed orthogonally to the view. However, this step is only planned for the transition phase since the title block is no longer needed in the long term.

*Is a parts list needed in assembly files?* Parts lists are essential in PDP and indispensable. Especially when assemblies are opened with lightweight viewers, there is no possibility to retrieve information about the parts of the assembly. The parts list is implemented as a table, and placed orthogonally to the main view, next to the assembly.

*How is a collective specification of surface finishes realized?* Downstream processes to the design phase have also shown the need for an association of surface finishes to each machining feature. In this case, however, each surface subject to the collective specification would have to be explicitly referenced with the surface symbol manually. The rather time-consuming and tedious referencing of all surfaces with the collective specification could be automated with the MBD Logical Rules of Siemens NX so that all surfaces that are not subject to a specific surface condition are referenced with the collective specification.

### 3.2. Results of the feasibility study in the design division

The feasibility study in the design has shown that (1) there are no restrictions in attaching the PMI, and (2) all the information on the traditional drawings is also available as PMI. In addition, the time required to apply the PMI was compared with the time required to create a technical drawing. The team of experts, creating about fifty 3D masters, found that the application of PMI allows saving about 30% of time. This can be attributed to the fact that the complexity is lower than a traditional technical drawing. Detail views are no longer required. The space-saving attachment of the views in an technical drawing, which certainly involves a lot of effort, no longer has to be considered in the MBD since enough space is available for the PMI. Also, the possibility of special symbols like own factory standards can be defined as PMI.

### 3.3. Data formats, data structure, and data consistency

The data structure, data formats, and data consistency are subject to the following requirements: (1) Effort of the information possibilities for the user without additional expenditure, (2) Elimination of redundant data storage, central information provision (3D master) and SPOT, (3) Front-loading (savings in the overall process), (4) Elimination of preparation, management, and storage of drawings, and (5) Pervasive MBD data exchange across the Siemens NX CAD, CAM and CAQ process chain.

However, in the criteria for data formats, a distinction must be made as to whether the MBD data is human- or machine-readable and whether the design history is required as an information carrier. For example, the 3D data should not contain the design history when outsourcing work to an external service.

For this purpose, all data formats available in Siemens NX were checked to what extent they fulfill the requirements mentioned above. The result of the feasibility study corresponds to the already mentioned results from the benchmarks in subsection 2.6. However, it was found that the bidirectional association between machining feature and PMI is supported by the native data format of Siemens NX and JT format. The PMI is preserved when converting to the STEP format, but the association is lost.

### 3.4. Computer-Aided Manufacturing (CAM) automation

The aim of the feasibility study in the area of CAM automation is, on the one hand, to show the automation potential. On the other hand, the feasibility study establishes whether MBD is sufficient as an information carrier or whether further data is needed. The requirements for CAM automation are very high since any error can lead to a costly machine tool collision. The following subchapters address the individual issues and describe which solutions or problems were identified in the feasibility study.

Siemens NX offers the possibility to create a rule library for machining processes via the Machining Knowledge Editor (MKE). This rule library makes it possible to learn and recognize machining features and automatically generate a machin-

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ing operation, including tool selection and associated cutting values. All data, operations, and functions available in the CAM environment can be accessed and manipulated via the MKE.

Since a machining strategy including tool selection and corresponding cutting values is created during automatic CAM programming, machining operations can be standardized, optimized and automated via the machining rule library. The NC program for simple geometric parts, which only require 2,5D machining, can easily be created fully automatically.

The effort required to create a machining rule is minimal. The problem here is to determine whether the created rule creates a collision-free machining strategy in all possible scenarios and whether the required data is consistent. Complete exclusion of a collision cannot be realized since all manufacturing scenarios must be considered. A collision check or CAM simulation must be performed even with automatic CAM programming.

In general, it must be considered that CAM programming is data-driven programming. Most of the company's data with its production are processed in the work preparation or CAM programming. In addition to the 3D data such as finished part, blank part, machine tool model, tool, clamping device, the cutting value library, and machining rule library must show data consistency, whereby the cutting value library takes into account part material, tool material, and machining operation. Furthermore, there is also the possibility to use attributes such as feature color both for the feature recognition and for selecting a machining operation or inspection plan creation. With the combination of geometry, PMI, feature color as well as other attributes, there is a variety of options that support the automation of frequently occurring machining features.

### *3.5. Coordinate Measuring Machine (CMM) Automation*

Traditionally, for the creation of control programs for CMM the particular software from the manufacturer is used. In this case, CMM from Zeiss and Wenzel have been used with Zeiss Calypso and Quartis software. There are three different approaches to import the data: (1) Import via the Dimensional Measuring Interface Standard (DMIS) standard [8], (2) Import via I++ Dimensional Measurement Equipment (DME), and (3) Native import of Siemens NX files.

Two different approaches were tested and compared: (1) CMM programming in Siemens NX CMM and import in Quartis via DMIS standard, and (2) import of the native MBD files created in Siemens NX and CMM programming Zeiss in Calypso.

