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Ontology-based information modeling method for digital twin creation of as-fabricated machining parts

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Abstract

The Digital Twin concept, as the cutting edge of digital manufacturing solution for modern industries, plays a significant role in the Industry 4.0 era. One key enabling technology for developing a DT is the information modeling of physical products, so as to combine the physical world with the cyberspace more extensively and closely. Therefore, the modeling approach to managing as-fabricated data of physical products, which faithfully reflects the product's physical status, emerges to be pivotal. This paper addresses the problem of modeling as-fabricated parts in the machining process, which is difficult to accomplish by relevant methods, and hinders the long-term data archiving and reuse of process data. Furthermore, to fill the gap, an ontology-based information modeling method of as-fabricated parts is proposed as the recommendation to create DTs for as-fabricated parts. It provides a simple and standardized process for companies to create DTs of as-fabricated parts by specifying the information classification, the contents to be modeled and the modeling method. To validate the effectiveness of the proposed approach, a case study is undertaken in an aviation manufacturing plant at last. The result shows that the proposed information modeling methodology is readily to DT creation of as-fabricated parts.

Keywords:
Information modeling; As-fabricated data; Digital twin; Ontology; Machining part

Nomenclature

BIM	Building Information Modeling
CAD	Computer-Aided Design
CNC	Computer Numerical Control
CPS	Cyber-Physical System
DT	Digital Twin
ERP	Enterprise Resource Planning
GD&T	Geometric Dimensioning and Tolerancing
ISO	International Organization for Standardization
MES	Manufacturing Execution System

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NASA	National Aeronautics and Space Administration
OWL	Ontology Web Language
PLM	Product Lifecycle Management
STEP	Standard for the Exchange of Product Model Data
TCP/IP	Transmission Control Protocol/Internet Protocol
UML	Unified Modeling Language
USAF	United States Air Force
XML	EXtensible Markup Language

1. Introduction

With the advent of smart manufacturing era, modern manufacturing operations are facing numerous challenges, including mass customization, predictive manufacturing systems and quick production responsiveness [1]. For example, one of the previous problems with only being able to work with a physical product is that the range of investigation into its behavior was both expensive and time-consuming [2]. The answer for these issues may reside in the increasing resource of virtualization or creation of DTs [3]. Because DT can reflect the dynamic mapping of physical product and its digital counterpart, it is considered to comprise the next wave in modeling, simulation and optimization technology [4]. Since the DT concept was proposed [5], it has been applied in many industrial fields such as health management of damaged aircraft structures [6], smart BIM [7], maintenance of nuclear plants [8, 9], design and production engineering [10], assembly-commissioning of high precision products [11] and some other application scenarios of smart manufacturing [12–23].

However, the development of DT applications is still at a very early stage and how to apply the DT concept to the machining process has not attracted enough attention [24]. It is suggested that DT-based machining process knowledge reuse could help engineers optimize the process planning [25]. To achieve these goals, all the data related to the machining process of a machining part should be modeled because the technical core of the DT concept is "a data model that encapsulates physical data and information relationship with its external environment" [26]. Similar to the concept of "as-built" data in BIM, this paper uses the term "as-fabricated" data to describe all the data of the status as a machining part appears upon completion. Therefore in this paper, the as-fabricated data refer to all the elements that gave birth to a machining part, including the measured value of GD&T, the data of machining process stored in a MES and other data that need to be recorded. Through the modeling of as-fabricated data, engineers may perform evaluation and optimization of machining processes by discovering the hidden knowledge.

After our investigation in an aviation manufacturing plant, the as-fabricated data of a machining part are easily ignored and discarded in the e-documents or even paper documents because at the time of delivery more attention is paid to the qualification rate rather than the real status of a machining part. On the other hand, how to model as-fabricated data following the DT concept has not been effectively resolved and no paper has mentioned how to create DT of a as-fabricated machining part at present. In details, there are three main challenges:

- **Not enough attention to model the as-fabricated data.** Most of the latest research are focused on the complex scenarios such as aircraft, power plants and production engineering.
- **Lack of research on modeling process.** How to model the as-fabricated data in a simple and practical way still remains blank.
- **Unclear modeling elements.** All the critical concepts for modeling an as-fabricated part still need to be discussed.

As a result, the DTs of as-fabricated machining parts are not comprehensive due to the lack of modeling method, which hinders the as-fabricated data reuse and long-term data archiving. The information modeling approach to the as-fabricated data seems to be significantly important for the landing of new patterns in smart manufacturing. Based on the above motivations, this paper proposes a systematic methodology for developing the information model of as-fabricated parts and creating DTs of the test parts using the model. The framework using a proper modeling language with the help of a notable industry standard is considered as the key contribution of the presented research. Certainly a DT is required to be synchronized with its physical counterpart using the best available sensor updates. This is not the focus of this research. A sample semantic model for a real as-fabricated part produced in an aviation manufacturing company is presented as a case study.

The remainder of this work is organized as follows: Section 2 reviews the literature in related works and highlights the research gaps that motivated the presented work. The proposed information modeling framework is presented in Section 3 with detailed discussions. A case study of the application is presented in Section 4 to validate the proposed method. Finally, discussion of the results, future direction of the research and concluding remarks are provided in Sections 5 and 6, respectively.

2. Related works

The assumption of DT, which was named ”conceptual ideal for PLM information mirroring”, was introduced by Dr. Michael Grieves in 2002 when he gave a lecture about PLM. ”Mirrored Space Model” [27] and ”Information Mirroring Model” [28] had also been used. Finally, Dr. Michael Grieves and his partner chose ”Digital Twin” [5] to replace all the terms above in 2011. In the same year, the USAF research laboratory adopted the conception as a novel method to predict the aircraft structural life. Based on the initial assumption, NASA defined DT as ”an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history and so forth, to mirror the life of its flying twin” [29].

After several years, kinds of definitions and explanation of DT came out. For example, DT was seen as the next generation of simulation [30]. Tao et al. believed that DT is a method to complete the convergence between physical and cyber spaces [13]. Especially, Dr. Michael Grieves redefined DT as ”a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level and any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital twin” [2].

These discussions had significantly broadened the concept and consequently DT refers to a virtual representation of manufacturing elements such as personnel, products, assets and process definitions, a living model that continuously updates and changes as the physical counterpart changes to represent status, working conditions, product geometries and resource states in a synchronous manner [31]. In conclusion, the role of DT in smart manufacturing is to allow a physical ”thing” in a factory to be understood for computers and machines by reflecting its physical status. This section reviews the related works of DT in machining process and highlights the research gaps.

2.1. DT in machining process

Although how to apply the DT concept to the machining process has not attracted enough attention, several related initiatives have been done to expand the boundaries. These studies can be divided into three aspects:

- **The discussion on application possibilities of DT application in machining process.** The possibility of DT-based specific simulations of the machining process in the detailed engineering phase is discussed, which helps to develop the computer aided manufacturing program for the CNC machine and to calculate effects for the work pieces, tool kits and machine tools [4]. The future possible mode of DT-driven product manufacturing is proposed and an example to illustrate the mode is taken using the drive shaft machining process [15]. The DT in the paper refers to the physical production factors in the machining shop floor such as raw materials, CNC machine, finished/semi-finished machining parts, shop floor environment and so on, their corresponding virtual models and the DT data. Tao et al. [25] also discussed the DT-based process planning, including the key technologies and the main challenges.

- **The DT applications to optimize the manufacturing systems.** A new MES following the DT concept, which combines MTConnect data with production data collected from operators is developed and validated by the production of titanium parts [1]. Bao et al. [32] proposed an approach to modeling product DTs, process DTs and operation DTs using Automation Markup Language. A digital thread is developed to link as-planned to as-fabricated product data using dynamic time warping by using ISO 10303/G code [33]. A DT-based system for the waste electrical and electronic equipment recovery was developed by using extended ISO 10303 standard to support the manufacturing/remanufacturing operations throughout the product's life cycle [34]. Liu et al. [35] proposed a novel process evaluation method based on DT technology, including the real-time mapping mechanism, the construction of DT-based machining process evaluation framework and the process evaluation. Zhou et al. [36] proposed a general framework for knowledge-driven DT manufacturing cell towards smart manufacturing, including DT model, dynamic knowledge bases and knowledge-based intelligent skills for supporting the above strategy. Lu et al. [19] illustrated a generic architecture for cloud-based manufacturing equipment based on technologies such as DT and big data analysis.
- **The DT-based modeling method of manufacturing resources.** Before the rise of the DT concept, several initiatives have been done to define a machine tool model compliant to ISO 14649 [37–39]. Recently, the process to construct a DT for a sheet metal punching machine is presented to support the interactive design of optimal NC machining programs [40]. Luo et al. [41] established a multi-domain unified modeling method of CNC machine tool DT, which can optimize the running mode, reduce the sudden failure probability and improve the stability of CNC machine tool. Botkina [42] focused on building a DT of a cutting tool as a digital replica of a physical tool, its data format and structure, information flows and data management, as well as possibilities for further applications and analysis of productivity. Zheng et al. [43] introduced a generic CPS system architecture for DT establishment in smart manufacturing with a novel tri-model-based approach for product-level DT development and then conducted a case study of an open source 3D printer DT establishment. Oyekan et al. [21] presented the use of a virtual reality DT of a physical layout as a collaborative mechanism to understand human reactions to robot motions.

2.2. Semantic modeling in machining process

Angrish et al. [26] pointed out that the technical core of a DT is a virtualized version of a physical entity, which means a data model that encapsulates physical data and information relationship with its external environment. In other words, it is the virtualization of physical entities [44]. Lim et al. [45] also suggested that knowledge representation tools such as ontology are potential choices for DT creation. Moreover, ontology is favored as it addresses integration and domain-specific modeling concerns, knowledge reusing and knowledge sharing. From this point of view, a common practice for DT creation is to develop a information model using semantic web languages such as OWL [3]. The OWL is a widely used ontology formalization language, which supports abundant semantics and has great ability to exchange machine-readable content. In conclusion, the semantic modeling using OWL is critical for DT creation in machining process. Thus, the related works of semantic modeling using the OWL in machining process are listed below and they can be divided into three aspects:

- **The representation and exchange of product model.** An approach to enable the translation of STEP schema and its instances to OWL is presented with a model called OntoSTEP [46]. The OntoSTEP model can be integrated with any OWL ontologies to create a semantically rich model by combining geometry information represented in STEP with non-geometry information, such as function and behavior. In a more recent study, Wan et al. [47] focused on the creation methods of 3D machining process model by establishing machining ontology and modeling ontology. These studies aimed to use the rich semantics of OWL to overcome the shortcomings of 3D product models.
- **The process planning and process knowledge management.** Eum et al. [48] presented an ontology based modeling method of the process planning knowledge for machining operation selection regarding multi-axis machining feature. Solano et al. [49] developed an ontology as a specialist offshoot of the product and processes development resources capability ontology. Similar research presented an approach to modeling manufacturing process information based on some predefined ontologies [50]. The use of OWL provides a formal description

for entities and their relationships. Therefore, the internal concepts in manufacturing process can be defined unequivocally by using OWL. These studies aimed to use the querying and reasoning abilities of OWL.

- **The manufacturing resource virtualization.** Jang et al. [51] demonstrated the capability of querying the semantic model of virtualized manufacturing resources and presented an illustrative process for a discrete part manufacturing case by providing OWL-based definitions for manufacturing service capability profiles and a description logic-based reasoning procedure. Kjellberg et al. [52] explored the possibility of modeling machine tool concepts defined in established industry standards using OWL language and discussed the mapping mechanism between ontology model and concepts in existing industry standards in detail. Zhao et al. [53] proposed a more systematic model for describing manufacturing equipment resources. Until recently, a novel methodology to enable the development of a semantic model that supports DT creation for machine tools as well as other physical assets in a factory was developed on the basis of combination of ISO 14649 and ISO 13399 standards [3]. These studies have successfully filled the gap that the industry needs a effective approach to virtualizing manufacturing resources for developing a smart factory solution.

2.3. Research gaps

The above literature has well suggested that complex physical objects in a factory such as machine tools can be virtualized in the cyberspace to support DT creation. The possibilities of DT application in machining process are proposed and key technologies are explained. The use of DT to optimize the traditional machining processes has also begun to bear fruit. However, to completely fulfill the DT concept in machining process, there are several critical challenges:

- **Not enough attention to model the as-fabricated data.** Most of the latest research are focused on the DT application in complex scenarios such as aircraft, power plants and production engineering. Although kinds of physical assets in a factory such as machine tools, manufacturing resources and cutting tools are modeled based on the DT concept, no paper has mentioned how to model the as-fabricated data of a machining part at present. There is a gap in terms of representing middle- and end-of-product lifecycle-related semantics [54]. This situation leads to the incompleteness of DT creation in machining process.

- **Lack of research on modeling process.** How to model the as-fabricated data in a simple and practical way still remains blank. Considering of the existing semantic modeling method in machining process, even though some prototypes presented kinds of methodologies for modeling of manufacturing systems successfully as well as high-level enterprise assets, there is still a gap in terms of describing the ”reality” of the specific domain [54].

