The Ontology-Based Modeling and Evolution of Digital Twin for Assembly Workshop

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The ontology-based modeling and evolution of digital twin for assembly workshop

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Abstract Digital twin (DT) technology has been entrusted with the tasks of modeling and monitoring of the product, process and production system. Moreover, the development of semantic modeling and digital perception provides the feasibility for the application of DT in the manufacturing industry. However, the application of DT technology in assembly workshop modeling and management is immature for the discreteness of assembly process, diversity of assembly resource and complexity of dataflow in the assembly task execution. A method of ontology-based modeling and evolution of DT for the assembly workshop is proposed to deal with this situation. Firstly, the ontology-based modeling method is given for the assembly resource and process. By instantiating in the ontology, resources and processes can be involved in the modeling and evolution of the DT workshop. Secondly, the DT assembly workshop framework is introduced with the detailed discussions of dataflow mapping, DT evolution, storage and tracing of historical data generated during the operation of the workshop. In addition, a case study is illustrated to show the entire process of construction and evolution of DT modeled on an experimental field, indicating the feasibility and validity of the method proposed.

Keywords Assembly workshop · Digital twin modeling · Digital twin evolution · Ontology · Dataflow · Historical data

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1 Introduction

Nowadays, with the trend of agile and personalized manufacturing, modern enterprises are facing emerging problems, such as real-time perception and modeling of production data within fields, timely adjustment and distribution of production instructions, lightweight storage and tracing of historical data[31][26]. To address these problems, the concept of Industry 4.0[29] was proposed with the initiative of developing efficient production with flexible workflow for producing high-quality personalized product at low cost. With the deepening of Industry 4.0, the explorations of smart manufacturing and smart factory are gradually transitioning from theoretical research to engineering application.

In the research and practice of Industry 4.0, the concept of digital twin (DT) was proposed firstly by Grieves[13][12] as a set of virtual information structures that fully describes a potential or actual physical product or system. The idea of DT provides a solution of reference model constructing in mirroring the actual condition of object or system instead of 3D model, fulfilling the physical-virtual convergence to a large extent[51].

As an important part of the manufacturing field, assembly is also evolving into a new stage with intelligence, as shown in Figure 1. The prospect of smart assembly based on DT model and digital document is increasingly clear as the future-oriented assembly pattern. With the characteristics of discreteness, complexity and unpredictability, the development of intelligent assembly requires a comprehensive and extensible model that can describe the assembly production system. Address this need, the DT modeling of assembly workshop can provide an effective scheme in dealing with the abundant data interactions and various data sources in the workshop[5].

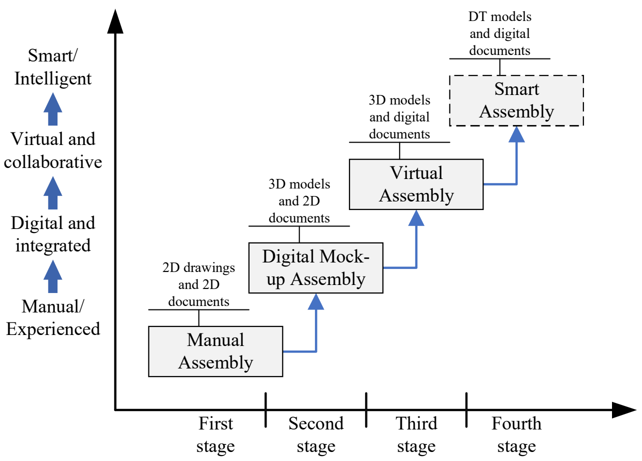

Fig. 1 Product assembly technology development[54].

Meanwhile, the mature developments and extensive applications of semantic web provide a suitable modeling method for the DT assembly workshop. As the representative language of the semantic web, ontology web language (OWL) has been researched in a large scale, resulting in certain advantages in the modeling of multi-source heterogeneous data. During the execution of the assembly process in the workshop, massive data describing attributes and relationships will be generated by the equipment, tool, material, personnel and other resources. With OWL, the modeling of DT assembly workshop can be unified in one evolving ontology, which creates the condition for the sharing of production capacity under the trend of cloud manufacturing. On the other hand, the ontology file with tiny size and excellent readability provides convenience for the long-term archiving and tracing of historical data. Generated with preset time interval or by triggering mechanism, one ontology snapshot can describe a momentary state of the assembly workshop. An evolving ontology and considerable static ontology snapshots constitute the data carrier of the assembly workshop jointly, participating in the modeling of DT assembly workshop.

Based on the ontology technology, a method of DT assembly workshop modeling and evolution is proposed in this manuscript. In this approach, the assembly resource and process are analyzed and modeled separately. On this basis, the framework of DT assembly workshop is constructed, which is considered as the key contribution of the presented research. Then, the operating mechanism of the framework are discussed in detail to evidence the feasibility and advancement of the DT presented.

The remainder of this work is organized as follows: Section 2 reviews the related work about modeling of DT workshop and ontological approaches in manufacturing and assembly. Section 3 explains the methodology of DT assembly workshop modeling with detailed discussions. On this basis, Section 4 describes the framework of DT assembly workshop concerning the mapping of assembly dataflow, evolution pattern, storage and tracing of historical data. In addition, a case study of the application is provided in Section 5 to validate the rationality of the method proposed. Finally, Section 6 presents the conclusions and discusses future work.

2 Literature review

This research aims to establish an ontology-based DT assembly workshop which can express the status of resource and process along with the dataflow generated in the field semantically. This section gives a systematic literature review of the latest development in the areas of DT workshop modeling and representative ontological approaches in manufacturing and assembly.

2.1 Modeling of DT workshop

DT refers to digital equivalents of the physical product, process and system, which are used for describing and modeling the corresponding physical counterparts[1]. The researches on DT principally concentrate on the product, process and system, which reflects that the applications of DT are transformed from static modeling to dynamic operation and service.

Product DT modeling and monitoring, as the original intension of DT technology, have been studied continuously to meet the increasingly diverse needs of analyses and applications. On one hand, automation markup language (AutomationML) plays a crucial role in information modeling[41][44]. As a standardized modeling language, AutomationML offers a possibility for product description, leading to a collaborative and interactive network-centric approach of product design and process planning. On the other hand, a comprehensive reference model[40] and an extended model-based definition[30] for shaping the DTs of products were provided. Besides, multiple DT models of products have been established and discussed to solve the problems of health monitoring[20][55], maintenance[43], fault diagnosis and quality prediction[27] such as finite element analysis model, Modelica Multiphysics model and statistical model, which greatly enriches the methodology of DT modeling.

The execution of the process is the primary force for workshop operation in physical space as well for dataflow circulation in cyber space. Kuliaev et al.[18] proposed a comprehensive solution that allows product-centric manufacturing and covers lifecycle from digital product description to physical assembly. Furthermore, the reference model for the classification of product assembly data was presented with multiple dimensions[59], in which the primary structure and version management of process were taken into account. Some applied studies[38] have shown that DTs of the product and process can effectively speed up the information interaction in manufacturing, thus improving the processing quality and time.

With the development of DT technology, modeling of the manufacturing system has attracted most attention. The concept of DT workshop was firstly proposed in 2017 by Tao et al.[51] with the operation mechanism, modeling method and key technologies, which has pioneered DT attempts in the dimension of workshop or manufacturing system. Thanks to the progress of sensory perceptual system and communication technology, the construction of manufacturing systems in cyber space by sensor systems[53] and machine vision[17] becomes feasible. DT-driven cyber-physical production system (CPPS), as the key technology, has been the significant topic of smart workshop to meet the needs of agility, personalization in production[19][14][34][57]. With the promotion of intelligent production equipment, the DT-based frameworks for human-robot collaborative assembly[3] and smart industrial robot production[49] were proposed. Along modeling and monitoring, feedbacks from DTs and decision making systems in the virtual space have expanded engineering applications by error states detection[32], quality control[16], processes pre-analysis[48][7] and optimization[28]. In the dimension of enterprise, Guo et al.[15] proposed a combined layout design scheme and modular-based DT model for factory design. Furthermore, Cheng et al.[4] attempted to construct a DT-II (DT enhanced Industrial Internet) reference framework towards smart manufacturing, which fully considered the trends and characteristics of cloud manufacturing.

2.2 Ontological approaches in manufacturing and assembly

Ontology, as a widely used semantic modeling method, has unique advantages of being explicit, formal and shared in modeling of objects, attributes and relationships[22]. The strong descriptive ability enables ontology to model static resource and dynamic process[10], for which the research of ontology in manufacturing field has been concerned.

Ontology modeling methods and the applications of ontology-based technologies have been widely studied in information virtualization, knowledge representation and expert system. Manufacturing resource virtualization has been one of the primary application methods of ontology technology[25][35]. Focus on the field of assembly, the modeling methods aiming at product, process, resource[8][9] and system[6][37] in the assembly scenarios have been proposed in succession, enriching the description approaches of multifarious information in assembly. For further application, knowledge can be abstracted and stored[56] in the form of semantic web rule language (SWRL), waiting for retrieval[47] when facing appropriate scenes. In solving practical engineering problems, Zhu et al.[58] presented a light-weight access to CAD data with ontology reasoning at both assembly and component level. On the other hand, knowledge entries are widely used to build various expert systems to provide aids in decision making such as resource recommendation during assembly process planning[21].

2.3 Research gaps

In summary, the literatures above have studied the modeling methods of DT workshop with multiple tools to meet various requirements. However, there are still some critical challenges in the construction of DT model for assembly workshop, as follows.

- The DT modeling method that can uniformly describe the heterogeneous data from the resource and process in assembly workshop turns out to be immature. In the assembly workshop, there may be various resource entities and process items, each with its own independent parameter setting, which may bring difficulties for the modeling with traditional methods.
- The research on the evolution of semantic DT assembly workshop is still in its infancy. The evolution of ontology provides an appropriate theoretical basis for the information iteration of DT assembly workshop mapping the dataflow of the physical counterpart, which seems not to be appreciated sufficiently.

– There is not enough attention paid to the efficient storage and tracing of historical data in the DT workshop. With the production in the field, huge amounts of data will be generated, seeking to be stored and further recycled in a reasonable way. So far there has been insufficient discussion about the methodology of storage and tracing of historical data.

Based on the foregoing observations, existing research results are still insufficient in some respects when constructing DT assembly workshop. Motivated by these needs, this manuscript proposes a DT framework for assembly workshop with the methodology of ontology, in which the process of construction and evolution will be presented as well. With the ontology built in this paper, challenges like modeling of multi-source heterogeneous data, evolution of DT assembly workshop, storage and tracing of historical data will be addressed to some extent.

3 Modeling of DT assembly workshop

If the parts involved in assembly are considered as resource entities, the data in the assembly workshop can be roughly divided into two categories including assembly resource data and assembly process data. In this section, the ontological modeling method of the assembly resource and process are presented with emphasis.

3.1 Methodology of ontological modeling

As a mature formal expression method, ontology has been extensively researched by scholars in various industries. In recent years, numerous ontology structures have been constructed to describe and share knowledge in respective domain. However, the ontological approaches in the manufacturing field are still immature, due to the diversity of enterprises, workshops and process items. In this manuscript, the methodology of ontological modeling oriented to DT assembly workshop is presented and the seven-step method[33] proposed by Stanford University is used to develop the ontology.

In order to ensure the information accuracy and real-time evolution of DT assembly workshop[24], some further interpretations for the modeling of ontology are proposed as follows.

– The ontology of DT assembly workshop is built to describe the objects, attributes and relationships that exist in the assembly workshop and participate in or affect the assembly behaviors.
– In the absence of existing ontology which can describe the assembly workshop, some ontology structures and modeling methods that describe resource entities can be reused or referenced.
– The classes and properties in the ontology should cover the common resource entities and process items in assembly workshop as much as possible on the basis of ensuring semantic consistency to improve the versatility and evolution of the ontology presented. The instantiation should be carried out according to the actual situation of the specific workshop.

3.2 Modeling of assembly resource

The modeling of the assembly workshop resource is the main component of the DT assembly workshop, which is responsible for providing methods for the description of entities of material, personnel, tool and equipment in the workshop. Meanwhile, the modeling focus and data structure are diverse for various types of resource entities. In order to describe the status of resource, the main information classification of DT resource is analyzed, as shown in Figure 2.