#### *3.5.1. CMM programming in Siemens NX CMM and import in Quartis via DMIS standard*

Siemens NX offers the possibility to program CMM in the graphical programming environment Siemens NX CMM. The advantage of using Siemens NX CMM is that all model-based information created in the design can also be used for CMM programming. Primarily, these are attributes related to the features. In addition, there is no need for an interface between the design and CMM programming since they are based on the same application system. Instead, the text-based DMIS standard is used to load the control program into Quartis. A disadvantage of DMIS is that this interface is practically not supported by Zeiss Calypso. Furthermore, it should be mentioned that the DMIS file is interpreted individually and partly incorrectly by the respective machine control after import. This means, for example, that scan operations can be captured within DMIS but not read by Quartis. Another disadvantage of CMM programming in Siemens NX is that at the time of the feasibility study, automatic inspection plan generation was not supported via the MKE. Instead of the MKE, it is possible to realize an automatic inspection plan generation in Siemens NX via the MBD Logical Rules.

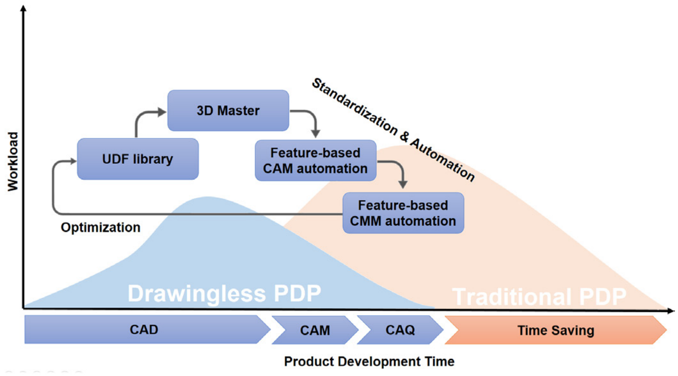


Fig. 1. Frontloading and downstream automation

#### *3.5.2. Import of the native MBD files created in Siemens NX and CMM programming Zeiss in Calypso*

Importing the native MBD data and CMM programming into Zeiss Calypso has the great advantage that there are no functional limitations since all machine-specific measurement functions and libraries can be used by the software with Zeiss Calypso. In addition, the software also enables automatic control program creation by means of a rule library, which creates a rule-based measurement program using the geometry found and the PMI located on it. The disadvantage of this approach is that when Siemens NX is updated, the interface or Zeiss Calypso must also be updated. However, it must be taken into account that a new interface is not always available. Furthermore, during the feasibility study, complex dimensions, especially chain dimensions, can cause problems with the automatic test program generation. Chain dimensions are PMI that are referenced to other PMI.

## 4. Conclusion and Future Work

In summary, there are no significant limitations when switching from traditional drawing creation to MBD. When creating MBD files, it should be considered that the PMI are associated with the machining features so that the information can be processed by computer and thus subsequent/downstream processes can be automated. For downstream automation, however, data exchange between CAD, CAM and CAQ (see Fig. 1) should be done natively in Siemens NX. For clarity, multiple views should be generated, and the views should act as a filter function for PMI. The header should be placed in the main view, orthogonal to the main view.

It should be noted that an appropriate infrastructure such as a computer, tablet, or smartphone must be available throughout the company so that employees can open and view the MBD files. For external manufacturing, technical data packages consisting of 3D PDF with title block and parts list can be generated. In addition, if required, a 3D model can be embedded in the 3D PDF as a neutral data format that supports PMI (STEP AP242, JT).

A significant advantage is the concept of the 3D master. Especially in large companies, document-driven processes can be time-consuming. By eliminating the technical drawings and through the centralized, machine- and human-readable information provision of the 3D master, everyone is up-to-date across the entire PDP.

Control programs for machine tools and coordinate measuring machines can be automated via the information gain of the bidirectionally associated PMI with the machining feature. The automation must not be related to the part but to the machining feature. For robust and flexible automation, feature attributes such as feature name, color, and identification number are required in addition to feature geometry and PMI. The automation is rule-based. As a result, feature-specific machining processes and inspection processes can be subject to revisions, enabling significantly higher optimization potential. This approach enables a modular approach in product development with those machining features that are already standardized, optimized, and automated in the company. Due to the feature-related standardization in production and quality inspection, manufacturing costs can be precisely determined and significantly reduced.

Still, the data continuity of MBD files remains a problem, especially in the area of CMM programming, users are forced to change the application system from Siemens NX to Zeiss Calypso or Quartis. The interfaces available for this purpose, such as DMIS, or the native import of MBD files, do not provide the desired robustness to create feature-related inspection standards automatically. It would be helpful for the CMM automation if manufacturers supported the DMIS standard by providing the user with a description of the machine-specific interpretation of the DMIS standard, so that the DMIS code, similar to NC code for machine tools, can be adapted via post-processors. Currently, the data exchange of 3D models can only be realized to a limited extent. It is very important for the industry if software manufacturers realize the data exchange via neutral data formats such as STEP or JT, so that attributes and PMI do not lose their bidirectional association to the feature.

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