- **Unclear modeling elements.** Although some discussions [15] about the DT creation of finished/semi-finished machining parts have been done, but all the critical concepts for modeling an as-fabricated part are still unclear and need to be analyzed. Especially, in order to maximize the reuse of existing ontologies and related domain knowledge, the data should be reasonably classified.

As a result, the DT creation of as-fabricated machining parts is not comprehensive due to the lack of modeling method, which hinders the as-fabricated data reuse and long-term data archiving. Therefore, the research on semantic modeling of the physical as-fabricated data is becoming increasingly important. The as-fabricated data should be taken seriously to complete the DT creation in machining process.

Besides, especially in a manufacturing plant, the real data of a machining process (e.g., the feed rate, the chosen cutting tools and the temperature) are usually recorded and stored using a commercial MES, which means a large expense for a small manufacturing company. Meanwhile, after our investigation in an aviation manufacturing plant, some of the as-fabricated data such as real value of GD&T are usually saved in Excel files generated from the measuring tools. The separation of these data leads to difficulties in the long-term data archiving and data reuse. Therefore, the implementation of the DT concept is conducive to the management of the as-fabricated data. There is a strong need to create a framework and proper tools that support a manufacturing company to conveniently create DTs of as-fabricated machining parts for daily use. How to implement the existing approaches with as-fabricated data in machining process is critical to the DT concept as well as the industry practices. The framework should specifically contain all the necessary information of as-fabricated parts and the DTs of as-fabricated parts should be easily transported base on the browser/server architecture through semantic modeling and certainly will support the long-term data archiving. The following work was motivated to develop such a framework that meet all the requirements above.

3. The proposed methodology of DT creation

It is indicated that a DT should both predict what the actual form can be and then reflect what the actual form is because it is a set of ”virtual information constructs” that fully describes a actual physical manufactured product [2]. This section introduces a practical modeling framework that is pictured to enable a company to virtualize all the essential as-fabricated data of machining parts. Moreover, DT creation is equivalent to manufacturing elements virtualization, which means building a data model that encapsulates physical data and information relationship with its external environment [3, 26]. Hence, building a DT of an as-fabricated machining part requires answering two main questions and the rest of this section tries to solve the problems and present the details:

- The systematic procedure of DT creation for an as-fabricated machining part.
- The reasonable and simple information modeling approach to as-fabricated data.

3.1. The overview of the proposed framework

In this paper, the term ”as-fabricated” refers to the status as a machining part appears upon completion. When a machining part is finished and delivered to the downstream workshop, all the lifecycle data of a machining part should be definite. Several studies classify these data into geometric and non-geometric types [55, 56]. Considering of data sources and structures, the data are then divided into four types in this paper as shown in Fig. 1. To be more specific, the as-fabricated data refer to all the elements that gave birth to a machining part, namely the measured value of GD&T, the original topological relationships between geometric features, the data of machining process stored in the MES, the supplementary data stored in the ERP system and some additional data.

Based on the concept explanation and data classification, the overview of the proposed framework is illustrated in Fig. 2. It is seen that the proposed framework contains four key parts.

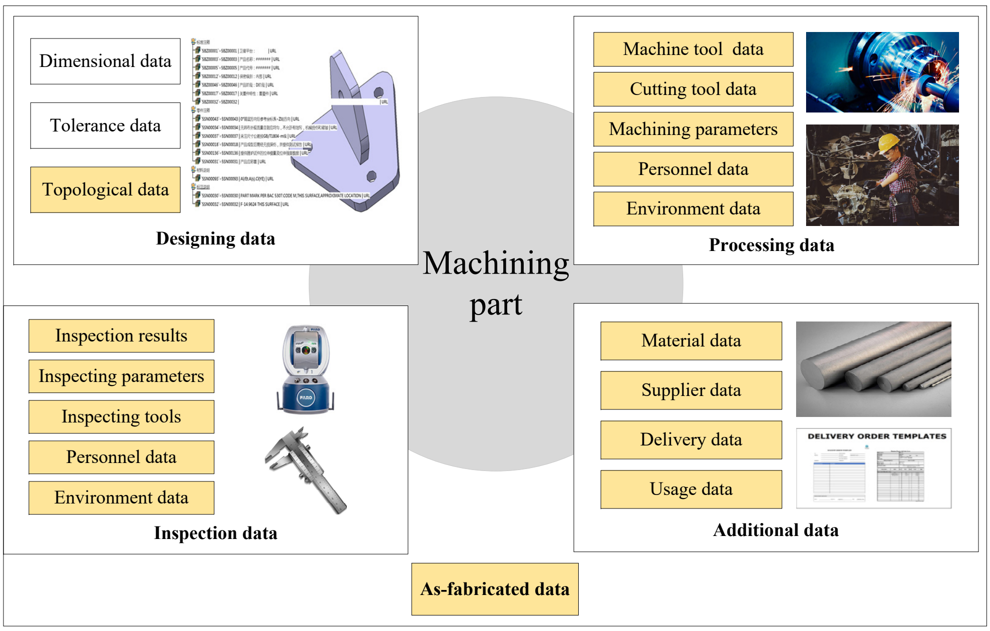

Figure 1: The data set of an as-fabricated machining part.

- **Data acquisition.** This part is the bridge that connects the entire framework to the physical world. Through physical equipments (e.g., coordinate measuring machine, vernier calipers and laser tracker) and data exchange protocols (e.g., TCP/IP and MTConnect), the DTs of machining parts can acquire the required data in real time and update their status. A lot of relevant data are generated around the as-fabricated part and these data are stored in different media such as MES, ERP systems, Excel files and even paper documents. In this article, we assumed that the data to be modeled had been collected and stored in specific files. Therefore, data acquisition is not the focus of this article.

- **Information modeling.** This part is the basis of the proposed framework. As mentioned in Section 2.2, DT creation means building a data model that encapsulates physical data and information relationship with its external environment. On the other hand, "model-dependent realism" asserts that all we can know about "reality" consists of networks of world pictures that explain observations by connecting them with rules to concepts defined in models [57]. The realism also suggests that we cannot know "reality-as-it-is-in-itself", but only an "approximation" of it provided by the intermediary of models. From these perspectives, the model-dependent realism also applies to the DT concept since it is impossible to create a complete DT as same as its physical counterpart. Hence, a rational and practical information model which encapsulates critical concepts and their internal relationships of a physical object can be seen as a DT of its physical counterpart. Now the question becomes how to build a reasonable information model for an as-fabricated machining part. Fortunately, industry standards play a saliently important role in providing the accurate information model for industry products in the manufacturing domain since they can provide the high-level information model for describing physical objects. Lu et al. [31] suggested that the most helpful industry standards for developing product DT may be ISO 10303 (STEP) and ISO 14649 (STEP-NC). Several early research [37–39] indicated that the innate abilities and advantages of STEP-NC make it easy to use for developing information model of manufacturing systems in a factory even before the appearance of the DT concept. Recently, a novel methodology to enable the development of a information model that supports DT creation for machine tools in a factory was developed on the basis of combination of ISO 14649 and ISO 13399 [3]. The as-fabricated data modeling approach proposed in this article is also inspired by these similar studies based on industry standards, especially in non-geometric data modeling. These standards provide the information framework for data modeling and the ontology methodology provides the specific approach. After the ontology modeling is completed, all the as-fabricated data are saved in the form of ontology instances in an OWL file. According to the above analysis, the information structure filled with these instances should be seen as a DT of the corresponding as-fabricated machining part in the cyberspace. Using the OWL, creating a DT of a machining part by translating the established industry standards into the ontology model becomes more and more applicable and practical. The details of information modeling will be discussed in Section 3.2.

- **Knowledge engineering.** According to Rowley et al. [58], the wisdom hierarchy pointed out that data is a raw and unorganized fact that required to be processed to make it meaningful, and information is a set of data which is processed in a meaningful way according to the given requirement. Therefore, after the information modeling is completed by the ontology methodology, as-fabricated data forms effective information that can be further utilized. On this basis, the long-term data archiving is firstly resolved. With the powerful retrieval and sharing capabilities of ontologies and OWL, all the as-fabricated data can be accurately searched by graph theory algorithms. Secondly, only based on the information modeling, knowledge discovery and data mining can provide more new hidden knowledge for further application. Because this article focuses on information modeling, all research works that belong to knowledge engineering will be detailed in future articles.

- **Further application.** This part of the work is an extension of the previous parts. New knowledge based on knowledge discovery and data mining is helpful for processing planning, design optimization and reconfiguration. Besides, all the as-fabricated data can be accurately and efficiently transmitted to the downstream workshop. For example, by extracting key information and reusing knowledge, the assembly workshop can optimize the process planning and improve the level of collaboration in the process.

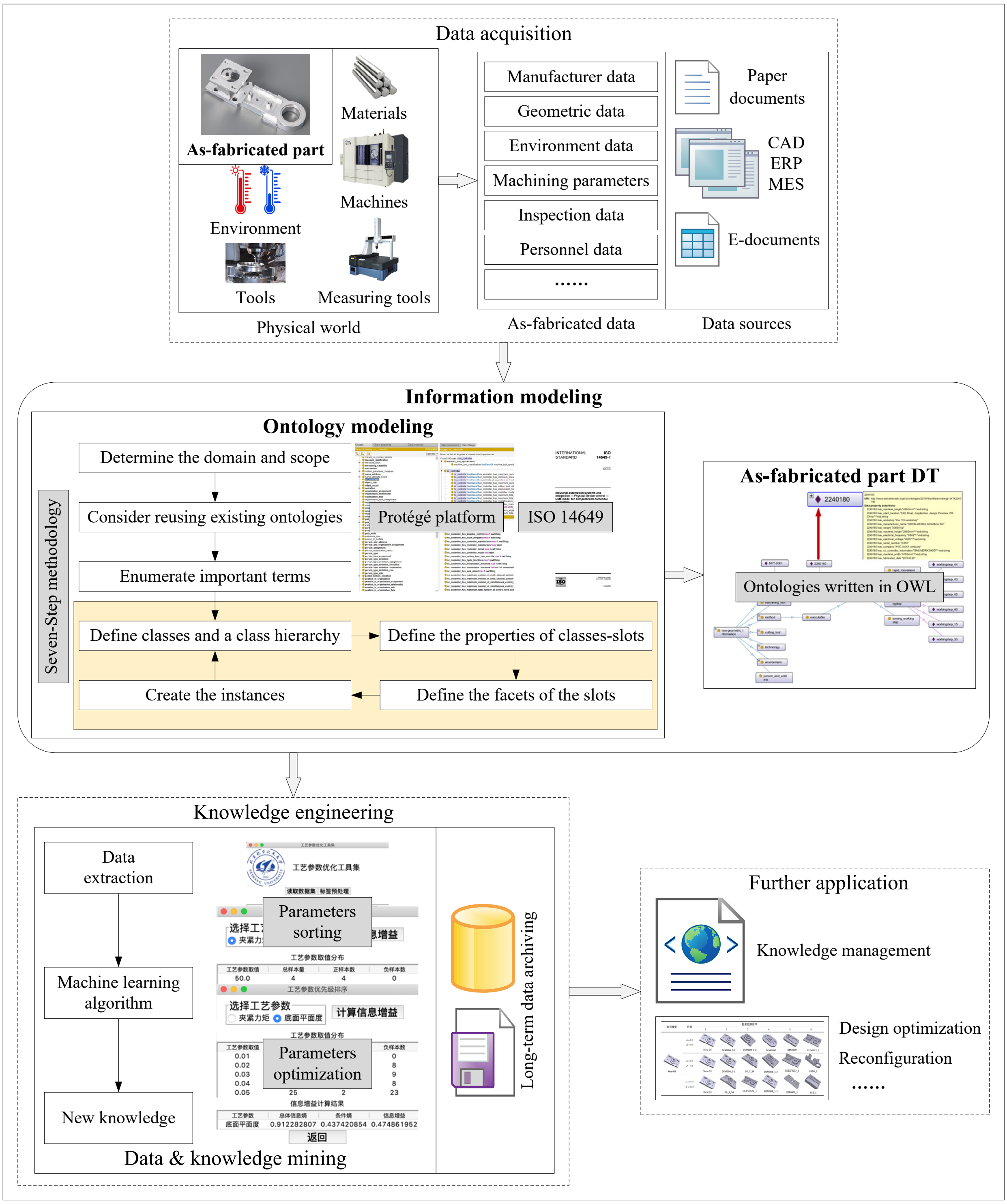

Figure 2: The framework for DT creation of as-fabricated machining part.

According to the research gaps mentioned in Section 2.2 and the detailed analysis in Section 3.1, the most important and indispensable step in building a DT of an as-fabricated machining part is the information modeling of the as-fabricated data. Information modeling of as-fabricated data is the soul of the entire research framework since it can connect the physical and virtual worlds and provide a systematic data structure and application logic. Without a reasonable and simple way to the information modeling, there is no way to talk about the use of as-fabricated data, and it is impossible to continue to mine and reuse the knowledge because all the data that could generate new knowledge are discrete and unstructured. For these reasons, the following paragraphs introduce a reasonable and simple information modeling method of as-fabricated data based on the classification of data into two categories, geometric and non-geometric.

3.2. The information modeling method of as-fabricated data

The machining process is a kind of systematic determination of activities by which a part is to be realized [50]. The increasing complexity of machining process and the emerging of the DT concept have led to more and more concerns on information modeling. The machining process information covers the data of multiple processes for making a part, including personnel, machine tools, cutting tools, material, process methods and environment data needed to transform a raw material into an as-fabricated machining part.