For personnel information in assembly workshop, the virtualization of operator and team is considered to be vital in mapping the working process of the personnel in the physical world. Similarly, tool and equipment are associated with assembly task through the object properties between ontology classes. Material mainly includes part and auxiliary material (e.g., screw, nut, washer, et al.). Type, position, performance parameters and other describable attributes are considered as the significant information for the purpose of locating, selecting and tracing in assembly. On one hand, the specific part information modeling method refers to the part information decomposition and ontology modeling proposed in [2]. Through ontology fusion, the part ontology provided by suppliers can be incorporated into the ontology structure of the assembly workshop to participate in the description of the material status in the workshop, which corresponds to the part delivery and warehousing process in the actual production. On the other hand, the assortment of auxiliary material entities is more complicated. With the ontology modeling method to construct the classification hierarchy of auxiliary material, the heterogeneous attributes and parameters can be effectively described through the properties mounted on different classes.

It should be noted that the ontology modeling in this manuscript mainly provides a modeling method for multi-source heterogeneous information of assembly resource entities. The diversity of assembly in the workshop is reflected in the variety of material, equipment,

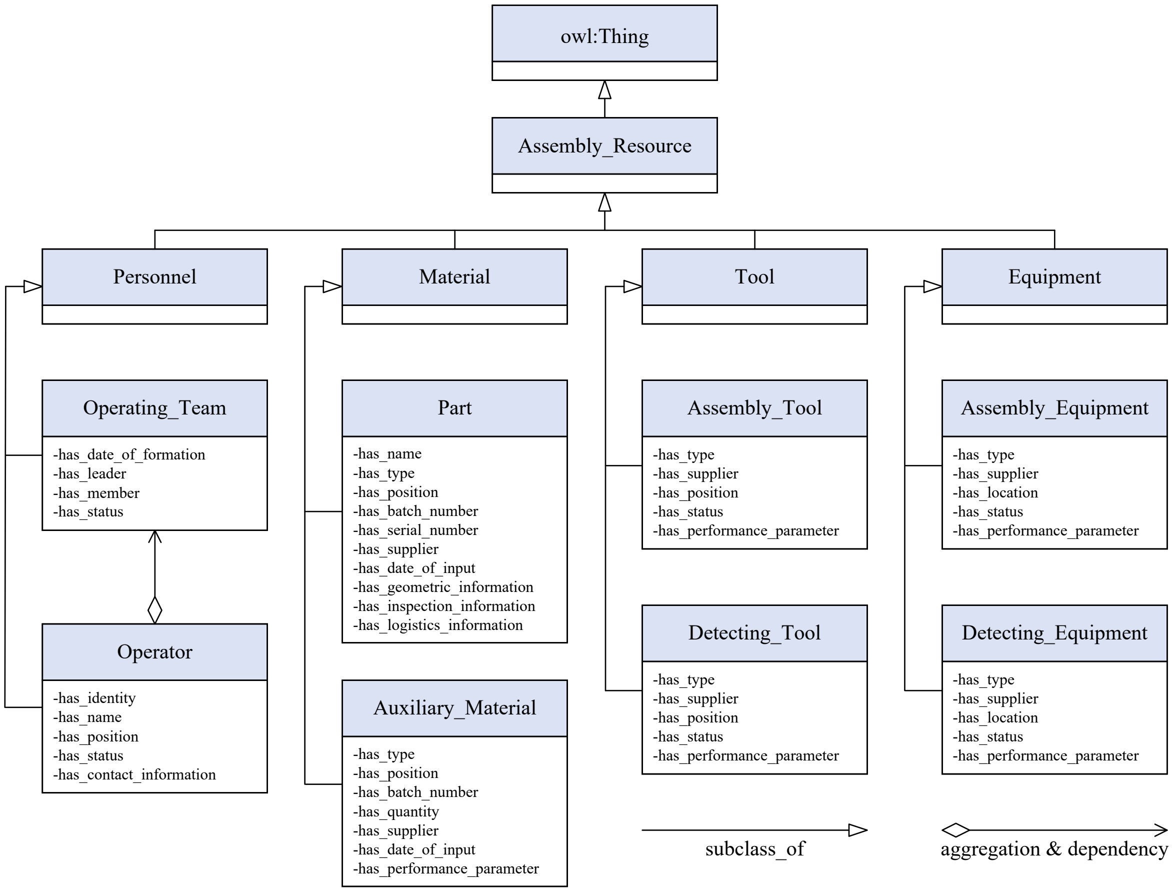

Fig. 2 The main information classification of DT resource.

tool and personnel to some extent, causing the difficulties in the modeling of distinctive information types and data structures with one single set of modeling language and framework. With the method proposed in this paper, new classes and corresponding data properties for various resource entities can be created in the assembly workshop ontology, and the object properties can be defined to establish association relationships with the assembly process.

It can be seen from the above attempts that the assembly process, as the primary driver event, promotes the dataflow in the assembly workshop. In order to ensure the semantic consistency and model unity of the DT assembly workshop, it is necessary to consider the ontology modeling of the assembly process items, which will be discussed in the next part of this manuscript.

3.3 Modeling of assembly process

In the assembly workshop, the execution of the assembly process can be regarded as several events occurring in a certain sequence and by predetermined triggering mechanism. The event involve multiple element, including time element, location element, participant element, and process status element, which makes the event an effective description method when modeling the process items in the assembly workshop.

Generally, an event is composed of a series of certain time and environment, several participating roles, several action characteristics and other elements. After semantic processing, the event can be expressed with OWL, which ensure the unity and semantic consistency of the assembly workshop modeling language.

A representation of event ontology was proposed as an event-oriented description logic to act as logical foundation of event ontology language. Formally, an event e can be defined as a six-tuple[23]:

$$e = (A, O, T, V, P, L) \quad (1)$$

The elements in the six-tuple are known as the event factors. In the scene of an assembly workshop, an event can represent an assembly workstep, for which the six-tuple can be regarded as a group of factors describing the workstep. The explanation of the six-tuple of assembly workstep events is shown in Table 1.

Table 1 The explanation of the six-tuple of assembly workstep events.

Factors	Paraphrases	Explanations in assembly worksteps
A	A happening action set	The actual operation performed in the assembly workstep
O	Objects that participate in	The associated assembly resources in this workstep
T	Period of time	The time information recorded in the process of workstep execution
V	Environment of event	The environment information recorded in the process of workstep execution
P	Assertions on the procedure of actions execution	Pre-condition, post-condition and intermediate assertions in the process of workstep execution
L	Language expressions	Description language of assembly workstep

In the modeling of assembly workstep events, A represents the actual operation performed in the workstep like constructing, cleaning, inspecting and transporting. This part records the main action of the assembly workstep, which is the core component of the event. O expresses the assembly resource entities associated with the assembly workstep. As mentioned above in section 3.2, assembly resource entities can be semantically modeled with OWL. In this part the object properties are defined between the workstep event and the resource entities in the ontology of assembly workshop. T and V represent the time and environment information in the assembly workstep respectively. As objective physical factors in the assembly workshop, the time and environment information will be generated naturally during the execution of the assembly workstep, recorded by the sensors and transmitted to the assembly workshop ontology through the data transmission path. In particular, environment information in the assembly workshop has received more attention with the increasing accuracy of assembly and the physical analysis of the assembly process. In the collection, the information of the acquisition frequency and location of sensors requires extra attention. P represents the conditions and judgment methods of assembly workstep execution. The order among assembly worksteps can be expressed through this factor to make sure that multiple worksteps in an assembly task can be kept in order. Meanwhile, the inspection in the assembly process can be regarded as the prerequisite for the next assembly workstep to ensure that the product meets the quality requirements. Finally, L records the description language of the assembly workstep. The modeling and corpus extraction methods differ on account of different language expressions, including core word sets, core word expressions and core word collocations.

With the assembly event modeling, the assembly process ontology modeling in the assembly workshop can be realized with the workstep as the minimum unit. The six factors of the workstep event can be extracted and filled by various means like workshop sensors, assembly process files or reasoning.

After the modeling of the assembly resource and process, the multi-source heterogeneous data in the assembly workshop can be recorded in one ontology, and act as the core of the twinning data of DT assembly workshop in the cyber world to constantly evolve in the interaction of information with the physical world.

4 DT assembly workshop framework

Based on the DT model of the assembly resource and process, the DT assembly workshop can be constructed by combining the characteristics of the physical workshop and the fusion method of virtual world and physical one. The application framework of DT assembly workshop consists of physical layer, perception & feedback layer, data layer and service layer, as shown in Figure 3.

The physical layer mainly refers to the work flow and all the associated physical entities in the assembly workshop, which is the basis of the DT assembly workshop modeling and the driving force of the DT evolution. Particularly, the DT of part is transmitted to the assembly workshop along with the physical part as the most significant sector of the material. The DT of part can provide data source of accuracy and promptitude, which is composed of designing data, processing data and quality inspection data.

The perception & feedback layer includes the method of the fusion and establishes connection between physical and virtual worlds. Thanks to the continuous development of sensor technology and communication mean, there are plenty of options for perceiving the physical workshop, such as ZigBee network and RFID network. With the dashboard in the workshop, operators can get feedbacks and make real-time adjustments. Meanwhile, wire communication and mobile terminal can build information pathways for workshop perception and feed-

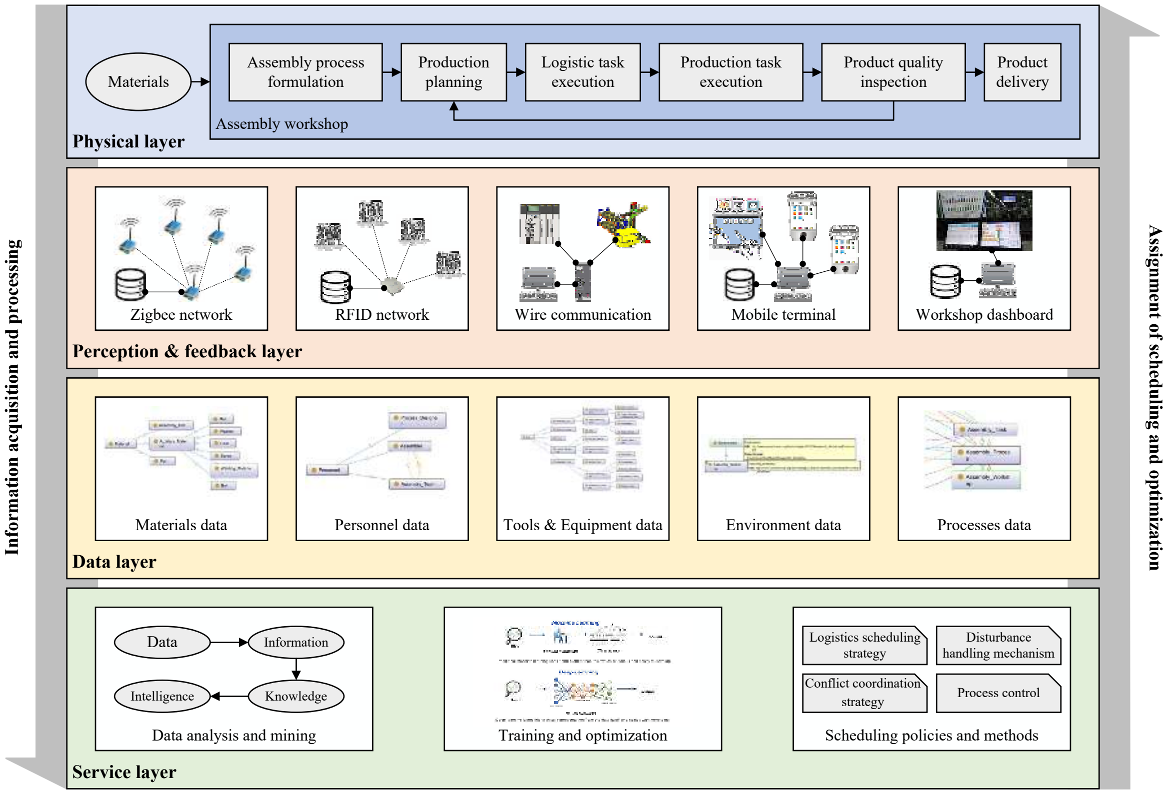

Fig. 3 The framework of DT assembly workshop.

back by means of automated and manual data interaction, respectively.

