Ontology-based Assembly Process Modeling with Element Extraction and Reasoning

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Abstract. In the context of collaborative manufacturing and cloud manufacturing, an ontology-based semantic modeling method of assembly process is studied to solve the problem of non-standard assembly process formulation. Firstly, assembly process is divided into worksteps according to the assembly topology relationships, which correspond to the concept of event ontology as basic units. Secondly, natural language processing technology is used to process workstep contents in assembly documents, further realize the transformation from human language to machine language, which constitutes a significant step of the extraction of workstep event elements. In addition, the workstep event elements is supplemented with ontology reasoning of assembly resources without directly specifying the relatedness with the worksteps as well. Finally, a case study is illustrated to show the entire process of element extraction and reasoning of assembly worksteps, indicating the availability and feasibility of method proposed.

Keywords: assembly process, ontology, element extraction, element reasoning
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1 INTRODUCTION

With the research and application of cloud manufacturing [23, 22], a standardized expression method is urgently needed to model manufacturing process and capabilities. Meanwhile, the requirement is particularly imperative in assembly process modeling, for that there are serious irregularities in the formulation and record of assembly process due to the diversity of assembly modes in assembly workshop [5]. The technology of semantic web with mature development provides a suitable modeling method for the assembly process, considering the extraordinary description and sharing abilities of semantic web languages in modeling. Furthermore, ontology web language (OWL) has been considered as the representative language of semantic web for the rich expression methods of individuals and relationships. The modeling of assembly process with ontology is of great significance to solve the problems of non-standard and poor sharing in traditional assembly process modeling, which is the focus of this research.

Meanwhile, corpus extraction technology has been widely used in various fields with the continuous development and maturity of natural language processing (NLP) technology. In industrial manufacturing, assembly process is usually recorded in process documents or procedures, in the form of statements. Although the promotion of BOM (Bill of Material) based PDM (Product Data Management) has made some exploration for modeling of assembly process, the degree of semantics is still insufficient in front of numerous elements and relationships at the assembly site. Through corpus extraction of process documents, semantic modeling of relevant elements in the execution of assembly process can be effectively carried out to meet the instantiation requirements of ontology.

With the deepening of the research on assembly technology, the modeling method of assembly process, as one of the most important parts, has been paid more attention. In terms of modeling languages, the modeling attempts of assembly process mainly include objected-oriented modeling [16], XML-based modeling [2], database-based modeling [21], ontology-based modeling [17] and Petri net-based modeling [25]. With the introduction of the concepts of digital twin (DT) [9, 8] and DT shopfloor [20], the purpose of assembly process modeling is gradually evolving from historical data storage and guidance for assembler to providing data source for intelligent services in manufacturing process. In the frame of DT, Bao et al. [1] presented a modeling method of process DT and illustrated the main content and data interaction mode in the process model. The position and role of process model in the DT framework of products, processes and operations are also discussed. Kuliaev et al. [10] proposed a framework for product-centric assembly process mapping, in which the execution of the assembly process in the virtual space can be mapped to the actual site in the physical world, and can be visualized by 3D models and scenes. Similarly, the DT of a set of assembly process with the modeling object of the production process of a truck was presented [14] to prove the feasibility and advancement of DT-oriented process modeling. Yi et al. [24] proposed a DT-based smart assembly process design and application framework for complex products, in which the detailed methodologies for the fusion of visual and physical workflow and data interaction are discussed. Zhuang et al. [27] analyzed the assembly process data in the dimensions of both version and period. Furthermore, the evolution and preservation mechanism of assembly process are given for modeling and tracing.