Speaking of information modeling, the common practice is to create an ontology model written in OWL since the OWL is a widely used ontology formalization language, which supports abundant semantics and has great ability to exchange machine-readable content. The use of ontology and OWL for information modeling provides a formal description of entities and their relationships. As a result, the internal concepts in manufacturing process can be defined unequivocally. The information modeling method of the as-fabricated data is illustrated in the Fig. 3. After both geometric information modeling and non-geometric information modeling are completed, a DT of an as-fabricated machining part can be obtained by combining these two parts. The next section will introduce the case we used to verify the method.

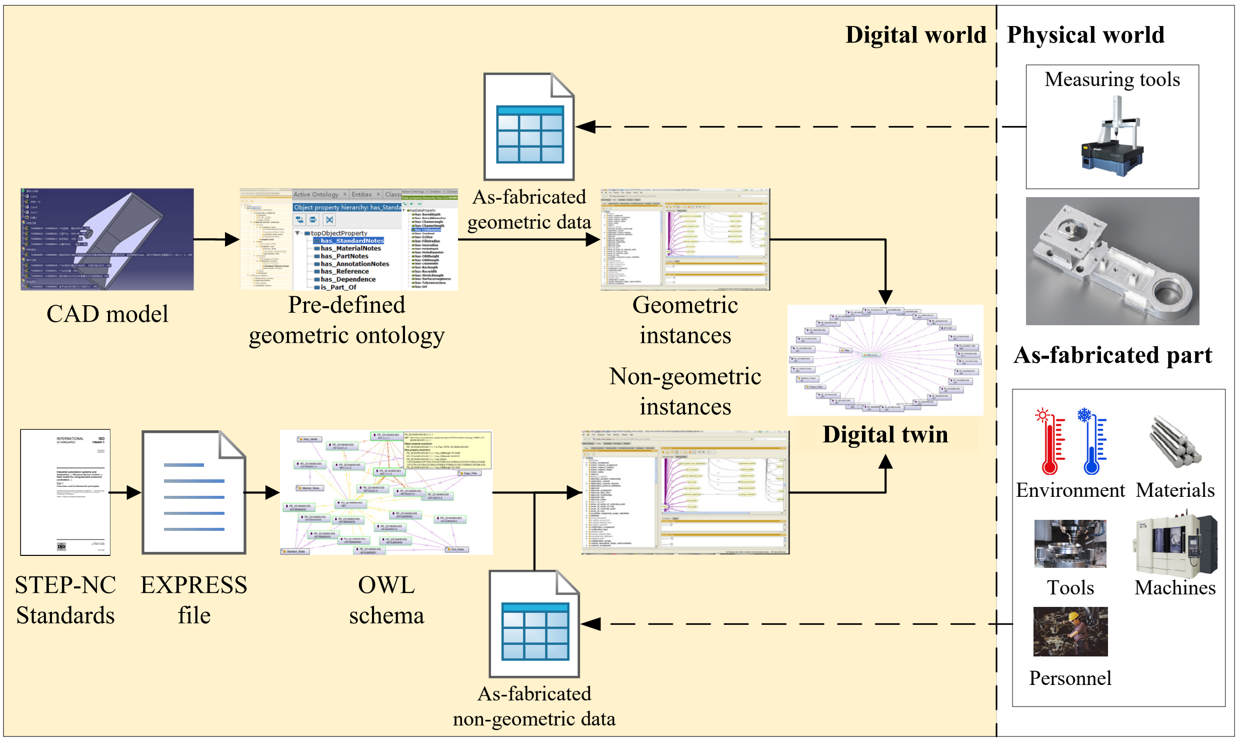

Figure 3: The information modeling method.

3.2.1. Geometric information modeling

As explained before, each part fabricated in a factory has the same information structure consisting of two aspects: geometric and non-geometric. To develop the ontology model requires all the necessary concepts for virtualizing the as-fabricated parts. The geometric ontology in this paper is manually pre-defined. In each CAD system, the relationship between each vertex, line and face is stored in a complex data structure, which is unique according to the system. The reason to manually define a geometric ontology without the use of STEP AP203/214 is that the features and modeling history defined in the CAD systems can be saved conditionally while the STEP AP03/214 can't support this requirement. In the field of mechanical engineering, the main opinion is that the "feature" is the basic semantic descriptor of a CAD model and it is the smallest unit to construct a CAD model. The process of geometric information modeling is divided into four steps and the implementation details will be discussed in the Section 4:

Step 1. The first step is to manually define the geometric ontology model according to the data construction built in the selected CAD system, including classes, object properties and data properties. In this paper, the CAD system is Dassault CATIA V5R18 because this edition is widely deployed and used by the aerospace and defense industry.

Step 2. Secondly, the original designing geometric data are abstracted from the CAD system through its application program interface. Among them, the most important data are the original topological relationships between geometric features. The raw data abstracted from the CAD system are then stored in a MySQL database.

Step 3. The next step is to translate the abstracted information into the pre-defined ontology model using Apache Jena API to create the instances. Apache Jena is a platform-specific rule engine language to interface with an OWL file.

Step 4. Finally, the real value of geometric dimensioning measured by the inspection tools is imported into the CAD system to replace the corresponding designing data.

3.2.2. Non-geometric information modeling

As for the non-geometric information modeling, it is constructed by reusing STEP-NC in this article. The STEP-NC standard is developed to cover the current and expected future needs for data exchange, create an exchangeable and workpiece-oriented data model for CNC machine tools. It is undoubtedly that STEP-NC is suitable for the information modeling of as-fabricated process data. All the concepts and terminologies which are critical for the information modeling are included and formalized. As illustrated in Fig. 4, the figure shows the beginning part of ISO 14649: 10. It can be seen that the schema name of the file is *machining_schema*, followed by the required referenced schemas, specific referenced entities and their corresponding source files. EXPRESS schema is expressed as a network structure of entities, and entities have their own attributes and their value ranges. Entities and attributes construct the basic structure of EXPRESS. The definition of an entity starts with the name of the entity, followed by a description of its relationship with other entities. The entity in Fig. 5 is *machining_workingstep*, which is a subtype of *workingstep*. *machining_workingstep* has three attributes and their corresponding value ranges. Meanwhile, the standard is based on the "closed-world assumption" while the common ontology libraries written in OWL are usually based on the "open-world assumption". In a formal system of logic used for knowledge representation, the open-world assumption believes that the truth value of a statement may be true despite of it is known to be true or not. In contrast the closed-world assumption holds that any statement that is true is also known to be true [59]. This means that if we only model the ontology based on OWL without the help of industry standards, then there is no correct and authoritative way to model the domain when developing a ontology. To ensure the rigor and future scalability of the information structure, the STEP-NC standard is selected to reuse the essential concepts and related important terminology defined in its EXPRESS schema. The modeling process includes four steps and the implementation details will also be presented in the Section 4:

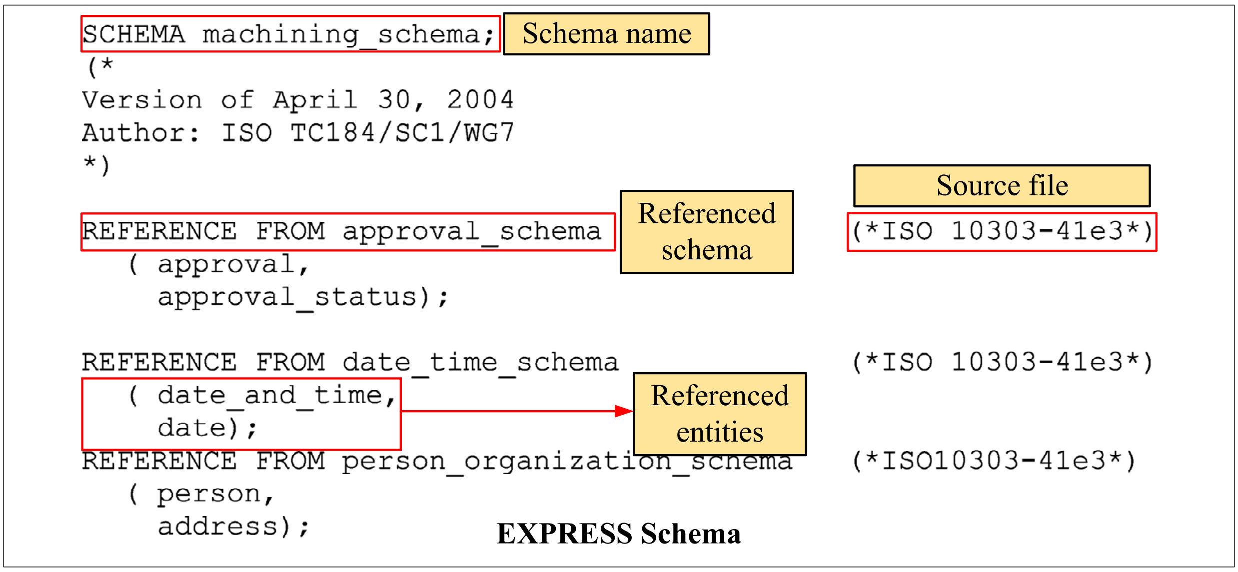

Figure 4: EXPRESS schema.

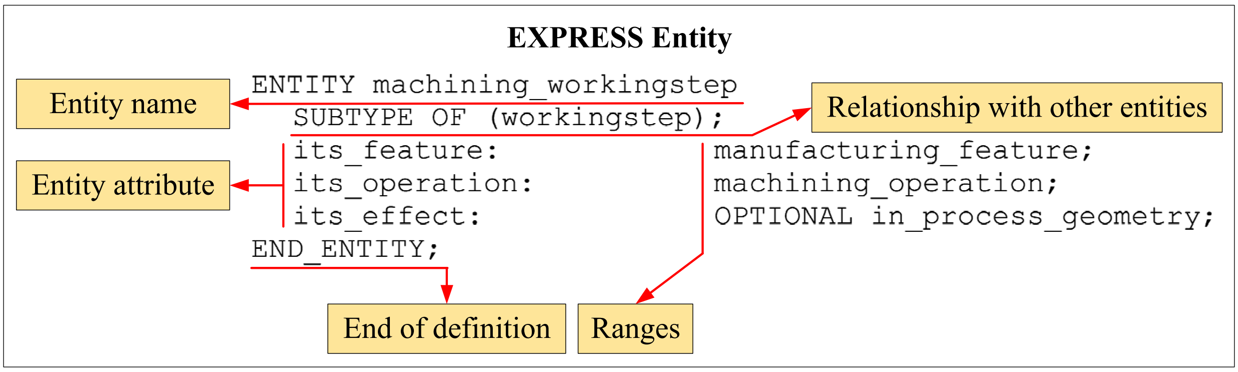

Figure 5: EXPRESS entity.

Step 1. As listed in Table 1, all the used STEP-NC parts in this paper, which are written in EXPRESS, are firstly merged into a combined schema and stored in a EXPRESS file. These parts are fairly enough for information modeling of as-fabricated machining parts because they have been revised several times by ISO and will continue to be updated in the future.

Step 2. Using the OntoSTEP plugin [46], the EXPRESS file is then translated to the OWL schema in the Protege software and stored in an OWL file. The mapping of the basic concepts from EXPRESS to OWL is shown in Table 2. The complete information about the translation rules is available at [46]. After installing the OntoSTEP plugin according to the steps in Fig. 6 and importing the merged EXPRESS file, the EXPRESS schemas will be automatically converted to the ontology written in OWL. After the aforementioned process, the schema shown in Fig. 5 is converted to the ontology shown in Fig. 7, and the relationships can be visualized in the Protege software.

Step 3. Considering the simplicity of the implementation phase in Section 4, the OWL schema are manually trimmed to match the types of as-fabricated data that can be collected in the actual situation. Moreover, to record the additional data such as the temperature and humidity of the workshop, a superclass called ”Environment” is then added because there is still no description about the working environment in the STEP-NC standard parts.

Step 4. Finally, the as-fabricated process data are extracted from the e-document, which are generated by the MES and ERP system, and then manually adjusted according to the manually edited OWL schema. Using the Cellfie plugin [60] built in the Protege software and the Manchester OWL Syntax [61], these data can be quickly imported to the corresponding locations in batches.