The data layer contains assembly resource and process information, in which the data structure and property entries are predefined. To add a resource category, the class can be defined in the ontology with the addition of corresponding object and data properties. Emerging physical entity or process item in the workshop can be virtualized by instantiating corresponding ontology class, and even a new workshop can be modeled in the same way.

In the service layer, multiple scheduling and optimization algorithms are constructed to guarantee the productivity and production quality in the assembly workshop, which cannot be enumerated in this manuscript.

The layers of DT assembly workshop have different characteristics and emphases, which ensure the basic function of DT framework, including:

- The dataflow during the assembly task execution should be mapped in the virtual space.
- The DT assembly workshop should evolve in real time to reflect the implementation of the assembly task and the variation of workshop condition.
- The storage method and tracing mechanism of vast production historical data should be considered in the DT framework.

4.1 Mapping of assembly dataflow in virtual space

Production task should enter into the DT assembly workshop with the form of process before the workshop starts production activities. Assembly process usually exists in the modality of process document and regulation, which needs to be disposed semantically to form effective language materials to fill into the assembly process events. The virtualization of the assembly process is the first step in the construction of the dataflow of the assembly workshop. Multiple dataflow paths will be generated in the workshop to ensure that the assembly process proceeds along the preset route.

With the execution of the assembly task, the data generated in the assembly process needs to be measured and transmitted to the DT platform as the main data source. For various attributes of the assembly resource analyzed in section 3.2, real-time information can be obtained through multiple measures, while scheduling and optimizing instructions can be issued to direct the execution of the assembly task in the workshop, as shown in Figure 4.

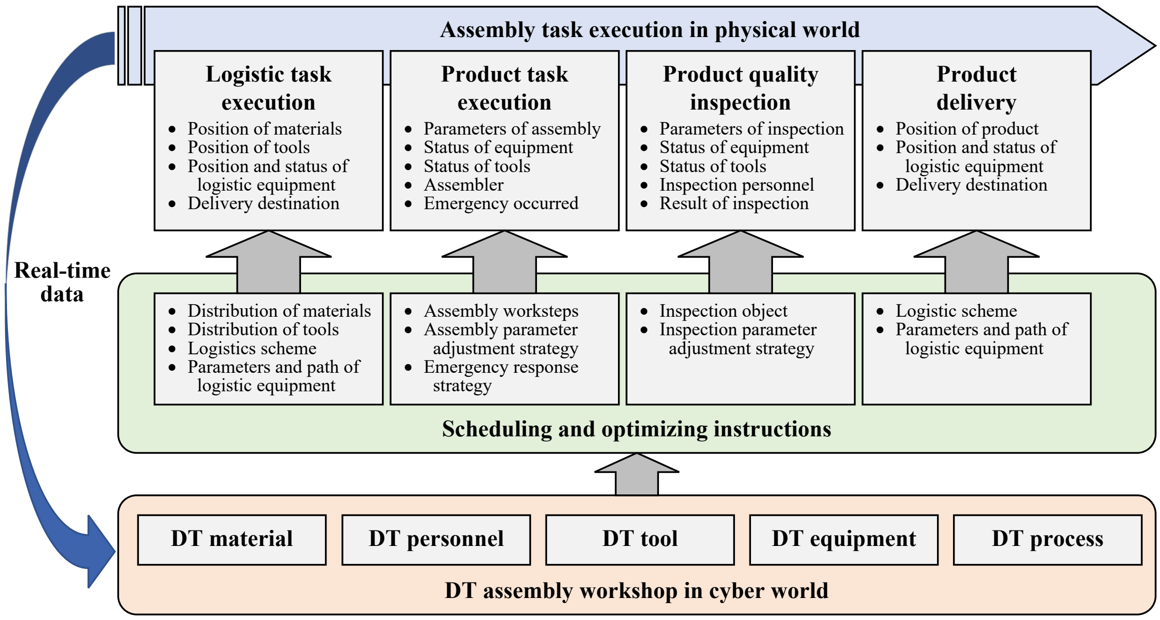

Fig. 4 Multiple methods of dataflow in assembly workshop.

There are three main data paths in the assembly workshop. Firstly, there is always a data path inherent in the physical world that advances with the execution of the assembly task. In the process of execution, the data contained in each assembly step will be naturally transmitted to subsequent steps through the physical medium of assembly object. Secondly, the real-time data acquisition and transmission related to the assembly task execution in the workshop forms a data path with the help of perceptual means. This data path provides a constant stream of data sources for the evolution of the DT assembly workshop, which is the foundation for the DT platform with the performance of real-time and high fidelity. Thirdly, there is a data path where the DT assembly workshop provides scheduling and optimizing instructions through relevant algorithms to guide the execution of the assembly task. The existence of this data path reflects the purpose of DT assembly workshop, which is the optimization of production quality and efficiency in the workshop through real-time data collection and analysis.

4.2 Evolution of DT assembly workshop

The core of DT is to reflect the real-time status of product or system[52], which means that a complete set of evolutionary mechanisms needs to be established for the DT assembly workshop. The implementation of DT evolution mainly consists of two aspects, including the acquisition of information changes and the evolutionary approach to the information model.

Ontology evolution refers to the timely adaptation of an ontology to the arisen changes and the consistent propagation of these changes to dependent artifacts[46]. In DT assembly workshop, the core function of the ontology is to continuously reflect the actual state inside the plant. During the execution of the production task, elements in the workshop are constantly changing. The changes can be collected and aggregated into the control terminal and drive the evolution of the ontology by modifying the properties and relations of the corresponding classes.

Status changes of existing resource entities in the assembly workshop can be acquired and transmitted through the sensors and communication networks, as shown in Figure 5. Position or location of the resource entities can be acquired through radio frequency identification devices (RFID) positioning system, while status, environment parameter and observed value can be measured by appropriate sensors and transmitted through ZigBee network. Meanwhile, the information interaction between various equipment entities and control terminal can be realized by respective communication protocols and gateways. On the other hand, when resource entities enter the assembly workshop, new instances can be appended in the DT workshop through information input manually. Subsequently, the establishment of new data path is realized through the arrangement of RFID tags and sensors to ensure that the newly added assembly resource entities can be perceived and added in the DT workshop.

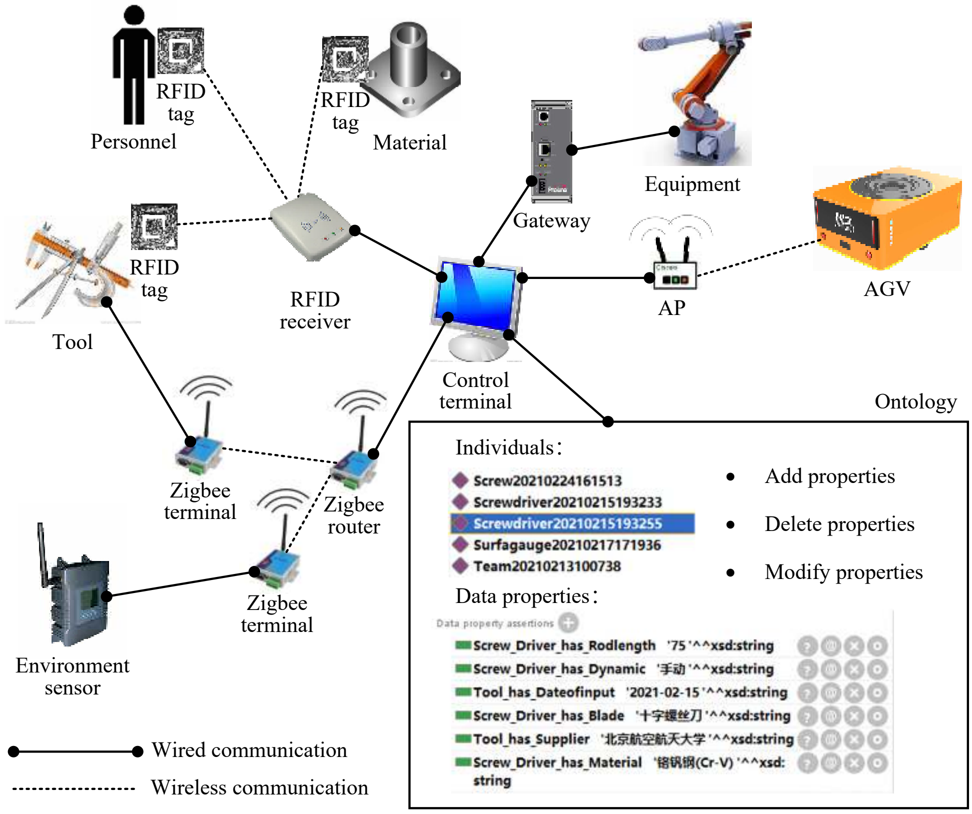

Fig. 5 Sensors and communication networks in mapping resources.

As for process information, the six-tuple mentioned in Section 3.3 can describe information contained in a single workstep, which can be considered as the elementary unit of the process. As three classes of ontology, task, process and workstep, together with the classes that describes the resource, participate in the construction of assembly workshop ontology. Process information is input by process designer in the control terminal and stored in the ontology as workstep event instances. According to the result of task scheduling and distribution, the control terminal transmits the relevant process information to the tablet on the station to instruct assembler to carry out operation. Meanwhile, the execution of the assembly task can be transmitted to the control terminal of the workshop via tablet along with the state of related assembly resource entities. The control terminal updates the ontology continuously through ontology editing tools to ensure that the ontology keeps evolving with the changes in the workshop. Furthermore, with the help of ontology analysis tools and other optimization algorithms, the ontology can be used as the data source to provide assistant for decision making and help to adjust the workshop. The transformation of process information during assembly task execution is shown in Figure 6.

Ontology, as the theoretical basis of DT assembly workshop modeling, has been extensively studied in the aspect of evolution. In the evolution of data-driven ontology, the semantization of driving data and maintenance of ontology semantic consistency are particularly important[42][39]. Since the variations in the workshop are semantically preprocessed before interacting with the ontology of the DT workshop, properties of ontology instances representing resource entities and process items in the workshop can be updated when new corresponding data arrive. Meanwhile, the semantic consistency of DT workshop ontology can be inspected with the help of ontology reasoner such as Pellet[45] and HermiT[11] to avoid the duplication of object names and incomplete correlation.

However, evolution of the ontology may cause the older data being overwritten, which impedes the manufacturing process optimization with historical data. Therefore, it is necessary to consider the historical data storage and tracing mechanism of ontology-based DT assembly workshop.

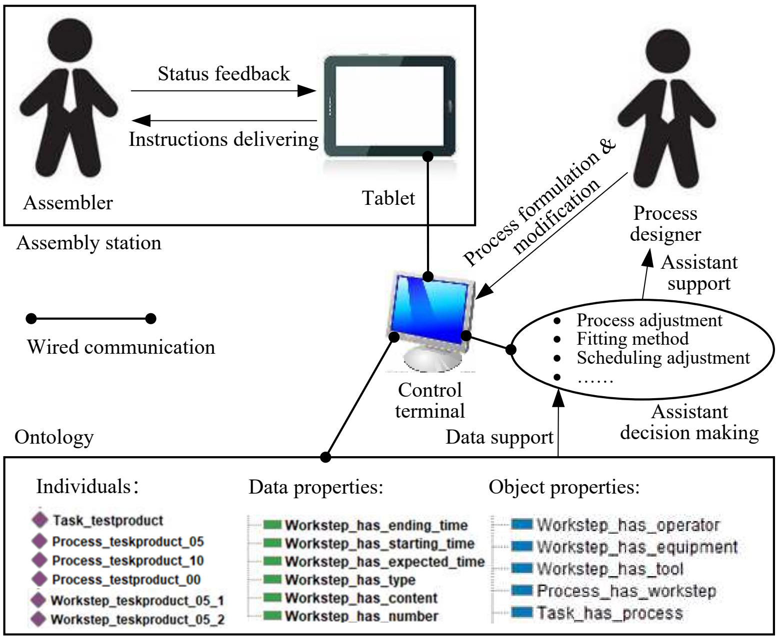

Fig. 6 Process information transfer during task execution.

4.3 Storage and tracing of historical data

There is no doubt that the data collected during the process in workshop, as an important part of manufacturing big data, is of great significance in the construction of DT framework of manufacturing systems[50][36]. The historical data retained in the completed production process can be analyzed and mined to be knowledge items to guide the implementation of new task.