On the other hand, ontology technology is widely used in manufacturing and assembly fields, for the strong descriptive abilities of modeling static resource and dynamic process [6]. Lu et al. [13] presented a framework for resource virtualization focusing on the description of manufacturing capacity. The framework can be extended to any type of resource virtualization in developing a cyber-physical system. Ulteriorly, Perzylo et al. [15] proposed a method of semantic modeling for geometry based on the OntoBREP ontology, as the geometrical supplement to the assembly resource modeling. Furthermore, Ramis et al. [18] analyzed a unified modeling approach of product, process and resource for knowledge-driven assembly automation, which can be used effectively to link data models from various engineering domains and engineering tools. In addition to modeling and virtualization research, ontology technology has also been applied to knowledge extraction and utilization. Knowledge can be abstracted and represented with semantic web rule language (SWRL) from product data in engineering applications [26], waiting for the reuse when facing appropriate situations [4]. Along this way, Li et al. [11] presented a framework for process semantic modeling and resource recommendation in the context of DT.

The research above has solved the problems of semantic modeling of assembly process to a certain extent. However, there are still some pressing concerns in the practical applications. There are certain difficulties in obtaining effective information directly from process documents due to the non-standard record and storage.

The deployment of semantic treatment of process documents is difficult to carry out, leading to the information loss when processing. In addition, if manual processing is adopted to review the information contained in the process documents, it will waste a lot of manpower cost and cannot guarantee the accuracy of process modeling. Motivated by these needs, an assembly process modeling method based on ontology is proposed in this manuscript. The accuracy and validity of the process model can be guaranteed by the extraction and reasoning of relevant elements involved in the process.

In this manuscript, the ontological approach of assembly process modeling is given. Firstly, the assembly process items are divided into worksteps as the modeling units and expressed with the concept of event ontology consisting of six elements. Secondly, the assembly documents are analyzed and decomposed, in which the elements are extracted with regular expression matching. Whereafter, the ontology-based reasoning is used to associate the assembly resources that are not directly indicated in the process documents to further complete the filling of assembly event elements. Finally, a case study is illustrated to demonstrate the availability of the method proposed.

2 MODELING OF ASSEMBLY PROCESS

Generally, assembly process is formulated and recorded with assembly documents by process designers. The assembly document of a certain task expands in the order of assembly operations, in which the assembly procedures and worksteps are defined corresponding specific operations to guide the assemblers to complete the assembly task in accordance with certain operational orders and requirements. The hierarchical relationships and attributes of assembly tasks, procedures and worksteps are shown in Fig. 1.

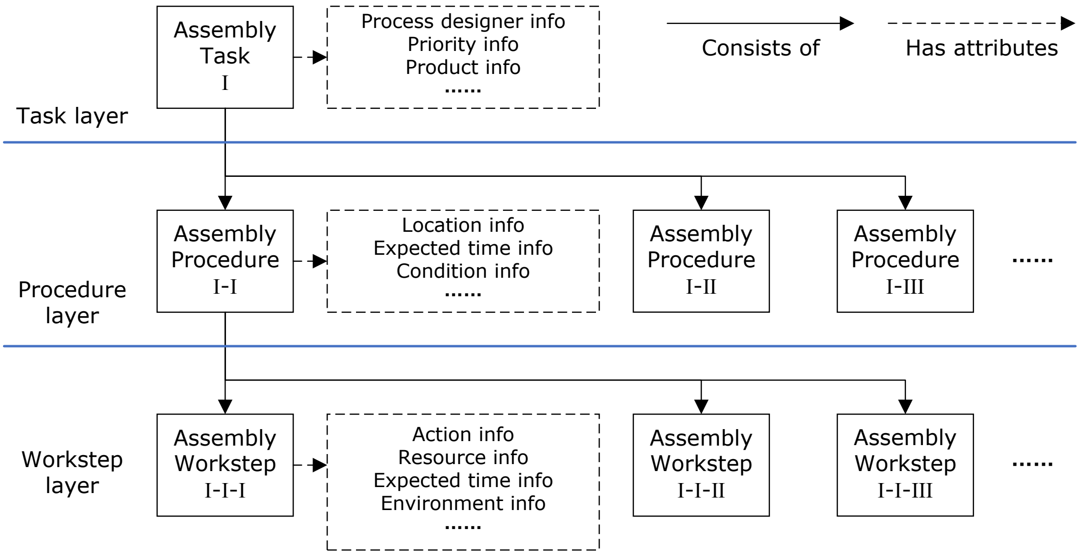


Figure 1: The hierarchical relationships and attributes of assembly tasks, procedures and worksteps