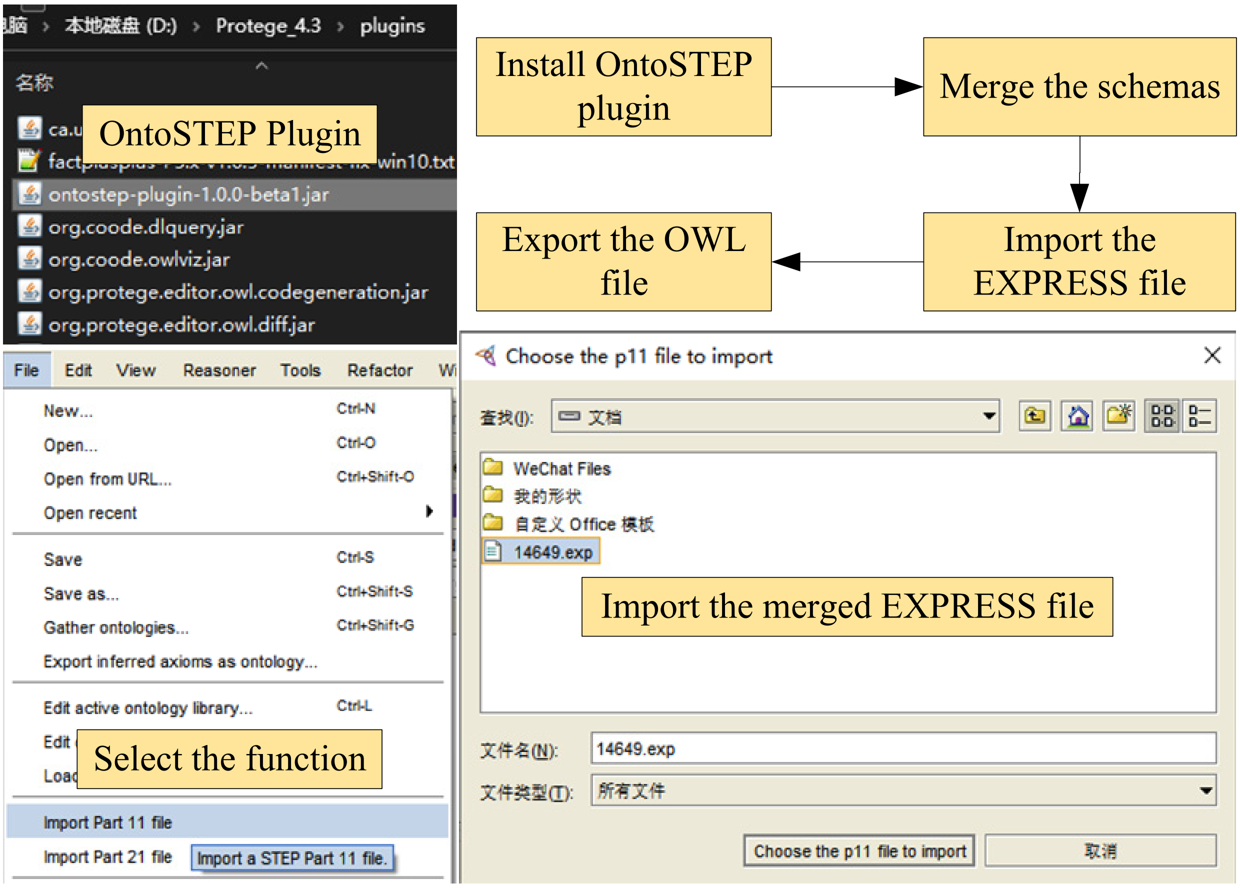

Figure 6: The core processes of translating EXPRESS file into OWL.

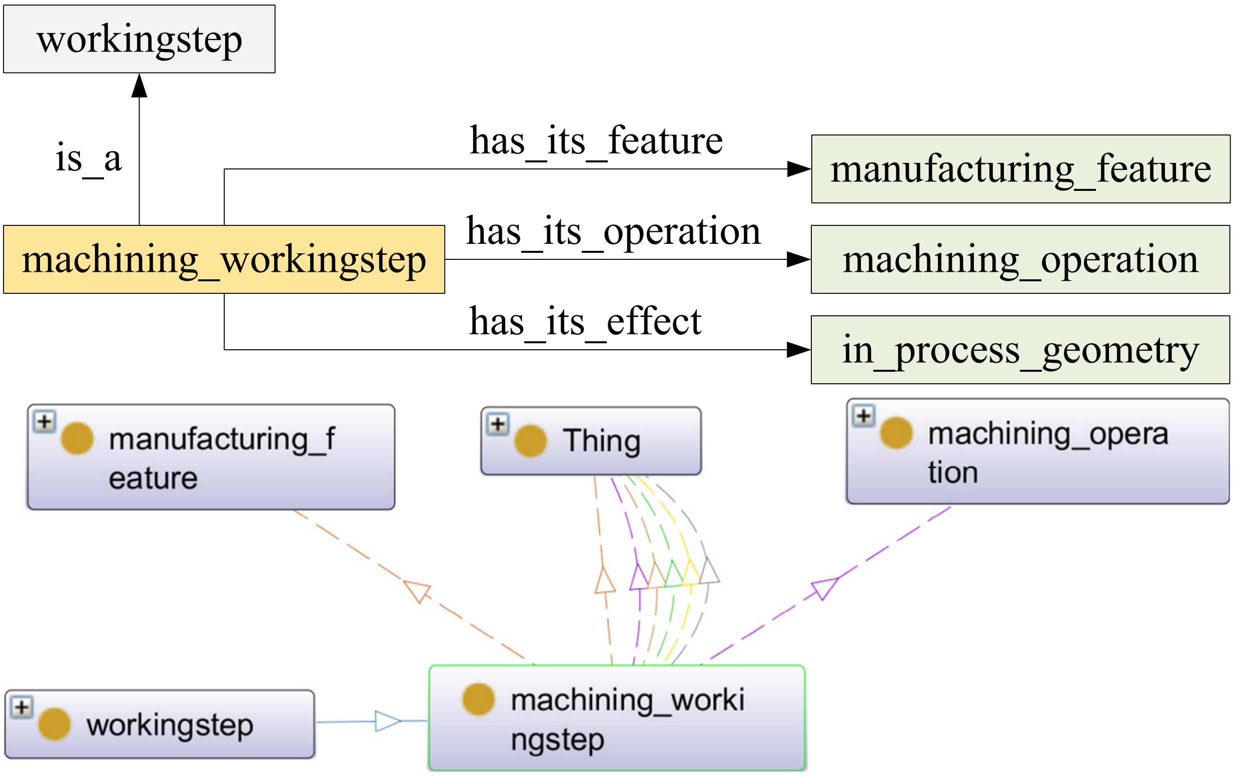

Figure 7: The example of translating EXPRESS into OWL.

Table 1: The used STEP-NC parts.

Part number	Title
ISO 14649: 10	General process data
ISO 14649: 11	Process data for milling
ISO 14649: 12	Process data for turning
ISO 14649: 111	Tools for milling
ISO 14649: 121	Tools for turning
ISO 14649: 201	Machine tool data for cutting process

Table 2: Mapping of the basic concepts from EXPRESS to OWL.

EXPRESS	OWL
Schema	Ontology
Entity	Class
Subtype of	Subclass of
Attribute with an entity type	ObjectProperty
Attribute with a simple data type	DataProperty

3.3. Evaluation of the proposed ontology

Before using the established ontology to create DTs of as-fabricated machining part, the evaluation of the ontology is critical to the quality assurance for the modeling. Various criteria (e.g., consistency, correctness and completeness) have been proposed for the evaluation of ontologies. The consistency can be easily determined by using the built-in reasoners of the Protege software, such as FaCT++, Hermit and Pellet. These tools provide automated ways to check for errors in the proposed ontology, such as redundant terms and inconsistencies between definitions. The correctness requires a domain expert to manually verify that the definitions are correct with reference to the real world. Fortunately, since the proposed ontology in this article was constructed by using the STEP-NC standards, which are based on the "closed-world assumption" and the authority of domain experts, the correctness of the proposed ontology can be guaranteed through the rigor and scalability of the standards. Some criteria can be difficult to evaluate as they may be difficult to quantify and there are no means in place to determine them. For instance, although the completeness of the ontology can be demonstrated, it cannot be proven [62].

4. Case study

This section shows a case study using the proposed method to virtualize the as-fabricated machining parts. The case study selected a typical machining part to validate the proposed methodology in an aviation manufacturing plant. The case study was aimed at the implementation of virtualizing as-fabricated parts in workshop and long-term archiving of as-fabricated data. The final result suggested that the proposed information modeling method and related tools are easy to use for DT creation of as-fabricated machining parts in the cyberspace. The remainder of this section details the process of virtualizing as-fabricated parts in this plant with an overview of the proposed ontology and how it can be used in the future.

4.1. Geometric information ontology

In the field of computer and information science, ontology represents knowledge as a set of concepts within a domain, using a shared vocabulary to denote the types, properties and interrelationships of those concepts [63]. Ontology model can be described as a set $O = \{C, RS, I\}$, where C is a set of concepts (also named classes), I is a set of individual instances, RS represents the relations between two classes. As recommended by the proposed geometric information modeling process in Section 3, the first step is to define the geometric information ontology manually. In this project, all the original CAD models were generated from Dassault CATIA V5R18. According to the definition and classification of modeling features built in CATIA V5R18, the geometric information ontology is defined as illustrated in Fig. 8.

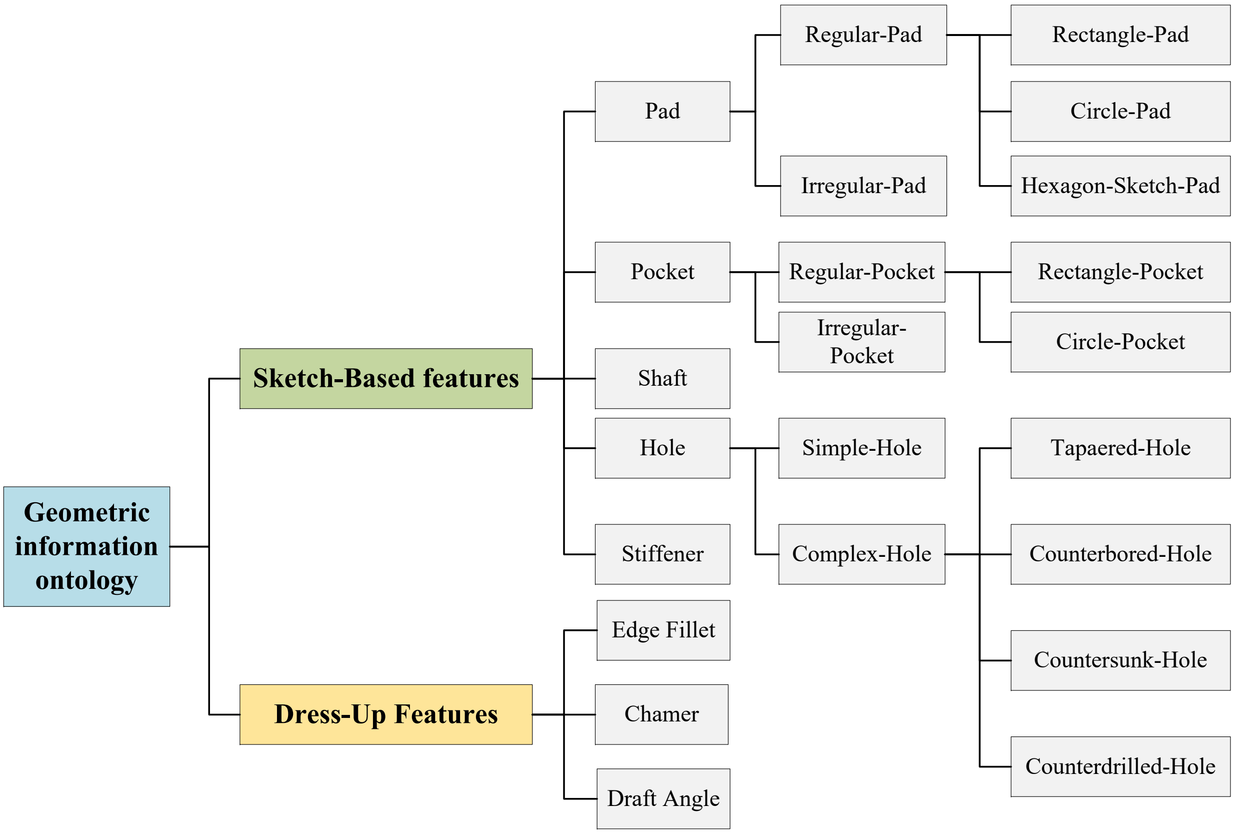

Figure 8: Geometric information ontology.

The *Sketch-Based Features* in CATIA play very significant roles of all the concepts defined in CATIA because they construct the typical geometry shapes. There are five common features belong to *Sketch-Based Features*, namely *Pad*, *Pocket*, *Shaft*, *Stiffener* and *Hole*. On the basis of regularity of the sketch, the class *Pad* can be grouped into *Regular-Pad* and *Irregular-Pad*. As for *Regular-Pad*, it is divided into *Rectangle-Sketch-Pad*, *Circle-Sketch-Pad* and *Hexagon-Sketch-Pad* as depicted in Fig. 9. The *Rectangle-Sketch-Pad* have two specific data properties: the length and width of the rectangle. The *Circle-Sketch-Pad* has the data property representing the diameter of the circle while the *Hexagon-Sketch-Pad* has the data property referring to the radius of hexagon. All of the three kinds of *Regular-Pad* have the same data property named *has-Stretchlength* to represents the height of the pad. Regarding to *Irregular-Pad*, it cannot be described as above because the sketch is irregular. Therefore, the D2 shape distribution [64] is brought in for the description of the shape and the oriented bounding box is used to describe the geometric dimension as given in Fig. 9. The modeling method of *Pocket* is the same as *Pad*. With regard to *Shaft* and *Stiffener*, the D2 shape distribution and the oriented bounding box are the basic descriptors just as *Irregular-Pad*. Finally, *Hole* consists of *Simple-Hole* and *Complex-Hole*. The former has two data properties named *has-Holedepth* and *has-Holediameter* and the latter one is described as shown in Fig. 9. The same approaches are taken to model the class *Dress-Up Features* as presented in Fig. 9. Besides, the class *Draft Angle* is described by the D2 shape distribution and the oriented bounding box.