The ontology of DT assembly workshop is constantly evolving with the data input resulting from the changes of task execution condition, resource condition, scheduling result and workshop disturbance. Nevertheless, the ontology file can be saved as a separate snapshot at an artificial point in time, in which the state of assembly workshop at that particular time is preserved, as shown in Figure 7. The time node can be based on a predetermined time interval, or on specific trigger point such as the start or completion of important assembly workstep, which depends on the specific analysis requirement and storage capacity. As OWL-based semantic description files, ontology files usually take up negligible storage space, providing the possibility of large-scale storage of historical data in the assembly workshop.

The historical data in the ontology file revolves around the execution of the assembly task, including the correlations between assembly task and resource. If necessary, the assembly worksteps that have utilized a particular assembly resource entity before a certain time node can be filtered and outputted by traversing all tasks to form a historical data set centered on the specific assembly resource entity, as shown in Figure 8. Similarly, a historical data set centered on a series of products can also be constructed with the traversing of relationships between product and task. With the rich ontological expression of relations, various historical data sets can be constructed to meet different analysis requirements, by which the tracing of historical data is guaranteed in the framework of ontology-based DT assembly workshop.

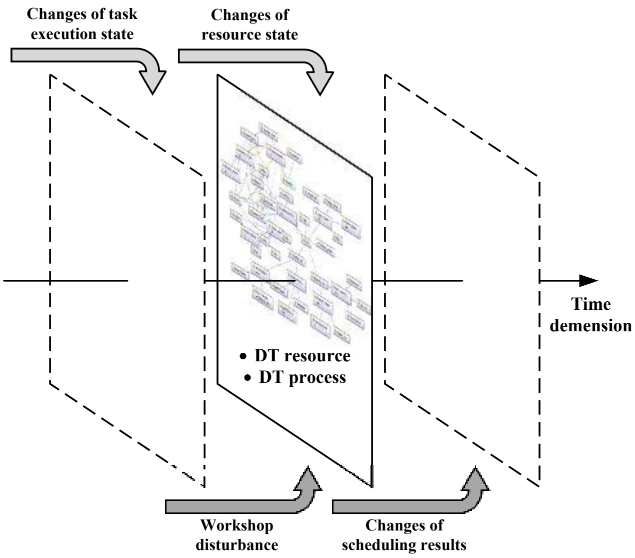

Fig. 7 Historical data storage mechanism of DT assembly workshop.

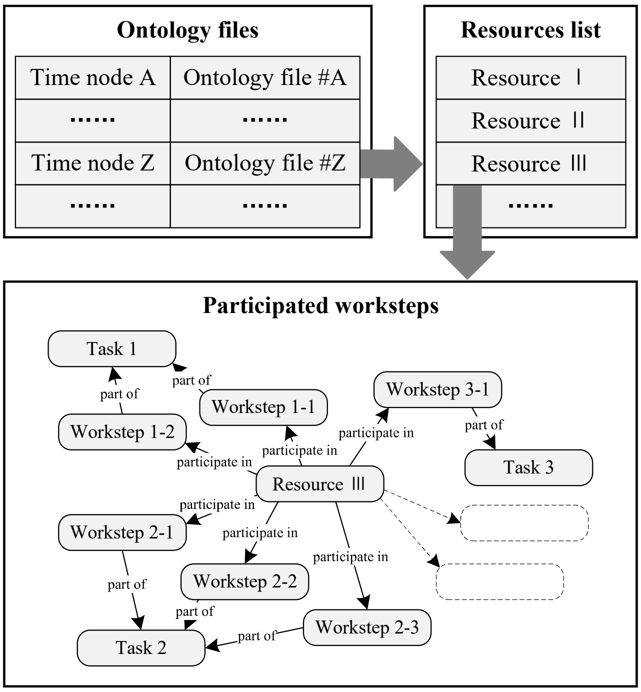

Fig. 8 The mechanism of tracing historical data centered on resource.

Meanwhile, the storage and tracing methods of workshop historical data based on ontology files has great advantages and application space under the trend of cloud manufacturing. On one hand, the historical data ontology files record the execution of process items and the use of resource entities, which can provide raw data for the evaluation of assembly resource capabilities. On the other hand, the resource entities of multiple assembly workshops can be integrated under the same modeling standard, by which the collaborative production of the large complex product can be realized based on the production scheduling of higher dimension.

5 A case study

The following chapter describes the case study of the construction and evolution of DT assembly workshop modeled on an experimental field in the laboratory. The methodology of DT assembly workshop modeling proposed in this manuscript will be verified to be feasible and validity in the aspects of assembly resource & process virtualization, dataflow mapping, DT evolution, storage and tracing of historical data.

In terms of hardware placement, various assembly resource entities are arranged in the experimental site, such as sensor network devices, RFID receivers, logistics equipment, material entities, et al. On the other hand, a management platform of assembly workshop based on DT is developed to be the interface among perceived data, manual input data and DT model of the workshop.

In performing the virtualization of assembly resource entities, the classes representing types of resource are defined in the ontology with Protg as the authoring software when new type of resource enter the workshop. Furthermore, the object and data properties that may exist for the description of new resource type also need to be appended in the ontology as the properties of the corresponding class. The above works only need to be done when resource of new type arrive in the workshop. For resource entities of existing types, the information about the resource entities is firstly entered through the workshop management platform, manually or batch imported using XML files or MS Excel files. As mentioned, the data storage of the platform does not depend on the NOSQL database as usual, but the ontology as the kernel. When a resource entity is entered, the platform instantiates the corresponding class in the ontology and attaches the attributes to the ontology instance. At this point, this resource completes the process of entering the workshop and start to participate in the production activities and information evolution of the workshop. In order to control the number of ontology instances so as to avoid ontology being too huge, there should be some differences with the granularity of the constructed DT resource entities depending on the types. For example, for the entities without complete interchangeability like parts, tools and personnel, independent DT modeling is essential for each individual. For auxiliary material entities like bolts, nuts or screws, DT models can be built for batches and an extra entry *quantity* can be defined to record the usage and reserve. The addition of assembly resource entities and the instances in the ontology are shown in Figure 9.

The traditional assembly process are usually recorded in the process documents, supplemented by 3D simulation animation to guide the assembly operations. In order to realize the virtualization of assembly process, the most important is to extract the effective language materials from the descriptive process documents and fill them into the six elements of the assembly workstep event, which can be supported by natural language processing (NLP) techniques. In this study, regular expressions are used to extract strings form the process texts. The extraction results of workstep event elements are illustrated with an example, as shown in Figure 10. The extraction steps are as follows:

1. A string-matching library is formed with the names of all assembly resource entities and all actions in assembly operations that could happen in this workshop.

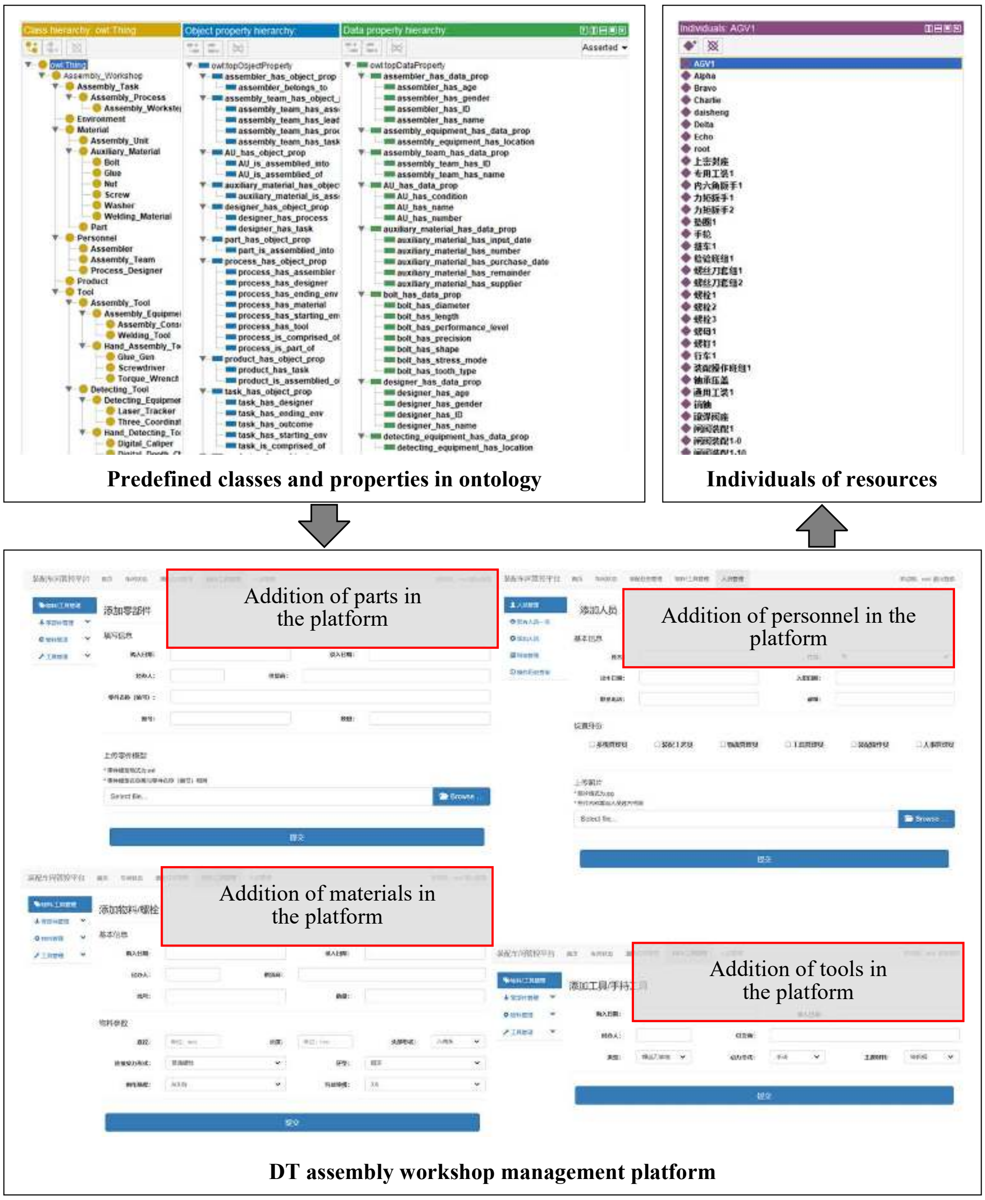

Fig. 9 The addition and instantiation of the assembly resource.

2. The strings in the matching library are matched with the process document respectively, and the matched strings are denoted as elements of the workshop event. Strings that describe different kinds of objects or actions correspond to different event elements.
3. Check and update the string-matching library to add the name of the materials generated by the last workstep if necessary.

However, the strings that appear in the assembly process documents pointing to assembly resource entities may not be comprehensive due to the non-normative of the assembly process charts. Ontology reasoning is used to complete the correlation between resource entities and workstep events. With the pre-defined rules of reasoning written in SWRL, the resource entities that related to the workstep events but not mentioned in the process documents can be identified. Continuing with the above example, the SWRL rules listed in Table 2. can be used to deduce the assembly resource entities related to the workstep, such as screwdriver, AGV, et al. or the location where the workstep could take place. The rules are abstracted from the knowledge in the workshop and are constantly updated iteratively. Meanwhile, time and environment elements can be populated based on system time and the value returned by environment sensors. The assertion element mainly records the logical relations such as the sequence among the assembly steps, which should be inputted along with the process documents. So far, the transition of this workstep from assembly process document to virtual event is complete.

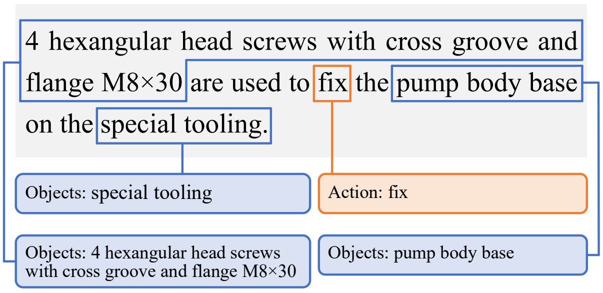

Fig. 10 An example of workstep event element extraction.

On the hardware side, a set of workshop perception and logistics control system is constructed, mainly including sensors, ZigBee network, RFID positioning system, AGV, intelligent logistics center, et al. Through a variety of communication protocols and hardware interfaces, the computer terminal in the workshop realizes communication and data interaction with other devices. By obtaining real-time information, the status of the workshop is perceived. On this basis, the ontology of DT assembly workshop can evolve in real time with the status information as data source. The layout of resource entities in an assembly station is shown in Figure 11.