Generally, an assembly task consists of several assembly procedures, which can be composed of corresponding assembly worksteps respectively. As the basic unit of assembly process, modeling of workstep requires a variety of information and attributes to be considered, including operation actions, associated resources, execution time, environment information, et al. Among the many methods of ontology modeling, an assembly workstep can be seen as an event that contains various information related to the operation. In the conceptual framework of event ontology, an event e can be defined as a six-tuple [12], as shown in Eq. (1).

$$e = (A, O, T, V, P, L) \tag{1}$$

The elements in the six-tuple are known as the event factors. In the scene of describing an assembly workstep, the elements of an event should cover various kinds of information of the corresponding workstep to guide or describe the assembly operation of this step instead of document and record all resources and data related to the operation. The explanation of the six-tuple of assembly workstep events is shown in Tab. 1.

Factors	*Paraphrases*	*Explanations in assembly workstep*
A	A happening action set	The possible operations 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 work-step 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

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

In the modeling of assembly workstep events, each factor represents a set of information of a certain type for the assembly worksteps. Detailed discussion of factors are as follows:

- *A* represents the actual operation performed in the assembly workstep by assemblers. Assembly operations can be expressed by a variety of actions, such as combining, constructing, cleaning, welding, et al. The operation is the most important part of an assembly workstep event, which is the core of the other elements.
- *O* represents the associated assembly resources in this workstep. Generally, the assembly resources include personnel, materials, tools and equipment in the workshop. The workstep event should contain the use of resources by establishing relationships between the workstep and involved resources to form an effective carrier for preserving the manufacturing historical data.
- *T* and *V* represent the time and environment information in the assembly workstep events respectively. With the execution of worksteps, the time and environment information will be generated naturally, recorded and transmitted to the event models.
- *P* represents the pre-condition, post-condition and intermediate assertions in the process of workstep execution. The conditions factors, e.g., the sequence of worksteps, the requirements of inspection results, the delivery status of materials, et al. can be modeled in this part to ensure that the assembly worksteps are executed in an orderly and quality manner.
- *L* represents the description language of assembly worksteps. The modeling and corpus extraction methods differ on account of different language expressions, including core words sets, core words expressions and core words collocations.

To construct the ontology of assembly worksteps, hierarchical relationships among classes need to be established firstly, as shown in Fig. 2. One major branch represents the inheritance relationship among assembly task, procedure, workstep information and elements describing worksteps. On the other hand, assembly resources of the assembly site should be ontologically modeled according to the types to realize the association between worksteps and resources. It is worth mentioning that the types of assembly resources may vary greatly in different workshops, the modeling method in Fig. 2 provides only one feasible example. For a variety of assembly resources, ontology modeling should be carried out in a similar way according to the actual situation of the specific workshop.