After the full description of common geometric features built in CATIA V5R18, we defined the property called *has-Dependence* to represent the *RS* between two concepts. As shown in Fig. 10, *F2* depends on *F1* since the sketch of *F2* depends on the top surface of *F1*.

Now that all the definitions of classes and relationship in geometric information ontology are prepared, the next step is to create the instances of all the classes in the ontology model using Apache Jena API. Jena is a platform-specific rule engine language to interface with OWL file. A test part with the real value of GD&T had been translated into the ontology and saved in an OWL file as demonstrated in Fig. 11. Using the Cellfie plugin built in the Protege software and the Manchester OWL Syntax, the real value of GD&T can be quickly imported to the corresponding instances to replace the original designing geometric data in batches.

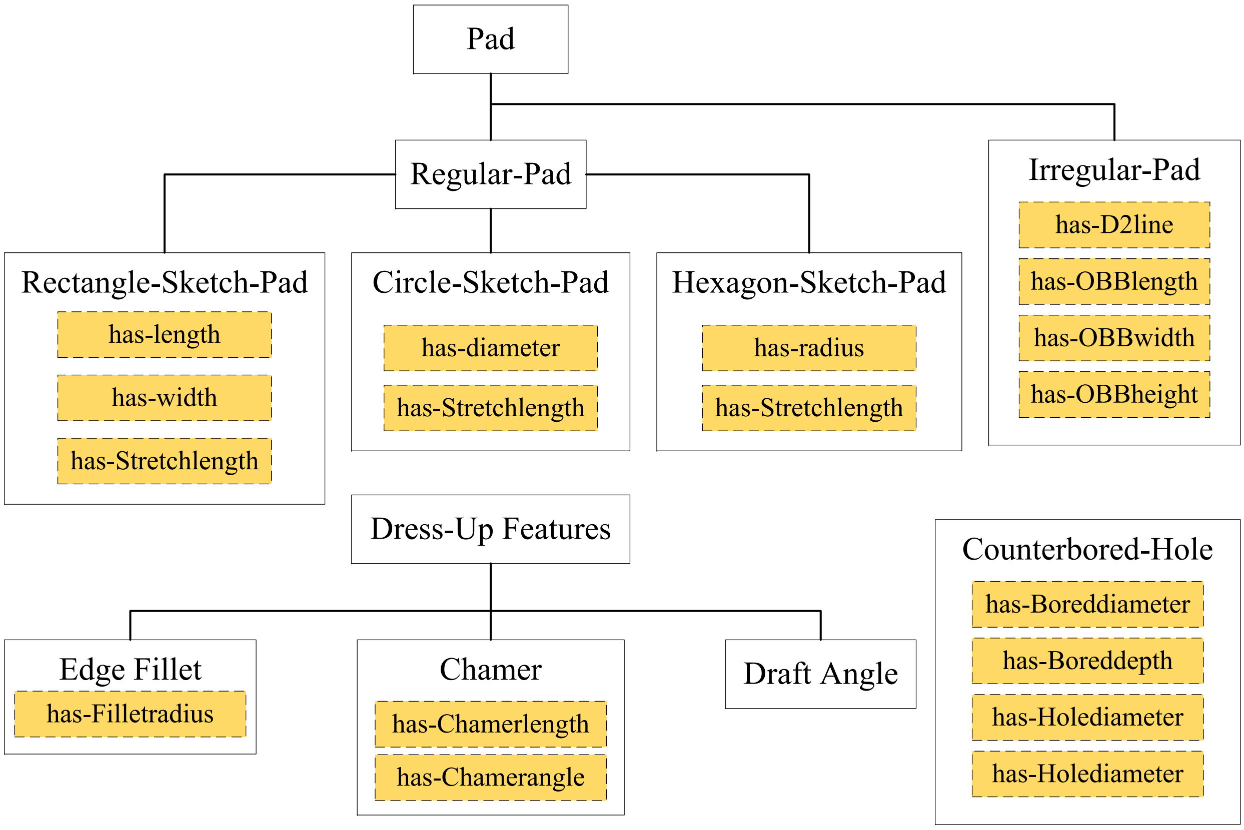

Figure 9: Details of features.

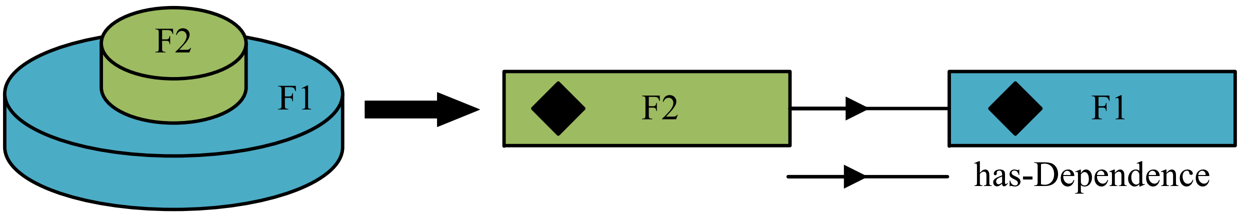

Figure 10: The description of dependence.

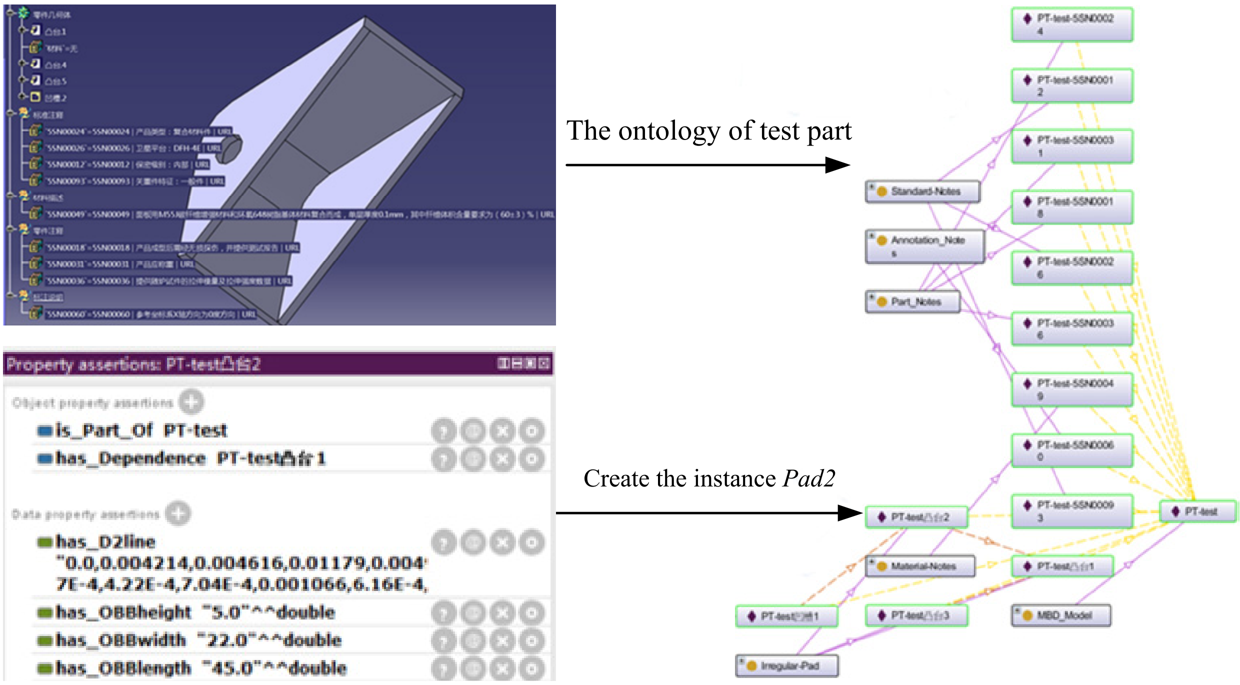

Figure 11: The geometric ontology of a test part.

4.2. Non-geometric information modeling

According to the seven-step method, the second step for creating an ontology is to consider reusing existing ontologies. However, at the time of this research, there is no recommended ontology for the machining process data modeling. Considering the formalization and expandability of the proposed ontology, we decided to use some parts of STEP-NC to translate the related EXPRESS schema to an ontology written in OWL. Thanks to the Protege plugin called OntoSTEP, it is easy to translate the EXPRESS schema into an OWL schema that contains the classes and property definitions. Hence, we merged all the relevant STEP-NC parts into a combined EXPRESS scheme, which consisted of Part 10, Part 11, Part 12, Part 111, Part 121 and Part 201. Then the combined EXPRESS scheme was imported into Protege software and converted into an OWL schema by using OntoSTEP plugin as shown in Fig. 12. The defined entities and instances were successfully translated to OWL classes and individuals.

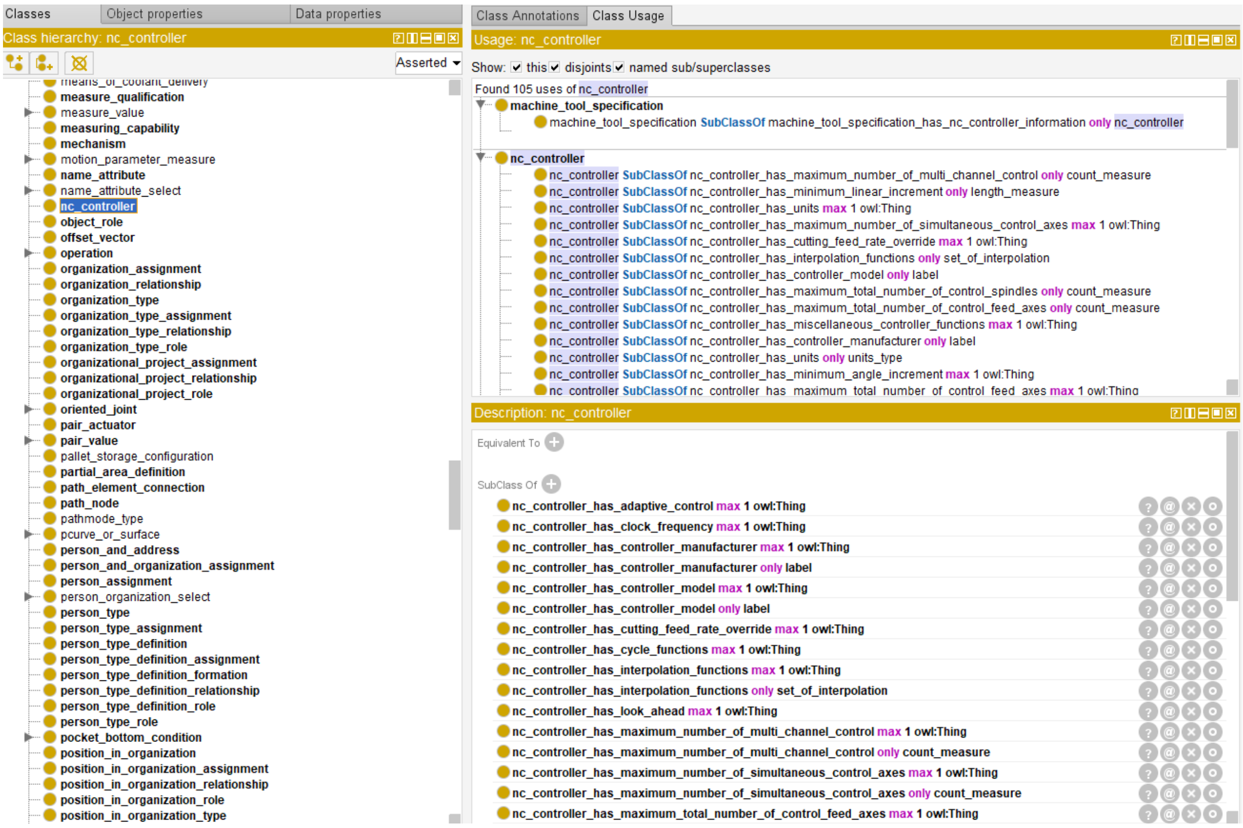

Figure 12: Screenshot of the translation.

To show the effect of conversions, a small subset of the resulting ontology for as-fabricated parts combined with geometric ontology and non-geometric ontology is presented as in Fig. 13. In the generated ontology, all the concepts and terminologies inherited from the superclass Material, Method, Machine and Person are translated from the combined STEP-NC EXPRESS schema. The object properties and data properties are not shown in the figure considering the readability. Also, to reflect the temperature and humidity of the workshop, we manually added the superclass "Environment" since there is no description about the working environment in these parts. So far, the ontology which represents the geometric and non-geometric information of as-fabricated parts is constructed.