In this case, the historical data is saved as the ontology files based on the preset time interval. The saved ontology files are stored in the database in chronological order. By inputting instructions in the management platform, any ontology file can be retrieved and parsed at any time, and the state of the assembly workshop at that time point can be clearly obtained.

6 Conclusions and future work

DT technology, as an emerging technology integrating information modeling, data management and process analysis, has been widely studied by scholars and enterprises from a variety of industries in recent years. In the field of assembly, the concept and idea of DT depict the roadmap for the reference model of assembly workshop as the data core of smart assembly when facing the diversity of assembly resource and the complexity of dataflow. Meanwhile, with the development of semantic modeling, perceptual hardware and communication technology, more options are given when facing the challenge of semantic modeling of DT assembly workshop. Based on the above status, this manuscript proposes an ontology-based approach to the modeling and evolution of DT assembly workshop. There are three main contributions of this paper, including:

- An ontology-based modeling method for describing assembly resource and process is presented. Through ontology technology and OWL, the assembly resource and process can be virtualized into multiple information sets under the same description framework, which provides a semantic scheme for the multi-source heterogeneous data in the assembly workshop.
- The evolution mechanism of DT assembly workshop is proposed. On the basis of outstanding evolution performance of ontology, DT assembly workshop can evolve driven by real-time perceived field status. Universal sensor and data transfer method are analyzed to ensure that variations of assembly workshop can be acquired and delivered.
- The method for storing and tracing historical data is given. In the process of DT evolution, ontology snapshots stored according to the predetermined time points constitute the main carrier of historical data along with the evolving ontology. Meanwhile, the actual state of the assembly workshop at a particular moment can be restored by analyzing the corresponding ontology file.

This paper explores an ontology-based method of modeling and evolution of DT assembly workshop, along with a case study to verify the feasibility and validity of the method proposed. However, there may be problems in the practical application when facing specific assembly workshop, such as the layout of sensors and communication equipment, real-time data transmission and multiple channels of interaction among devices, which will be continuously studied. The future research will also focus on two areas: the NLP-based accurate extraction of assembly process elements to solve the nonstandard problem in assembly process formulation; the algorithms of assembly sequence planning and process optimization on the basis of DT assembly workshop.

Declarations

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Table 2 Examples for the logical description and SWRL representation of rules.

Logical description	**SWRL representation**
When using cross grooved screws with an outside diameter greater than or equal to 8 mm, a PH3 screwdriver should be used to install.	$workstep(?ws) \cap hasscrew(?ws, ?sc) \cap hasheadshape(?sc, ?hs) \cap swrlb : SameAs(?hs, cross) \cap hasdiameter(?sc, ?d) \cap swrlb : greaterThanOrEqual(?d, 8) \cap tool(?t) \cap hastype(?t, ty) \cap swrlb : SameAs(?ty, PH3) \rightarrow hastool(?sc, ?t)$
When the assembly parts weigh more than 10kg, a AGV should be used for transportation.	$workstep(?ws) \cap haspart(?ws, ?part) \cap hasweigh(?part, ?hw) \cap swrlb : greaterThanOrEqual(?hw, 10) \cap AGV(?a1) \rightarrow hasAGV(?ws, ?a1)$
When special tooling for pump is used, the assembly point will be the second station.	$workstep(?ws) \cap hastarget(?ws, pump) \cap tooling(?t) \cap hasobjects(?t, pump) \cap hasequipment(?ws, ?t) \rightarrow haslocation(?wa, secondstation)$

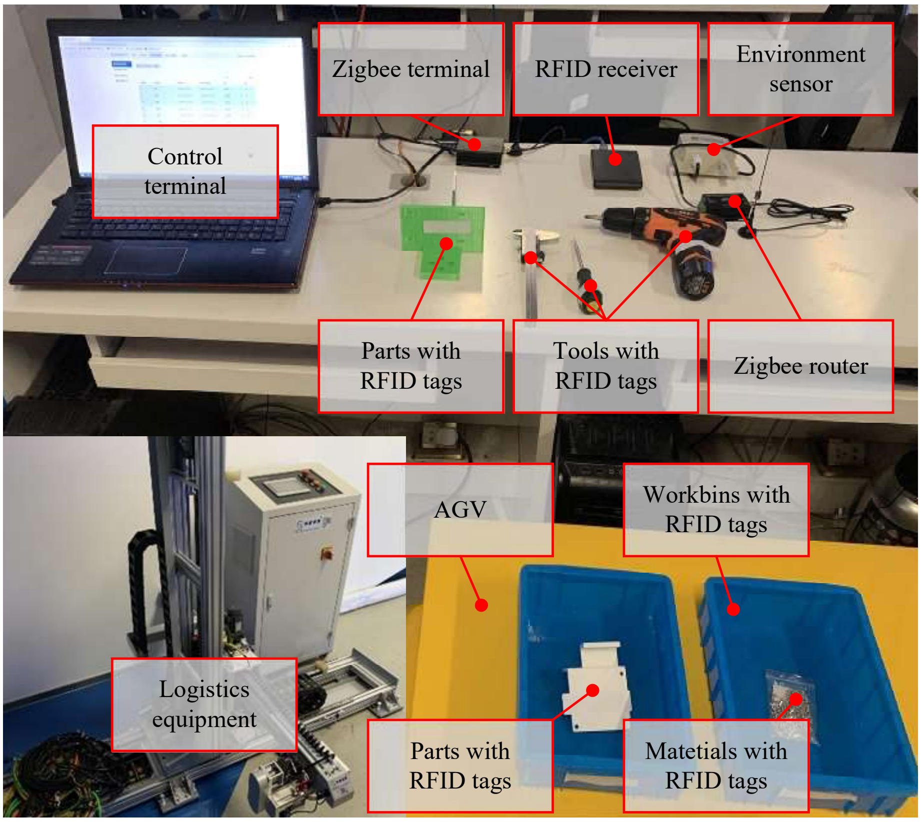

Fig. 11 The layout of resource entities in an assembly station of the experimental workshop.

Consent to Publish

Not applicable.

Authors Contributions

Qiangwei Bao was responsible for conceiving and writing the full text. Gang Zhao and Yong Yu provided the technical guidance and experimental environment for this research. Sheng Dai and Wei Wang provided a lot of help and suggestions for the implementation of this study. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no conflict of interest.

Availability of data and materials

Not applicable.

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References

1. Bao, J., Guo, D., Li, J., Zhang, J.: The modelling and operations for the digital twin in the context of manufacturing. Enterprise Information Systems **13**(4), 534–556 (2019)
2. Bao, Q., Zhao, G., Yu, Y., Dai, S., Wang, W.: Ontology-based modeling of part digital twin oriented to assembly. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture (2020)
3. Bilberg, A., Malik, A.A.: Digital twin driven human-robot collaborative assembly. CIRP Annals - Manufacturing Technology **68**(1) (2019)
4. Cheng, J., Zhang, H., Tao, F., Juang, C.: Dt-ii: Digital twin enhanced industrial internet reference framework towards smart manufacturing. Robotics and Computer-Integrated Manufacturing **62** (2020)
5. Cohen, Y., Naseraldin, H., Chaudhuri, A., Pilati, F.: Assembly systems in industry 4.0 era: a road map to understand assembly 4.0. International Journal of Advanced Manufacturing Technology **105**, 4037–4054 (2019)
6. Delamer, I.M., Lastra, J.L.M.: Ontology modeling of assembly processes and systems using semantic web services. In: 2006 4th IEEE International Conference on Industrial Informatics, pp. 611–617 (2006)
7. Fang, P., Yang, J., Zheng, L., Zhong, R.Y., Jiang, Y.: Data analytics-enable production visibility for cyber-physical production systems. Journal of Manufacturing Systems **57** (2020)
8. Ferrer, B.R., Ahmad, B., Lobov, A., Vera, D.A., Lastra, J.L.M., Harrison, R.: An approach for knowledge-driven product, process and resource mappings for assembly automation. In: 2015 IEEE International Conference on Automation Science and Engineering (CASE), pp. 1104–1109 (2015)
9. Ferrer, B.R., Ahmad, B., Vera, D., Lobov, A., Harrison, R., Lastra, J.L.M.: Product, process and resource model coupling for knowledge-driven assembly automation. Automatisierungstechnik **64**(3), 231–243 (2016)
10. Gao, J., Bernard, A.: An overview of knowledge sharing in new product development. International Journal of Advanced Manufacturing Technology **94**(5-8), 1545–1550 (2018)
11. Glimm, B., Horrocks, I., Motik, B., Stoilos, G., Wang, Z.: Hermit: An owl 2 reasoner. Journal of Automated Reasoning **53**(3), 245–269 (2014)
12. Grieves, M.: Product lifecycle management - Driving the next generation of lean thinking. McGraw-Hill Education (2005)
13. Grieves, M.: Product lifecycle management: The new paradigm for enterprises. International Journal of Product Development **2**(1-2), 71–84 (2005)
14. Guo, D., Zhong, R.Y., Lin, P., Lyu, Z., Huang, G.Q.: Digital twin-enabled graduation intelligent manufacturing system for fixed-position assembly islands. Robotics and Computer-Integrated Manufacturing **63** (2020)
15. Guo, J., Zhao, N., Sun, L., Zhang, S.: Modular based flexible digital twin for factory design. Journal of Ambient Intelligence and Humanized Computing **10**(3), 1189–1200 (2019)
16. Hao, B., Wang, M.Y., Fu, S.L., Xu, D.P., Wang, J.X.: Quality control mode of intelligent assembly workshop based on digital twin. Journal of Physics: Conference Series **1605**(1) (2020)
17. idek, K., Pitel, J., Adamek, M., Lazork, P., Hoovsk, A.: Digital twin of experimental smart manufacturing assembly system for industry 4.0 concept. Sustainability **12**(9) (2020)
18. Kuliaev, V., Atmojo, U.D., Sierla, S., Blech, J.O., Vyatkin, V.: Towards product centric manufacturing: From digital twins to product assembly. In: 2019 IEEE 17th International Conference on Industrial Informatics (INDIN), pp. 164–171 (2019)
19. Leng, J., Zhang, H., Yan, D., Liu, Q., Chen, X., Zhang, D.: Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop. Journal of Ambient Intelligence and Humanized Computing **10**, 11551166 (2019)
20. Li, C., Mahadevan, S., Ling, Y., Choze, S., Wang, L.: Dynamic bayesian network for aircraft wing health monitoring digital twin. AIAA Journal **55**(3), 1–12 (2017)
21. Li, X., Wang, L., Zhu, C., Liu, Z.: Framework for manufacturing-tasks semantic modelling and manufacturing-resource recommendation for digital twin shop-floor. Journal of Manufacturing Systems **58**, 281–292 (2021)
22. Lim, K.Y.H., Zheng, P., Chen, C.H.: A state-of-the-art survey of digital twin: Techniques, engineering product lifecycle management and business innovation perspectives. Journal of Intelligent Manufacturing **31**(6), 1313–1337 (2020)
23. Liu, W., Xu, W., Fu, J., Liu, Z., Zhong, Z.: An extended description logic for event ontology. Lecture Notes in Computer Science **6104 LNCS**, 471–481 (2010)
24. Lu, Y., Liu, C., Wang, I.K., Huang, H., Xu, X.: Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. Robotics and Computer Integrated Manufacturing **61** (2020)
25. Lu, Y., Xu, X.: Resource virtualization: A core technology for developing cyber-physical production systems. Journal of Manufacturing Systems **47**, 128–140 (2018)
26. Lu, Y., Xu, X., Wang, L.: Smart manufacturing process and system automation a critical review of the standards and envisioned scenarios. Journal of Manufacturing Systems **56**, 312–325 (2020)
27. Luo, W., Hu, T., Zhang, C., Wei, Y.: Digital twin for cnc machine tool: Modeling and using strategy. Journal of Ambient Intelligence and Humanized Computing **10**(3), 1129–1140 (2019)
28. Ma, J., Chen, H., Zhang, Y., Guo, H., Liu, L.: A digital twin-driven production management system for production workshop. The International Journal of Advanced Manufacturing Technology **110**(5-6) (2020)
29. MacDougall, W.: Industrie 4.0: Smart manufacturing for the future. Tech. rep. (2014)
30. Miller, M.D., Alvarez, R., Hartman, N.: Towards an extended model-based definition for the digital twin. Computer Aided Design & Applications **15**(6), 880–891 (2018)
31. Napoleone, A., Macchi, M., Pozzetti, A.: A review on the characteristics of cyber-physical systems for the future smart factories. Journal of Manufacturing Systems **54**, 305–335 (2020)
32. Negri, E., Berardi, S., Fumagalli, L., Macchi, M.: Mes-integrated digital twin frameworks. Journal of Manufacturing Systems **56** (2020)

33. Noy, N.F., McGuinness, D.L.: Ontology development 101: A guide to creating your first ontology. Tech. rep. (2001)
34. Park, K.T., Lee, J., Kim, H.J., Noh, S.D.: Digital twin-based cyber physical production system architectural framework for personalized production. International Journal of Advanced Manufacturing Technology **106**(5-6), 1–24 (2020)
35. Perzylo, A., Profanter, S., Rickert, M., Knoll, A.: Opc ua nodeset ontologies as a pillar of representing semantic digital twins of manufacturing resources. In: Proceedings of the IEEE International Conference on Emerging Technologies And Factory Automation (ETFA), pp. 1085–1092 (2019)
36. Qi, Q., Tao, F.: Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison. IEEE Access **6**, 3585–3593 (2018)
37. Ribeiro, L., Barata, J., Onori, M., Amado, A.: Owl ontology to support evolvable assembly systems. IFAC Proceedings Volumes **41**(3), 290–295 (2008)
38. Roy, R.B., Mishra, D., Pal, S.K., Chakravarty, T., Misra, S.: Digital twin: Current scenario and a case study on a manufacturing process. International Journal of Advanced Manufacturing Technology **107**, 3691–3714 (2020)
39. Sari, A.K., Rahayu, W., Bhatt, M.: An approach for sub-ontology evolution in a distributed health care enterprise. Information Systems **38**(5), 727–744 (2013)
40. Schleich, B., Anwer, N., Mathieu, L., Wartzack, S.: Shaping the digital twin for design and production engineering. CIRP Annals - Manufacturing Technology **66**, 141–144 (2017)
41. Schroeder, G.N., Steinmetz, C., Pereira, C.E., Espindola, D.B.: Digital twin data modeling with automationml and a communication methodology for data exchange. IFAC-PapersOnLine **49**(30), 12–17 (2016)
42. Sellami, Z., Camps, V., Aussenac-Gilles, N.: Dynamomas: A multi-agent system for ontology evolution from text. Journal on Data Semantics **2**(2-3), 145–161 (2013)
43. Seshadri, B.R., Krishnamurthy, T.: Structural health management of damaged aircraft structures using digital twin concept. In: 25th AIAA/AHS Adaptive Structures Conference (2017)
44. Sierla, S., Kyrki, V., Aarnio, P., Vyatkin, V.: Automatic assembly planning based on digital product descriptions. Computers in Industry **97**, 34–46 (2018)
45. Sirin, E., Parsia, B., Grau, B.C., Kalyanpur, A., Katz, Y.: Pellet: A practical owl-dl reasoner. Journal of Web Semantics **5**(2), 51–53 (2007)
46. Stojanovic, L., Maedche, A., Motik, B., Stojanovic, N.: User-driven ontology evolution management. In: Knowledge Engineering and Knowledge Management: Ontologies and the Semantic Web, pp. 285–300. Springer Berlin Heidelberg, Berlin, Heidelberg (2002)
47. Sugato, C., Rahul, C., M., L.R.: Ontology-guided knowledge retrieval in an automobile assembly environment. International Journal of Advanced Manufacturing Technology **44**, 1237–1249 (2009)
48. Sun, X., Bao, J., Li, J., Zhang, Y., Zhou, B.: A digital twin-driven approach for the assembly-commissioning of high precision products. Robotics and Computer-Integrated Manufacturing **61** (2020)
49. Tan, Q., Tong, Y., Wu, S., Li, D.: Modeling, planning, and scheduling of shop-floor assembly process with dynamic cyber-physical interactions: A case study for cps-based smart industrial robot production. International Journal of Advanced Manufacturing Technology **105**(9) (2019)
50. Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F.: Digital twin-driven product design, manufacturing and service with big data. International Journal of Advanced Manufacturing Technology **94**(9-12), 3563–3576 (2018)
51. Tao, F., Zhang, M.: Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing. IEEE Access **5**, 20418–20427 (2017)
52. Tao, F., Zhang, M., Nee, A.: Digital twin driven smart manufacturing. Academic Press (2019)
53. Um, J., Weyer, S., Quint, F.: Plug-and-simulate within modular assembly line enabled by digital twins and the use of automationml. IFAC Papersonline **50**(1), 15904–15909 (2017)
54. Yi, Y., Yan, Y., Liu, X., Ni, Z., Liu, J.: Digital twin-based smart assembly process design and application framework for complex products and its case study. Journal of Manufacturing Systems (2020)
55. Zakrajsek, A.J., Mall, S.: The development and use of a digital twin model for tire touchdown health monitoring. In: 58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (2017)
56. Zhan, P., Jayaram, U., Kim, O., Zhu, L.: Knowledge representation and ontology mapping methods for product data in engineering applications. Journal of Computing and Information Science in Engineering **10**(2), 021004 (2010)
57. Zhang, H., Yan, Q., Wen, Z.: Information modeling for cyber-physical production system based on digital twin and automationml. International Journal of Advanced Manufacturing Technology **107**(3-4) (2020)
58. Zhu, L., Jayaram, U., Kim, O.: Semantic applications enabling reasoning in product assembly ontologiesmoving past modeling. Journal of Computing & Information Science in Engineering **12**(1), 011009 (2012)
59. Zhuang, C., Gong, J., Liu, J.: Digital twin-based assembly data management and process traceability for complex products. Journal of Manufacturing Systems (2020)

Figures

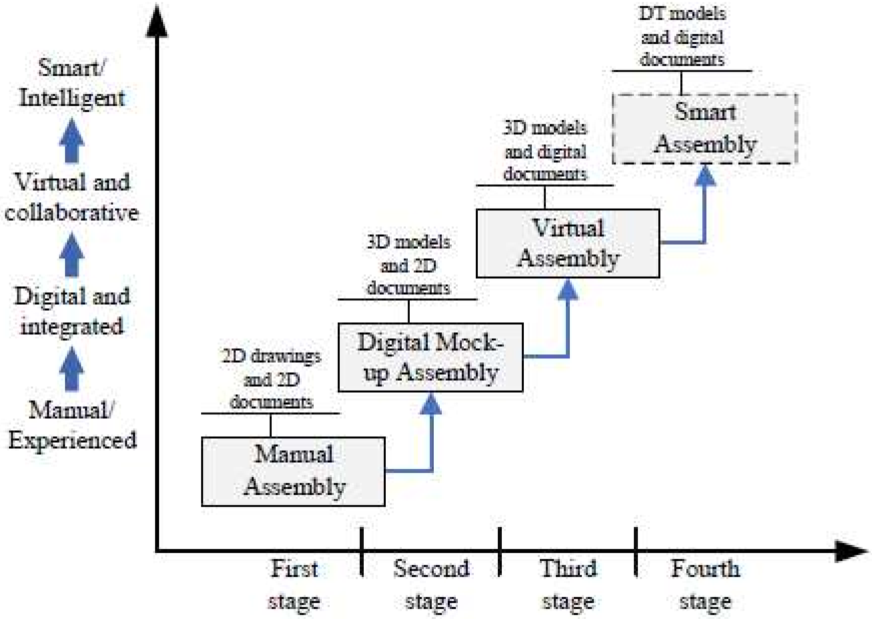

Figure 1

Product assembly technology development[54].