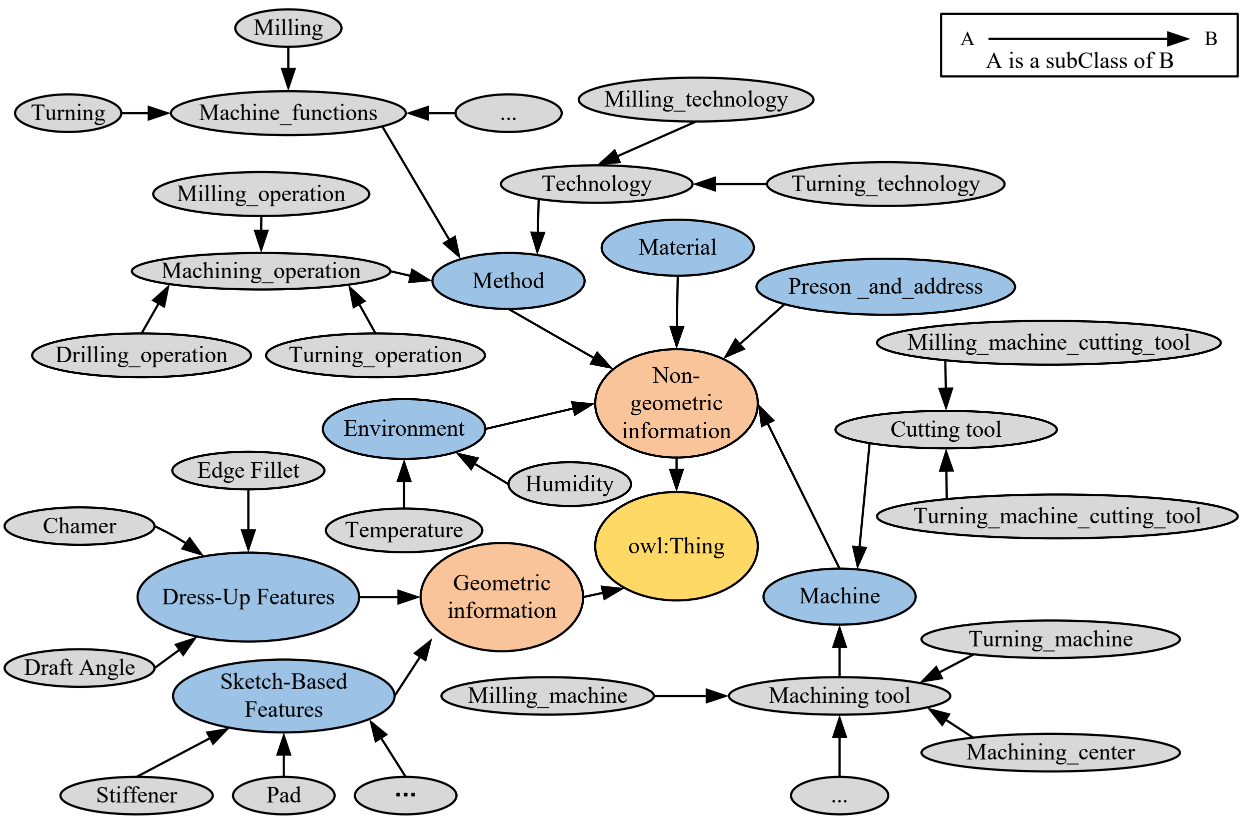

Figure 13: Subset of the as-fabricated part ontology.

4.3. DTs of as-fabricated machining parts

The final step is to create a DT of a test part in the selected plant after the ontology is developed. We took an as-fabricated part given in Fig. 14 in this example, which is much more complex and representative than the one in Fig. 11. Fig. 14 shows the customized graphics user interface to abstract original designing geometric information from the CATIA for creating the instances defined in the geometric information ontology. The raw data abstracted from the CAD system were then stored in the MySQL database. Normally, storing the different kinds of machining parts directly into the database with a fixed structure will lead to complex data structures. However, the types of geometric features of different parts are limited. By decomposing machining parts into collections of geometric features, the storage of features and their corresponding parameters can be easily realized in the database as shown in Fig. 14.

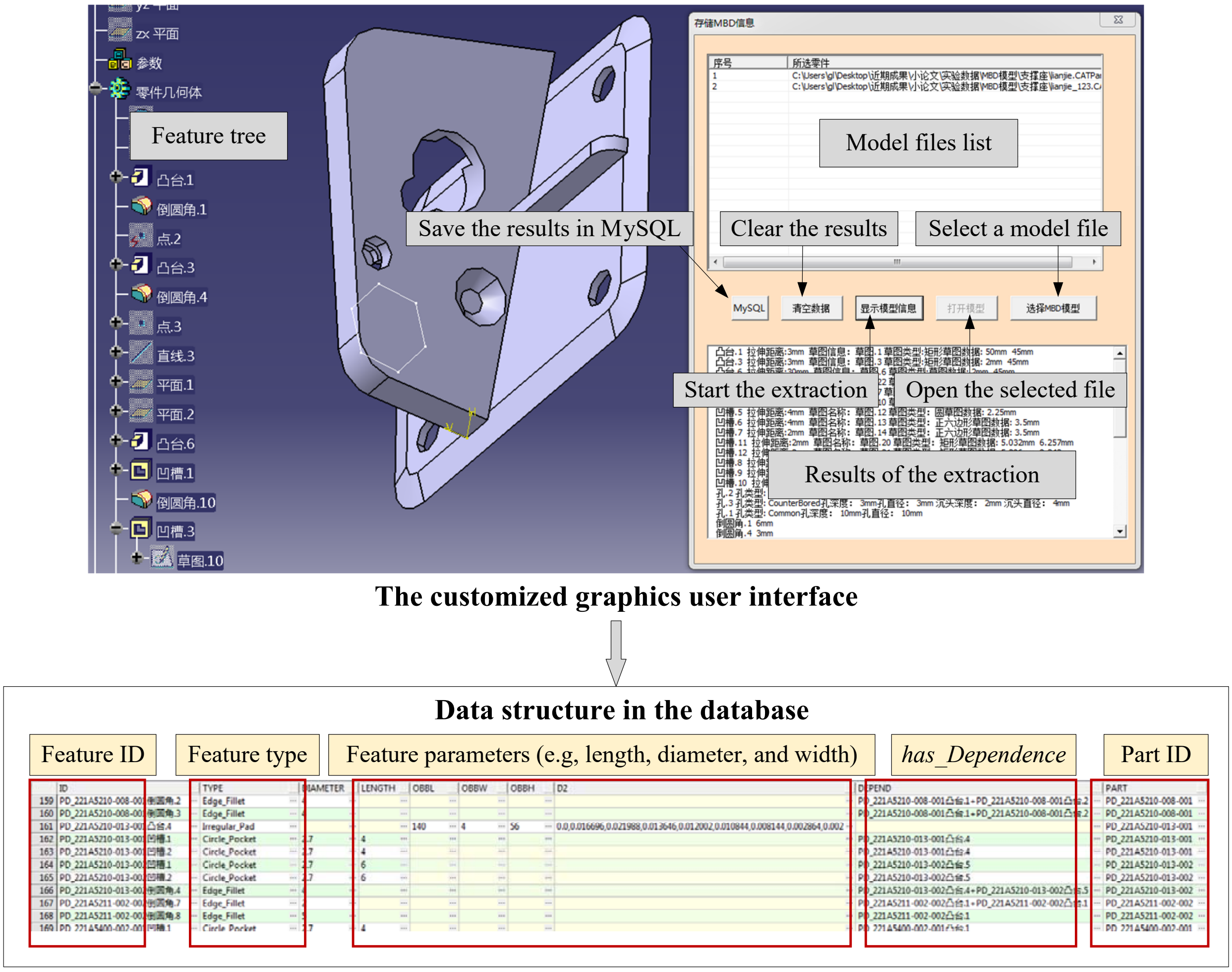

Figure 14: The abstraction of original geometric information.

As shown in Fig. 15, take *Pad 6* for example, the instance of *Irregular-Pad* was implemented with its serial number, object properties and data properties. The serial number acquired from CAD system was *NPT-0001-Pad.6*. The object properties included the relationship between *Pad 6* and the part *NPT-0001* as well as the dependence between *Pad 6* and *Pad 2*. Since the *Pad 6* belonged to the class *Irregular-Pad*, the data properties contained information about D2 shape distribution and the oriented bounding box.

As for the non-geometric information, we selected some process data, which were collected in the aviation manufacturing plant, to illustrate the effect of our proposed ontology model. For example, the type of machining tool used to fabricate the part *NPT-0001* was a machining center. This GROB G350 machining center, which was indexed No.2240180 in the manufacturing plant, was placed in the 17th workshop and the rest information of the machining center in the plant was demonstrated in Fig. 16. Meanwhile, the relevant working steps to fabricate the test part, especially the machining working steps, were also shown in the figure. As shown in Fig. 17, the raw data stored in e-documents were imported in batches with the help of Cellfie plugin and transformation rules manually written in Manchester OWL syntax. Unfortunately, according to the confidentiality regulations in the selected aviation manufacturing plant, the original data cannot be obtained directly from the database and must be manually modified by technicians in the plant. Thus, the original data we obtained for verification is stored in a modified Excel file.

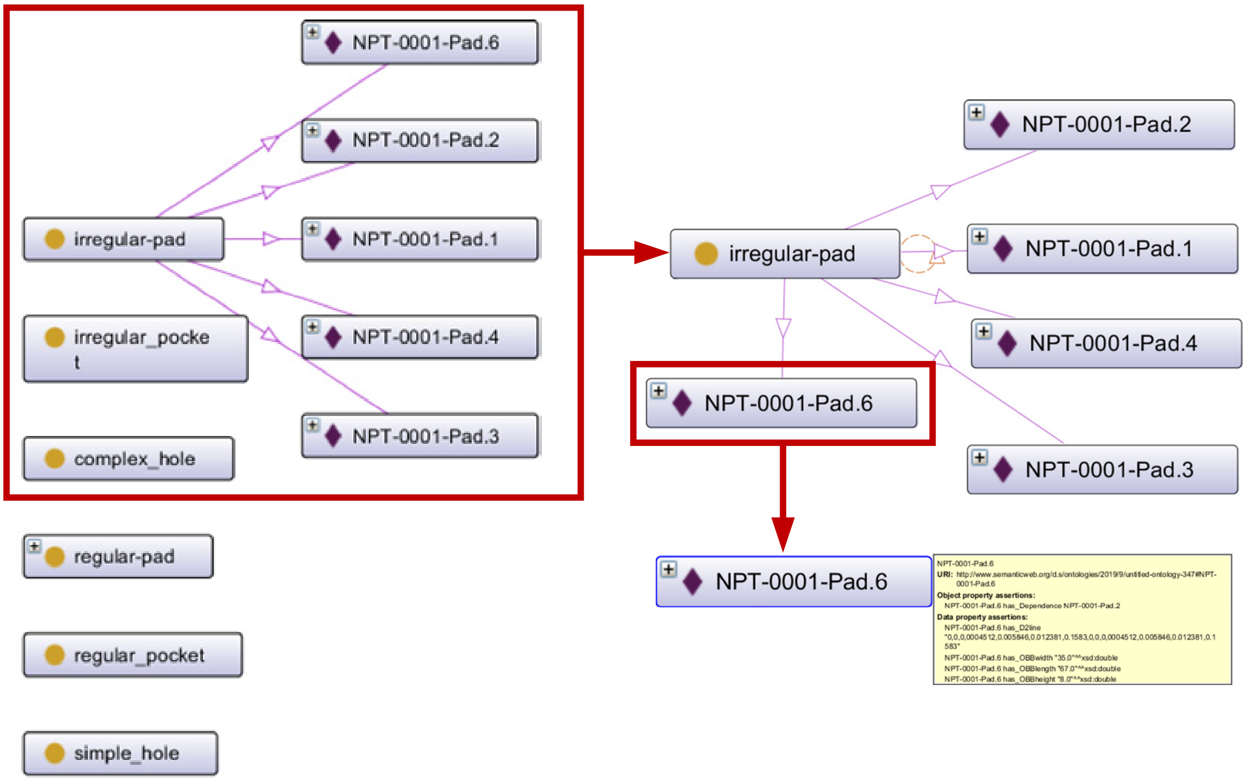

Figure 15: The demonstration of geometric information.

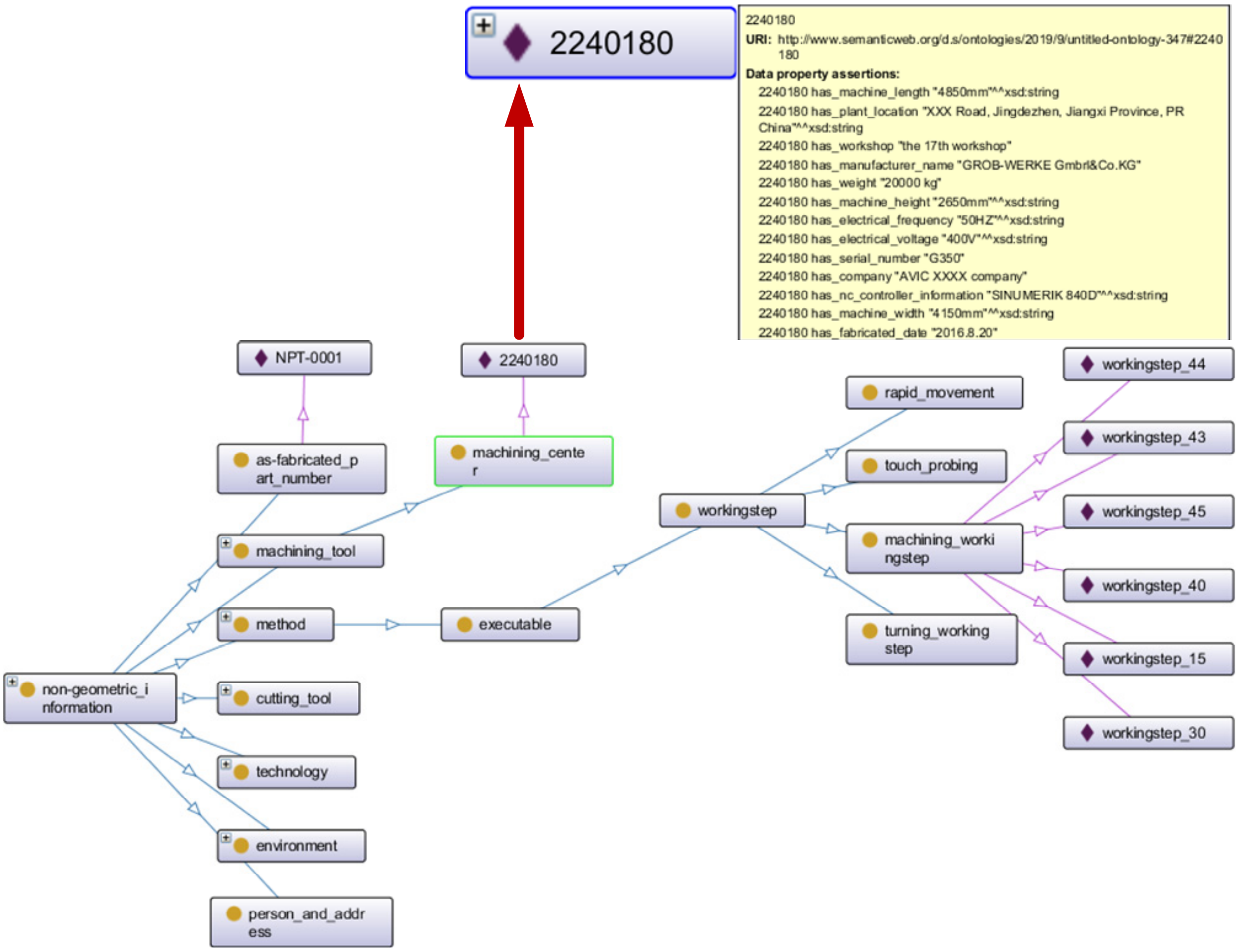

Figure 16: The demonstration of non-geometric information.

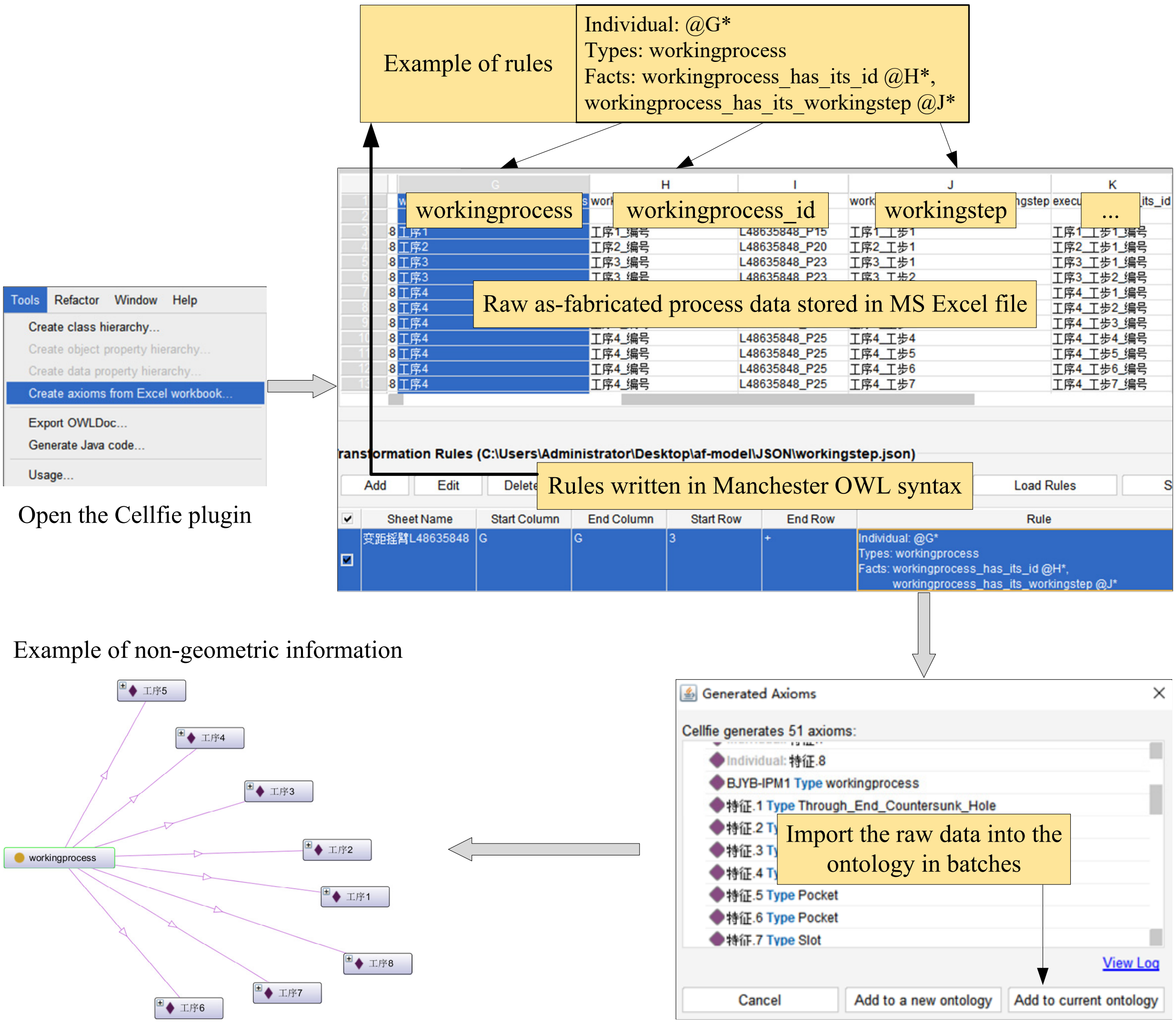

Figure 17: The batch import of as-fabricaed process data.

It can be seen from the above example that the user interface developed in the paper for extracting geometric information was human-friendly. Because the modeling process was visual, the Protege software for ontology modeling was very easy to use. Nevertheless, the Manchester OWL syntax corresponding to the Cellfie plugin is the only challenge for the engineer's exploitation. Fortunately, engineers can quickly master it through the use of the manual due to the clear and easy-to-learn grammar rules. Meanwhile, the Cellfie plugin itself had the function of grammar checking. On the whole, the method proposed in this article can be suitable for daily usage in a manufacturing company.

5. Discussions

With the booming growth of information technologies in the manufacturing industry, remarkable efforts about DT-driven applications are going to challenge the fundamentals of manufacturing systems and operations [31]. Many manufacturing companies nowadays believe that the DT concept could improve the utilization of process knowledge for machining planning. Meanwhile, the knowledge can be mined and discovered by information modeling. From this point of view, the modeling approach to as-fabricated data of machining parts emerges to be pivotal for applying the DT concept to the machining process.

Compared with usual information modeling methods using other languages(e.g., UML, XML and EXPRESS), the proposed method used OWL as a modeling language, which can describe objects and attributes in various fields. Also, it contained rich description vocabulary with better machine-readable capability, which can define complex relationships. Due to the introduction of the STEP-NC standards, the authority, rigor, consistency and scalability of the method may well guarantee the quality of the modeling. Since the amount of raw data was not enough, more detailed and systematic comparisons will be carried out in future research. On the other hand, the proposed method still had some limitations. Because the method was proposed for DT creation of as-fabricated machining parts by using the STEP-NC standards, its versatility in other manufacturing fields were insufficient. In addition, the proposed method focused on the expression of static concepts and their relationships, so it cannot describe dynamic events in the machining process. Therefore, it is necessary to introduce the construction of event ontology to solve the problem in the future.

The proposed ontology-based information modeling method enabled the case factory to create DTs of their as-fabricated parts at the semantic level easily and straightforwardly. The successful implementation was attributed to three key factors: a clear and concise as-fabricated data/information classification, a systematic framework of building DTs for as-fabricated parts and a reasonable and simple approach to modeling kinds of as-fabricated data. Further research with the case factory was found as a simple and standardized process because the data structure had been modeled with explicit machine-readable capability description. Feedback from the case company also highlighted that the proposed methodology made the long-term data archiving much easier because the OWL files were much smaller than original CAD files. Besides, it was much easier to locate and exchange the information stored in an OWL file through the Internet than the original e-documents. Other feedback from the case factory suggested that more complete and human-friendly tools should be provided for creating the instances of the proposed ontology model.

6. Conclusion and future work

With the increasing requirements of information technology in the manufacturing industry, DT-driven applications provide a new attempt to organize and utilize information. The application research of the DT concept is gradually deepening into all aspects of manufacturing industry such as designing, processing and maintenance. However, the development is still at a very early stage and how to model as-fabricated data under the guidance of the DT concept has not been effectively resolved at present. These circumstances are the biggest motivations leading to the study of this article.

Firstly, the recent contribution of DT applications in machining processing was listed and the main challenges were discussed in detail. Because the semantic modeling was used in this article, the recent applications of semantic modeling using OWL were also sorted out as well as the shortcomings. Following the classification of the as-fabricated data, the systematic overview of the proposed framework was illustrated and the four key parts were introduced. The information modeling part, which was the core basis of the proposed framework, was then explained in detail through figures and process demonstration. After the illustration and explanation of the proposed framework and the information modeling method, a case study was undertaken in an aviation manufacturing plant to validate the proposed approach. Based on the feedback of the case company, the project in this paper provided a clear and concise information classification, an easy way to implement geometry information extraction and a standardize information method of as-fabricated process data for companies to create DTs of as-fabricated machining parts easily with the assist of pre-defined geometric information ontology and STEP-NC. In a word, the most important contribution of the proposed methodology is its practicality in the modeling process, making it distinct and easy for companies to adopt. The ontology model can be extended to any type of physical objects virtualization in the plant accompanied with the help of new industry standards. More importantly, this research had broadened the DT concept into a much more practical level.

All in all, the proposed research in this paper tried to fill the gap that the industry requires a practical and easy way to enable companies to virtualize their as-fabricated machining parts for DT creation. As mentioned before, based on the as-fabricated information modeling method that follows the DT concept, the abandoned as-fabricated data can help engineers to perform evaluation and optimization of machining processes by discovering the hidden knowledge. Thus, further research can potentially be done in the area of the interconnection of Protege, MES, ERP and different

CAD systems. The attempts to merge full lifecycle product data should also be the focus of future research with the supports of other STEP APs.

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References

[1] P. D. U. Coronado, R. Lynn, W. Louhichi, M. Parto, E. Wescoat, T. Kurfess, Part data integration in the shop floor digital twin: Mobile and cloud technologies to enable a manufacturing execution system, Journal of Manufacturing Systems 48 (2018) 25–33. doi:10.1016/j.jmsy.2018.02.002.

[2] M. Grieves, J. Vickers, Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems, in: Transdisciplinary Perspectives on Complex Systems, Springer International Publishing, 2016, pp. 85–113. doi:10.1007/978-3-319-38756-7_4.

[3] Y. Lu, X. Xu, Resource virtualization: A core technology for developing cyber-physical production systems, Journal of Manufacturing Systems 47 (2018) 128–140. doi:10.1016/j.jmsy.2018.05.003.

[4] R. Rosen, G. von Wichert, G. Lo, K. D. Bettenhausen, About the importance of autonomy and digital twins for the future of manufacturing, IFAC-PapersOnLine 48 (2015) 567–572. doi:10.1016/j.ifacol.2015.06.141.

[5] M. Grieves, Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management, Space Coast Press, 2011.

[6] C. Li, S. Mahadevan, Y. Ling, S. Choze, L. Wang, Dynamic bayesian network for aircraft wing health monitoring digital twin, AIAA Journal 55 (2017) 930–941. doi:10.2514/1.j055201.

[7] M. Heidari, E. Allameh, B. de Vries, H. Timmermans, J. Jessurun, F. Mozaffar, Smart-BIM virtual prototype implementation, Automation in Construction 39 (2014) 134–144. doi:10.1016/j.autcon.2013.07.004.

[8] E. A. Patterson, M. Feligiotti, E. Hack, On the integration of validation, quality assurance and non-destructive evaluation, The Journal of Strain Analysis for Engineering Design 48 (2012) 48–58. doi:10.1177/0309324712444681.

[9] E. A. Patterson, R. J. Taylor, M. Bankhead, A framework for an integrated nuclear digital environment, Progress in Nuclear Energy 87 (2016) 97–103. doi:10.1016/j.pnucene.2015.11.009.