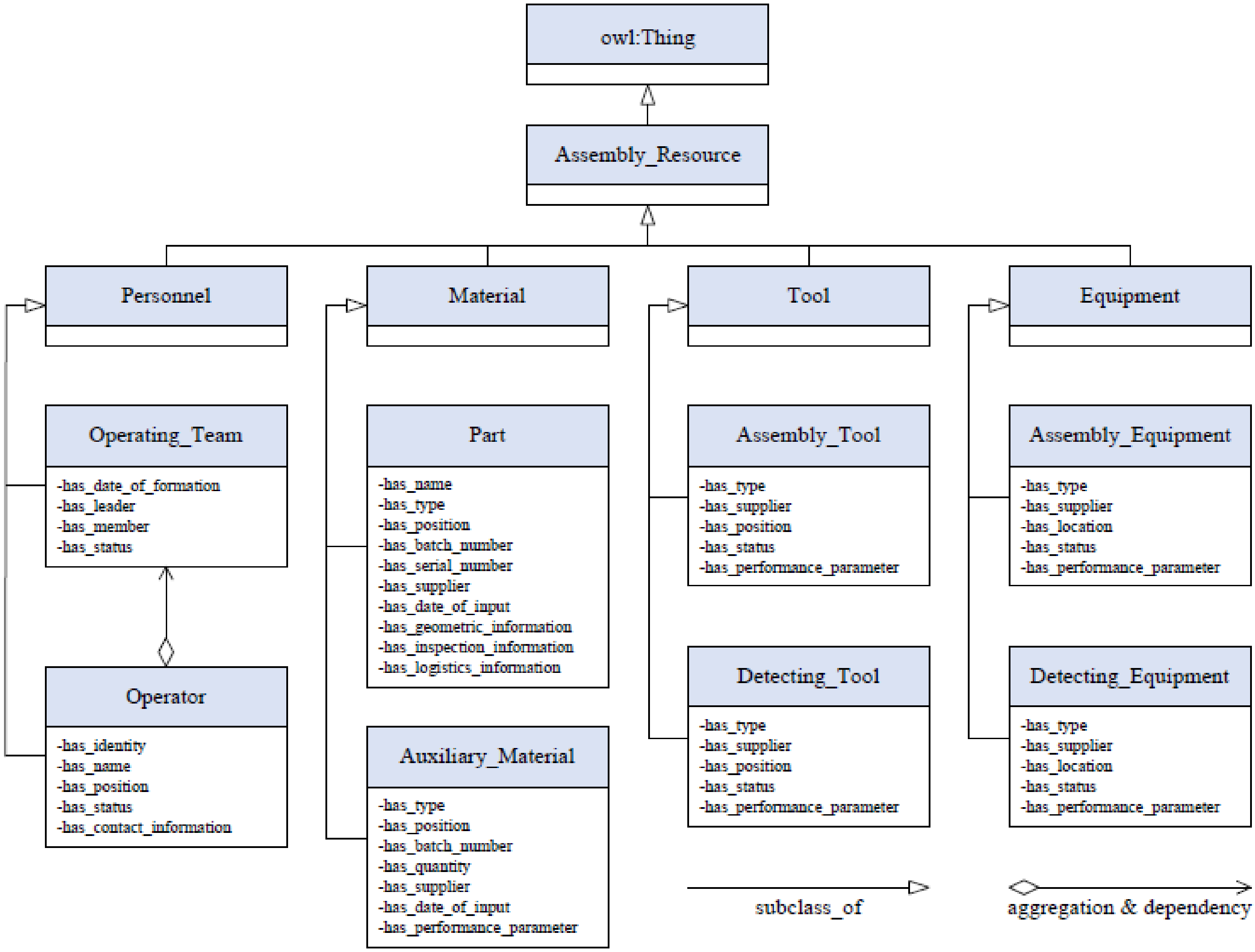

Figure 2

The main information classication of DT resou

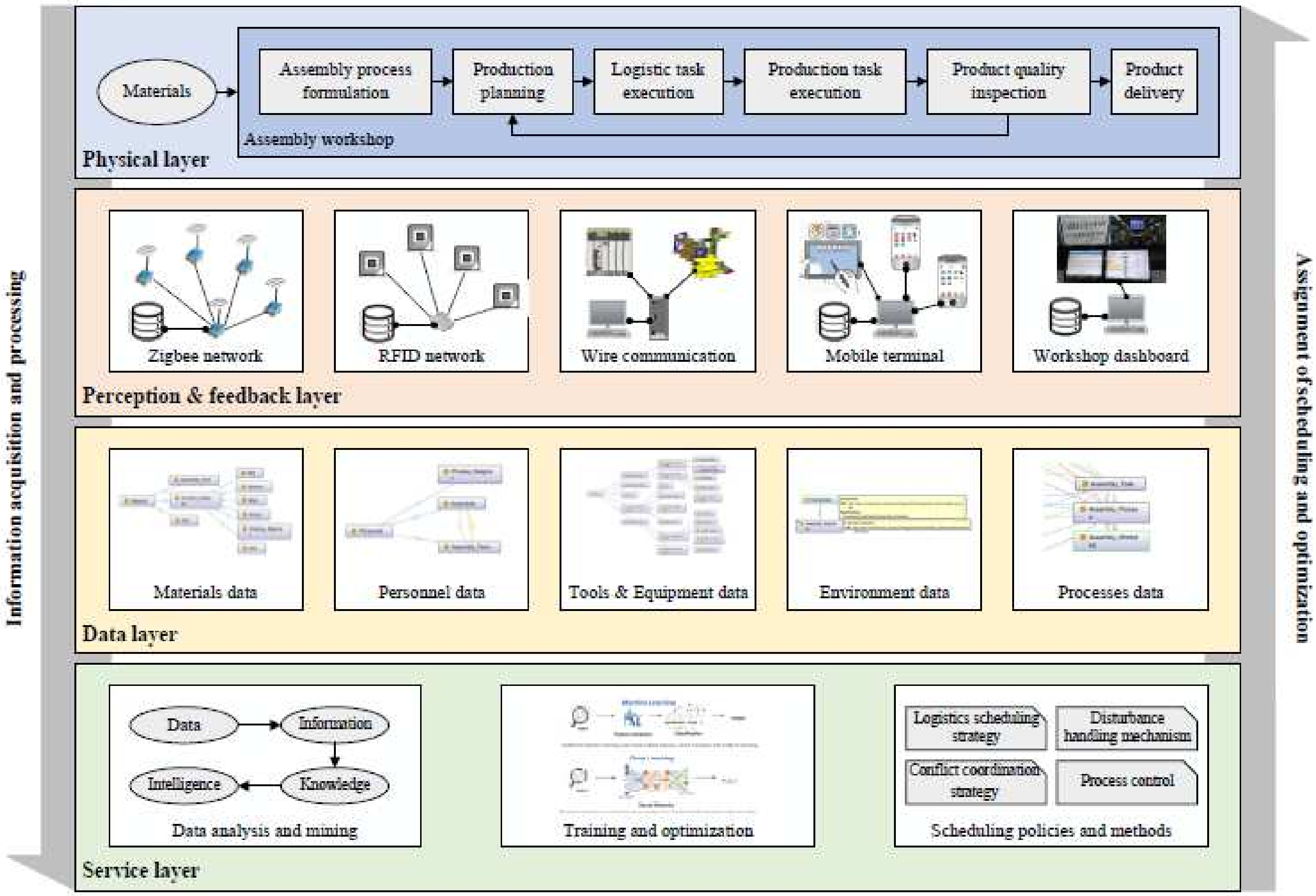

Figure 3

The framework of DT assembly workshop.

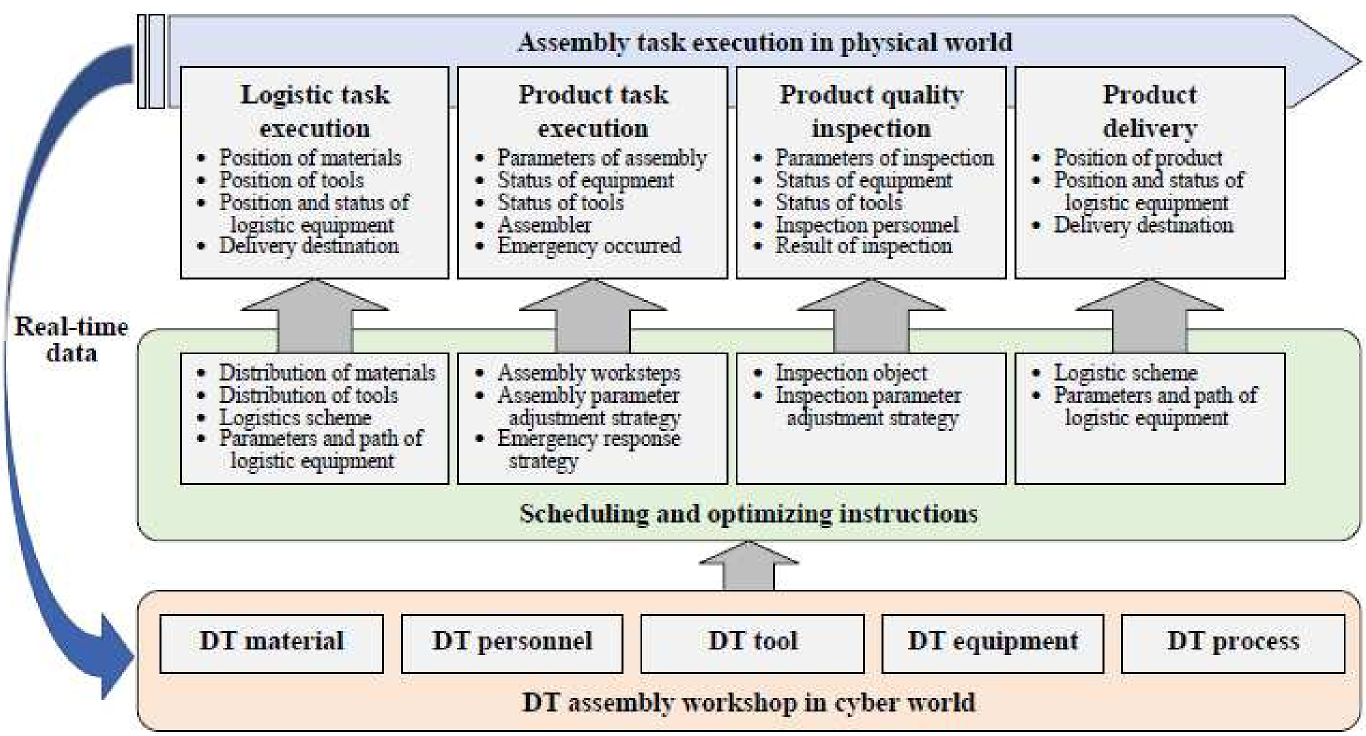

Figure 4

Multiple methods of data ow in assembly workshop.

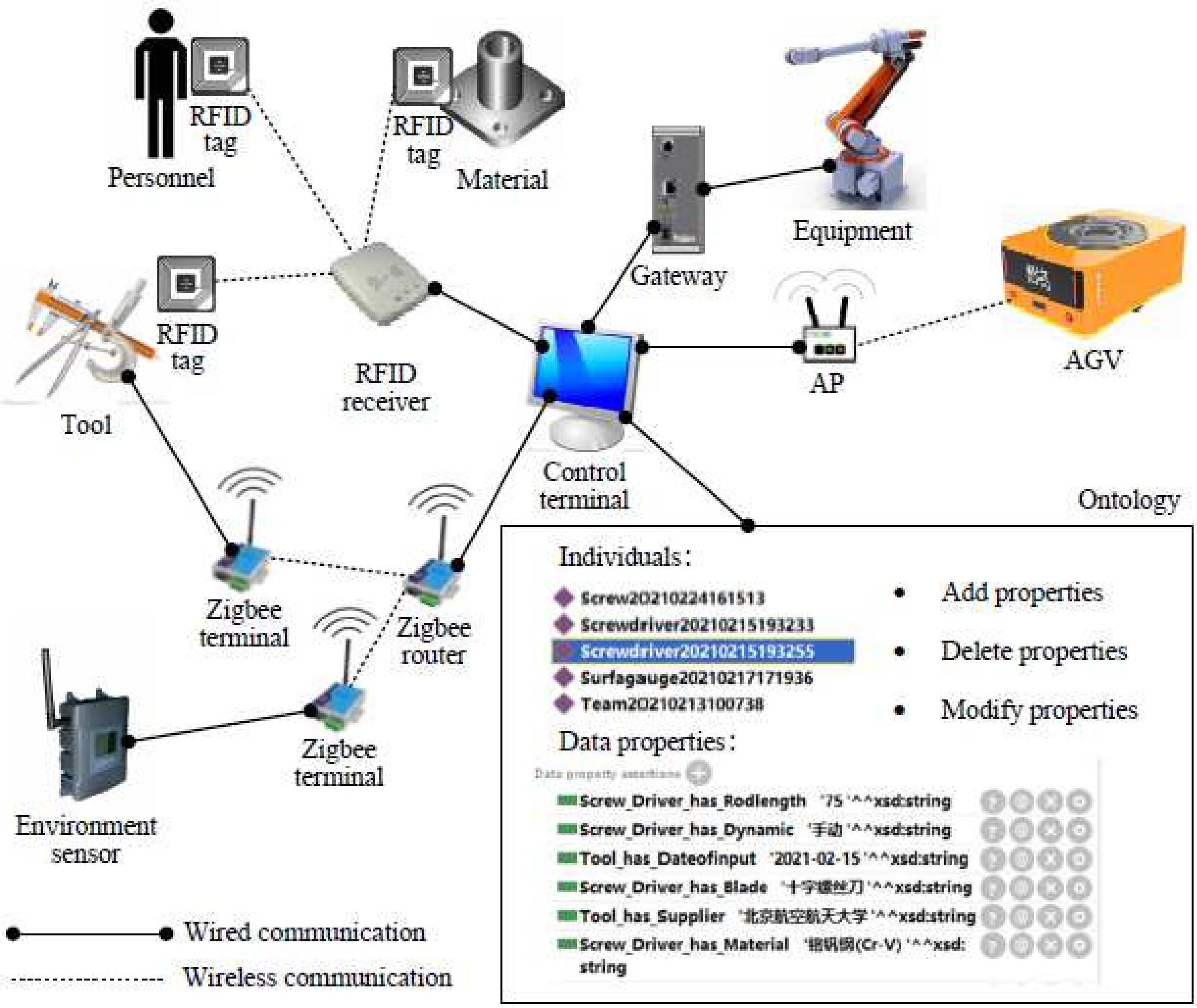

Figure 5

Sensors and communication networks in mapping resources.

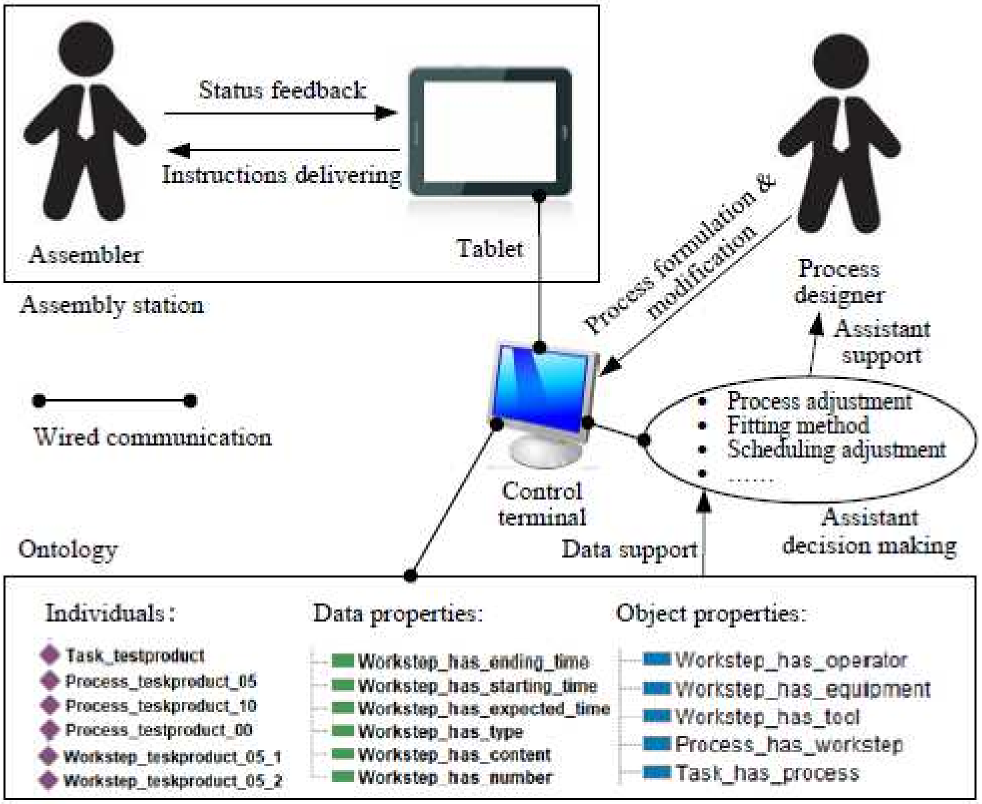

Figure 6

Process information transfer during task execution.