[10] B. Schleich, N. Anwer, L. Mathieu, S. Wartzack, Shaping the digital twin for design and production engineering, CIRP Annals 66 (2017) 141–144. doi:10.1016/j.cirp.2017.04.040.

[11] X. Sun, J. Bao, J. Li, Y. Zhang, S. Liu, B. Zhou, A digital twin-driven approach for the assembly-commissioning of high precision products, Robotics and Computer-Integrated Manufacturing 61 (2020) 101839. doi:10.1016/j.rcim.2019.101839.

[12] X. Xu, Machine tool 4.0 for the new era of manufacturing, The International Journal of Advanced Manufacturing Technology 92 (2017) 1893–1900. doi:10.1007/s00170-017-0300-7.

[13] F. Tao, M. Zhang, Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing, IEEE Access 5 (2017) 20418–20427. doi:10.1109/access.2017.2756069.

[14] F. Tao, M. Zhang, J. Cheng, Q. Qi, Digital twin workshop: a new paradigm for future workshop, Computer Integrated Manufacturing Systems 23 (2017) 1–9. URL: 10.13196/j.cims.2017.01.001.

[15] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, F. Sui, Digital twin-driven product design, manufacturing and service with big data, The International Journal of Advanced Manufacturing Technology 94 (2017) 3563–3576. doi:10.1007/s00170-017-0233-1.

[16] C. Liu, X. Xu, Q. Peng, Z. Zhou, MTConnect-based cyber-physical machine tool: a case study, Procedia CIRP 72 (2018) 492–497. doi:10.1016/j.procir.2018.03.059.

[17] C. Liu, H. Vengayil, R. Y. Zhong, X. Xu, A systematic development method for cyber-physical machine tools, Journal of Manufacturing Systems 48 (2018) 13–24. doi:10.1016/j.jmsy.2018.02.001.

[18] F. Tao, M. Zhang, Y. Liu, A. Nee, Digital twin driven prognostics and health management for complex equipment, CIRP Annals 67 (2018) 169–172. doi:10.1016/j.cirp.2018.04.055.

[19] Y. Lu, X. Xu, Cloud-based manufacturing equipment and big data analytics to enable on-demand manufacturing services, Robotics and Computer-Integrated Manufacturing 57 (2019) 92–102. doi:10.1016/j.rcim.2018.11.006.

[20] F. Tao, H. Zhang, A. Liu, A. Y. C. Nee, Digital twin in industry: State-of-the-art, IEEE Transactions on Industrial Informatics 15 (2019) 2405–2415. doi:10.1109/tii.2018.2873186.

[21] J. O. Oyekan, W. Hutabarat, A. Tiwari, R. Grech, M. H. Aung, M. P. Mariani, L. López-Dávalos, T. Ricaud, S. Singh, C. Dupuis, The effectiveness of virtual environments in developing collaborative strategies between industrial robots and humans, Robotics and Computer-Integrated Manufacturing 55 (2019) 41–54. doi:10.1016/j.rcim.2018.07.006.

[22] T. Petković, D. Puljiz, I. Marković, B. Hein, Human intention estimation based on hidden markov model motion validation for safe flexible robotized warehouses, Robotics and Computer-Integrated Manufacturing 57 (2019) 182–196. doi:10.1016/j.rcim.2018.11.004.

[23] W. Wang, Y. Zhang, R. Y. Zhong, A proactive material handling method for CPS enabled shop-floor, Robotics and Computer-Integrated Manufacturing 61 (2020) 101849. doi:10.1016/j.rcim.2019.101849.

[24] J. Liu, H. Zhou, G. Tian, X. Liu, X. Jing, Digital twin-based process reuse and evaluation approach for smart process planning, The International Journal of Advanced Manufacturing Technology 100 (2018) 1619–1634. doi:10.1007/s00170-018-2748-5.

[25] F. Tao, W. Liu, J. Liu, X. Liu, Digital twin and its potential application exploration, Computer Integrated Manufacturing Systems 24 (2018) 1–18. doi:10.13196/j.cims.2018.01.001.
[26] A. Angrish, B. Starly, Y.-S. Lee, P. H. Cohen, A flexible data schema and system architecture for the virtualization of manufacturing machines (VMM), Journal of Manufacturing Systems 45 (2017) 236–247. doi:10.1016/j.jmsy.2017.10.003.
[27] M. W. Grieves, Product lifecycle management: the new paradigm for enterprises, International Journal of Product Development 2 (2005) 71. doi:10.1504/ijpd.2005.006669.
[28] G. Githens, Product lifecycle management: Driving the next generation of lean thinking by michael grieves, Journal of Product Innovation Management 24 (2007) 278–280. doi:10.1111/j.1540-5885.2007.00250_2.x.
[29] E. Glaessgen, D. Stargel, The digital twin paradigm for future NASA and u.s. air force vehicles, in: 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, American Institute of Aeronautics and Astronautics, 2012, p. 1818. doi:10.2514/6.2012-1818.
[30] S. Weyer, T. Meyer, M. Ohmer, D. Gorecky, D. Zühlke, Future modeling and simulation of CPS-based factories: an example from the automotive industry, IFAC-PapersOnLine 49 (2016) 97–102. doi:10.1016/j.ifacol.2016.12.168.
[31] Y. Lu, C. Liu, K. I.-K. Wang, H. Huang, X. Xu, Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues, Robotics and Computer-Integrated Manufacturing 61 (2020) 101837. doi:10.1016/j.rcim.2019.101837.
[32] J. Bao, D. Guo, J. Li, J. Zhang, The modelling and operations for the digital twin in the context of manufacturing, Enterprise Information Systems 13 (2018) 534–556. doi:10.1080/17517575.2018.1526324.
[33] M. Helu, A. Joseph, T. Hedberg, A standards-based approach for linking as-planned to as-fabricated product data, CIRP Annals 67 (2018) 487–490. doi:10.1016/j.cirp.2018.04.039.
[34] X. V. Wang, L. Wang, Digital twin-based WEEE recycling, recovery and remanufacturing in the background of industry 4.0, International Journal of Production Research 57 (2018) 3892–3902. doi:10.1080/00207543.2018.1497819.
[35] J. Liu, H. Zhou, X. Liu, G. Tian, M. Wu, L. Cao, W. Wang, Dynamic evaluation method of machining process planning based on digital twin, IEEE Access 7 (2019) 19312–19323. doi:10.1109/access.2019.2893309.
[36] G. Zhou, C. Zhang, Z. Li, K. Ding, C. Wang, Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing, International Journal of Production Research 58 (2019) 1034–1051. doi:10.1080/00207543.2019.1607978.
[37] S.-H. Suh, Y. Seo, S.-M. Lee, T.-H. Choi, G.-S. Jeong, D.-Y. Kim, Modelling and implementation of internet-based virtual machine tools, The International Journal of Advanced Manufacturing Technology 21 (2003) 516–522. doi:10.1007/s001700300061.
[38] W. Yang, X. Xu, Modelling machine tool data in support of STEP-NC based manufacturing, International Journal of Computer Integrated Manufacturing 21 (2008) 745–763. doi:10.1080/09511920701810691.
[39] F. Tanaka, M. Onosato, T. Kishinami, K. Akama, M. Yamada, T. Kondo, S. Mistui, Modeling and implementation of digital semantic machining models for 5-axis machining application, in: Manufacturing Systems and Technologies for the New Frontier, Springer London, 2008, pp. 177–182. doi:10.1007/978-1-84800-267-8_36.
[40] A. Moreno, G. Velez, A. Ardanza, I. Barandiaran, Á. R. de Infante, R. Chopitea, Virtualisation process of a sheet metal punching machine within the industry 4.0 vision, International Journal on Interactive Design and Manufacturing (IJIDeM) 11 (2016) 365–373. doi:10.1007/s12008-016-0319-2.
[41] W. Luo, T. Hu, C. Zhang, Y. Wei, Digital twin for CNC machine tool: modeling and using strategy, Journal of Ambient Intelligence and Humanized Computing 10 (2018) 1129–1140. doi:10.1007/s12652-018-0946-5.
[42] D. Botkina, M. Hedlind, B. Olsson, J. Henser, T. Lundholm, Digital twin of a cutting tool, Procedia CIRP 72 (2018) 215–218. doi:10.1016/j.procir.2018.03.178.
[43] P. Zheng, A. S. Sivabalan, A generic tri-model-based approach for product-level digital twin development in a smart manufacturing environment, Robotics and Computer-Integrated Manufacturing 64 (2020) 101958. doi:10.1016/j.rcim.2020.101958.
[44] Q. Qi, F. Tao, Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison, IEEE Access 6 (2018) 3585–3593. doi:10.1109/access.2018.2793265.
[45] K. Y. H. Lim, P. Zheng, C.-H. Chen, A state-of-the-art survey of digital twin: techniques, engineering product lifecycle management and business innovation perspectives, Journal of Intelligent Manufacturing (2019). doi:10.1007/s10845-019-01512-w.
[46] R. Barbau, S. Krima, S. Rachuri, A. Narayanan, X. Fiorentini, S. Foufou, R. D. Sriram, OntoSTEP: Enriching product model data using ontologies, Computer-Aided Design 44 (2012) 575–590. doi:10.1016/j.cad.2012.01.008.
[47] N. Wan, R. Mo, L. Liu, J. Li, New methods of creating MBD process model: On the basis of machining knowledge, Computers in Industry 65 (2014) 537–549. doi:10.1016/j.compind.2013.12.005.
[48] K. Eum, M. Kang, G. Kim, M. W. Park, J. K. Kim, Ontology-based modeling of process selection knowledge for machining feature, International Journal of Precision Engineering and Manufacturing 14 (2013) 1719–1726. doi:10.1007/s12541-013-0231-7.
[49] L. Solano, F. Romero, P. Rosado, An ontology for integrated machining and inspection process planning focusing on resource capabilities, International Journal of Computer Integrated Manufacturing (2015) 1–15. doi:10.1080/0951192x.2014.1003149.
[50] L. Qiao, S. Kao, Y. Zhang, Manufacturing process modelling using process specification language, The International Journal of Advanced Manufacturing Technology 55 (2011) 549–563. doi:10.1007/s00170-010-3115-3.
[51] J. Jang, B. Jeong, B. Kulvatunyou, J. Chang, H. Cho, Discovering and integrating distributed manufacturing services with semantic manufacturing capability profiles, International Journal of Computer Integrated Manufacturing 21 (2008) 631–646. doi:10.1080/09511920701350920.
[52] T. Kjellberg, A. von Euler-Chelpin, M. Hedlind, M. Lundgren, G. Sivard, D. Chen, The machine tool model—a core part of the digital factory, CIRP Annals 58 (2009) 425–428. doi:10.1016/j.cirp.2009.03.035.
[53] Y. Y. Zhao, Q. Liu, W. J. Xu, L. Gao, Modeling of resources capability for manufacturing equipments in cloud manufacturing, Applied Mechanics and Materials 271-272 (2012) 447–451. doi:10.4028/www.scientific.net/amm.271-272.447.
[54] S. E. Kadiri, D. Kiritsis, Ontologies in the context of product lifecycle management: state of the art literature review, International Journal of Production Research 53 (2015) 5657–5668. doi:10.1080/00207543.2015.1052155.
[55] S. P. Ruemler, K. E. Zimmerman, N. W. Hartman, T. Hedberg, A. B. Feeny, Promoting model-based definition to establish a complete product

definition, Journal of Manufacturing Science and Engineering 139 (2016). doi:10.1115/1.4034625.
[56] X. Liu, X. Li, J. Xing, H. Chen, Z. Ni, Integrating modeling mechanism for three-dimensional casting process model based on MBD, The International Journal of Advanced Manufacturing Technology 94 (2016) 3145–3162. doi:10.1007/s00170-016-9479-2.
[57] E. V. Koonin, The Logic of Chance: The Nature and Origin of Biological Evolution (FT Press Science), FT Press, 2011.
[58] J. Rowley, The wisdom hierarchy: representations of the DIKW hierarchy, Journal of Information Science 33 (2007) 163–180. doi:10.1177/0165551506070706.
[59] P. N. Stuart Russell, Artificial Intelligence, Pearson, 2019.
[60] M. J. O'Connor, C. Halaschek-Wiener, M. A. Musen, Mapping master: A flexible approach for mapping spreadsheets to OWL, in: Lecture Notes in Computer Science, Springer Berlin Heidelberg, 2010, pp. 194–208. doi:10.1007/978-3-642-17749-1_13.
[61] M. Horridge, N. Drummond, J. Goodwin, A. L. Rector, R. Stevens, H. Wang, The manchester owl syntax., in: OWLed, volume 216, 2006.
[62] J. Yu, J. A. Thom, A. Tam, Requirements-oriented methodology for evaluating ontologies, Information Systems 34 (2009) 766–791. doi:10.1016/j.is.2009.04.002.
[63] M. Uschold, M. Gruninger, Ontologies: principles, methods and applications, The Knowledge Engineering Review 11 (1996) 93–136. doi:10.1017/s0269888900007797.
[64] R. Osada, T. Funkhouser, B. Chazelle, D. Dobkin, Shape distributions, ACM Transactions on Graphics 21 (2002) 807–832. doi:10.1145/571647.571648.