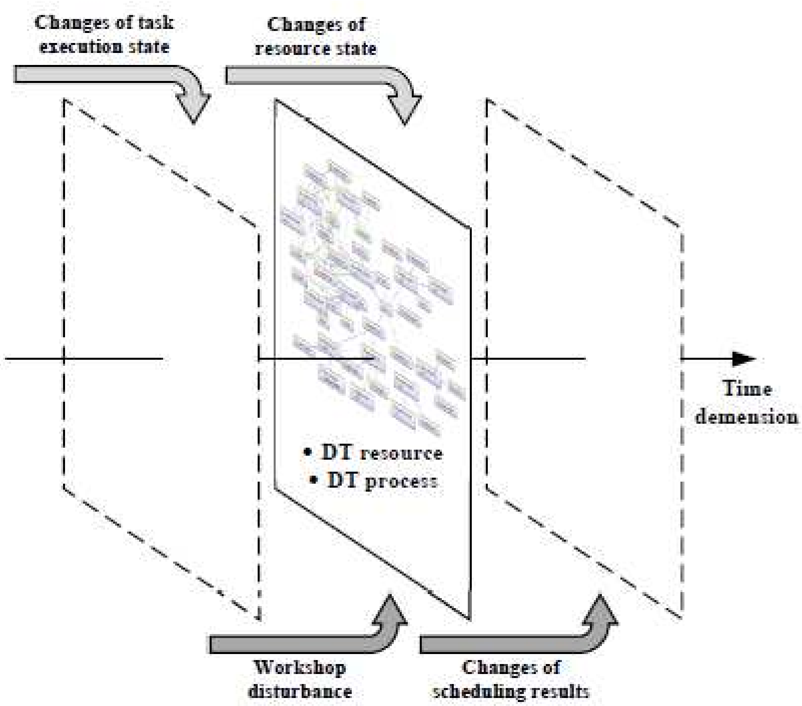

Figure 7

Historical data storage mechanism of DT assembly workshop.

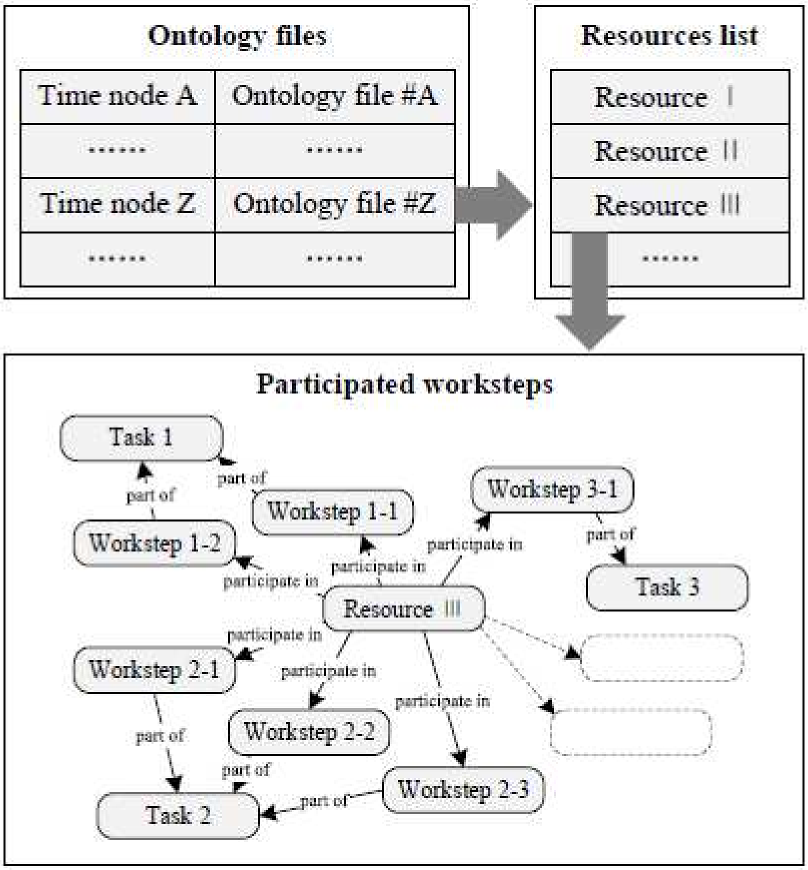

Figure 8

The mechanism of tracing historical data centered on resource.

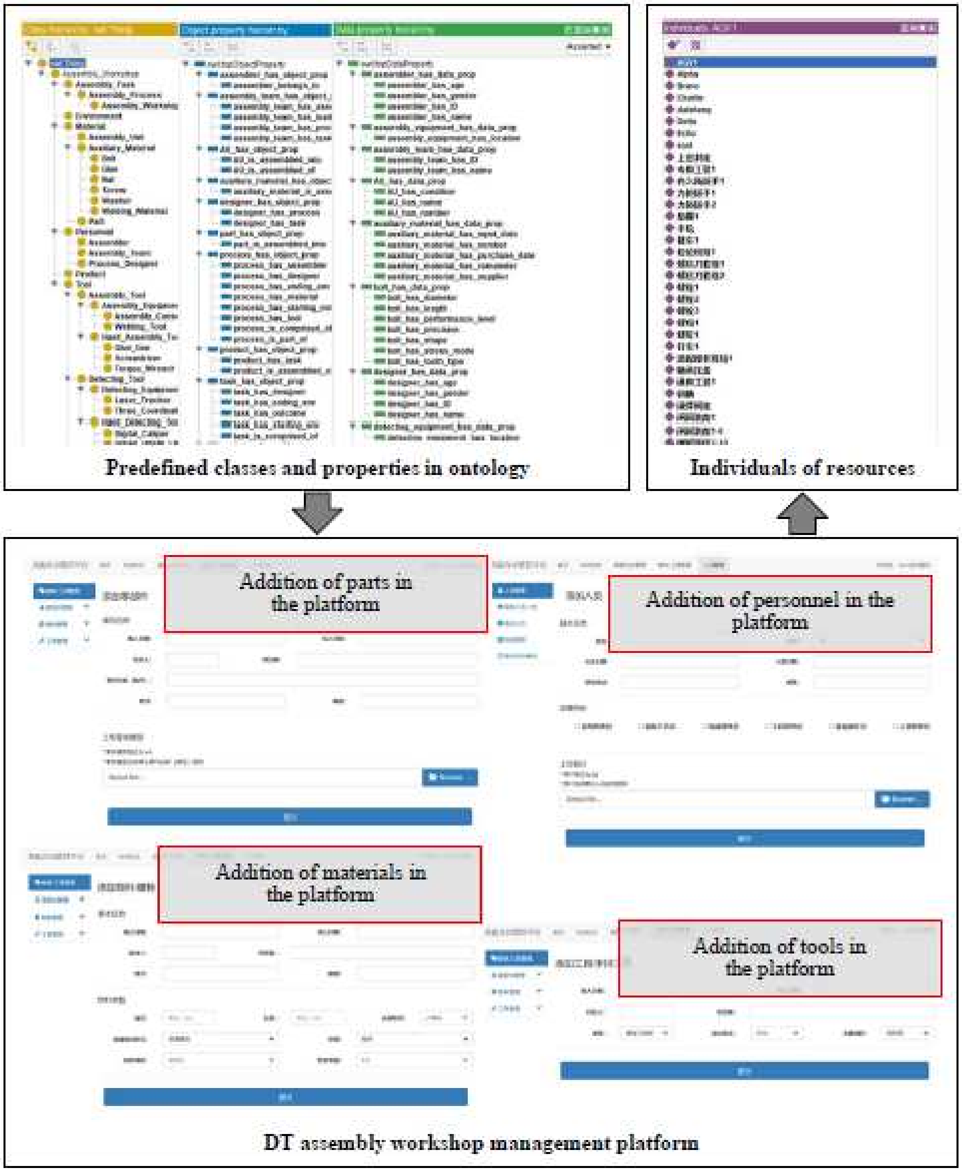

Figure 9

The addition and instantiation of the assembly resource.

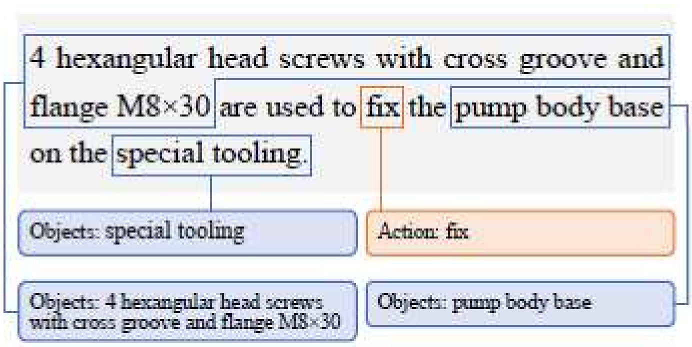

Figure 10

An example of workstep event element extraction.

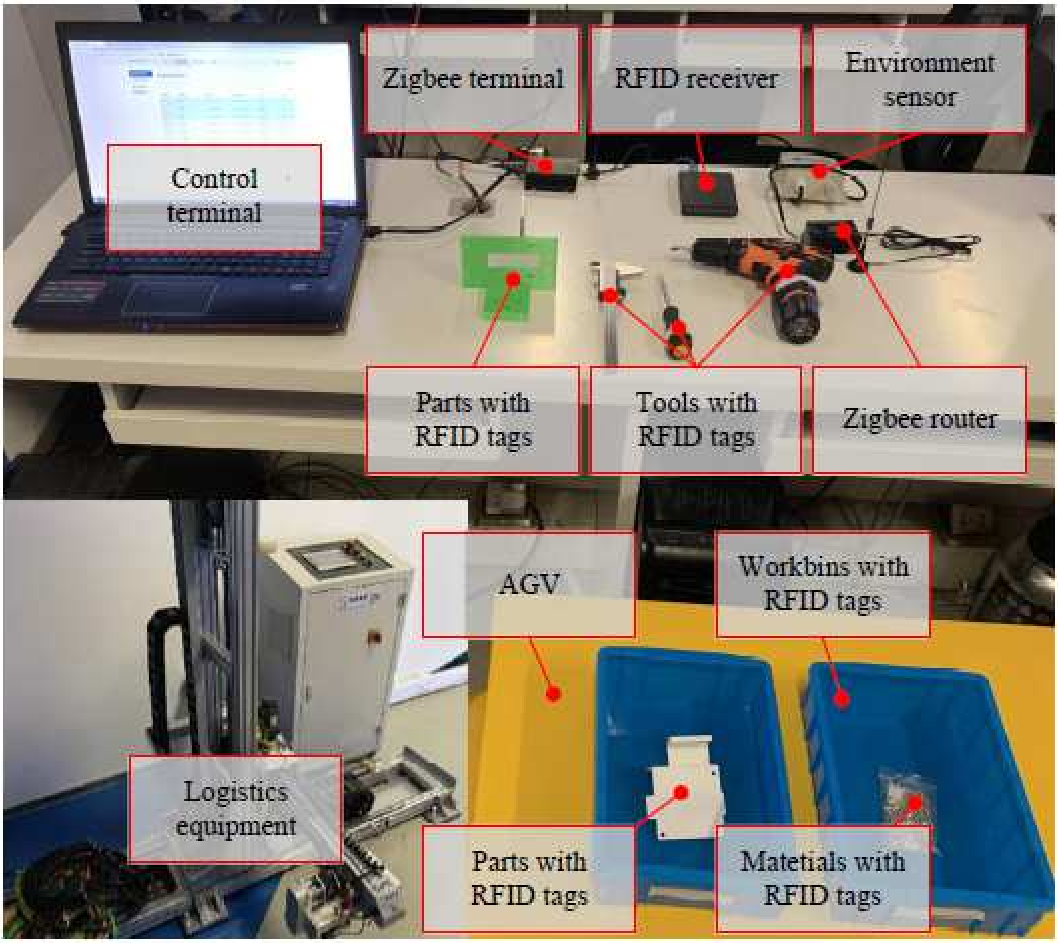

Figure 11

The layout of resource entities in an assembly station of the experimental workshop.