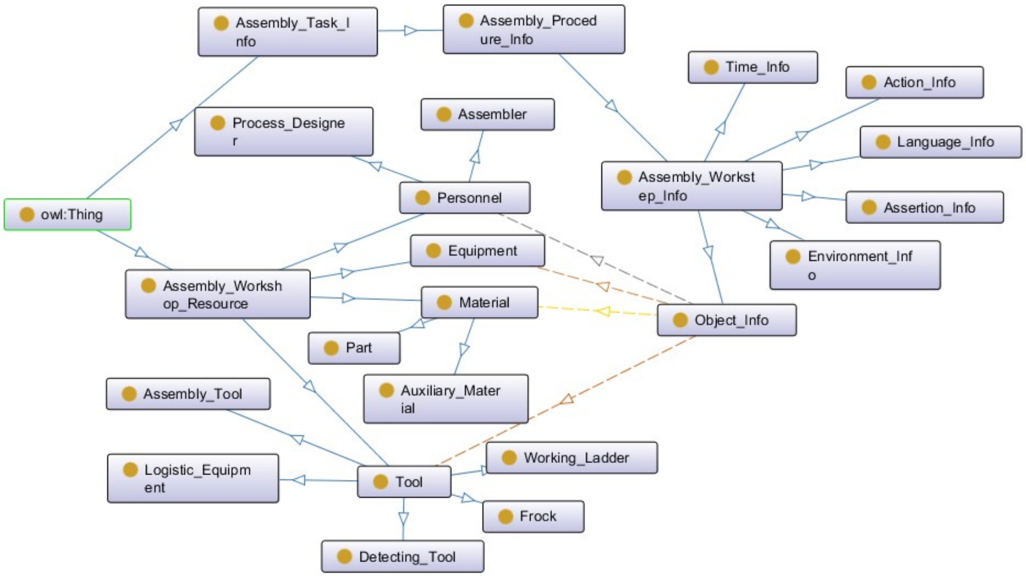


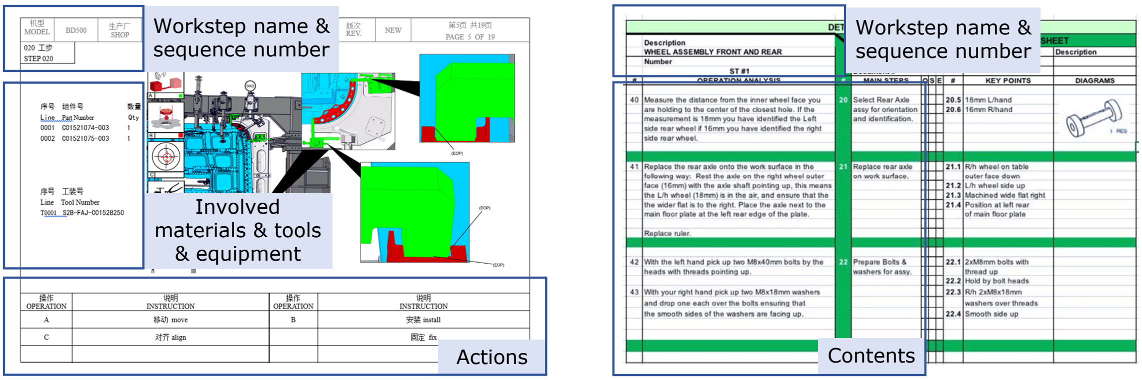
Figure 2: The ontology structure of assembly workstep events

As mentioned above, there are six elements involved in the assembly workstep events. Some elements are recorded by data properties of ontology classes, including action information, time information, environment information, assertion information and language information by predefined ranges of data properties for the corresponding classes. Object information of worksteps reflects in the object properties among specific classes. Assembly workstep events can be semantically expressed through ontology by instantiating worksteps and resources along with the assignments of data and object properties to instances.

3 ELEMENT EXTRACTION OF WORKSTEP EVENT

In the case of assembly operation, assembly worksteps are usually in the form of process document with sequence number, workstep name, content, et al. Some process documents also include tools, equipment, rated working hours and other information listed separately, which can be directly extracted to fill in the workstep events. Fig. 3 shows the assembly process documents with or without the separately listed resources entries and actions involved in the workstep.

For the process documents with detailed resource and action entries, the elements involved in the workstep can be extracted directly from the relevant location in the documents. Meanwhile, the listed entries should also be semantically processed to establish relationships in the ontology. However, for the documents where



(a) Process document with detailed entries (b) Process document without detailed entries

Figure 3: Process documents with detailed entries (a) and contents (b)

all the information is gathered in the contents, the workstep event elements should be extracted using relative NLP technology to extract valid fields from the contents to build associations.

NLP is a bridge between machine language and human language to achieve the purpose of man-machine communication. In the case of element extraction of workstep events, the human language refers to the contents manually specifying the operations by process designer in process documents. On the other hand, the machine language refers to the semantic six-tuple representing the assembly workstep events. Among the functions that NLP technology can achieve, natural language understanding (NLU) plays a key role in the transformation from assembly process documents to workstep events. Considering the characteristics of assembly process and the implementation method of NLU, the steps of corpus preprocessing are shown in Fig. 4.

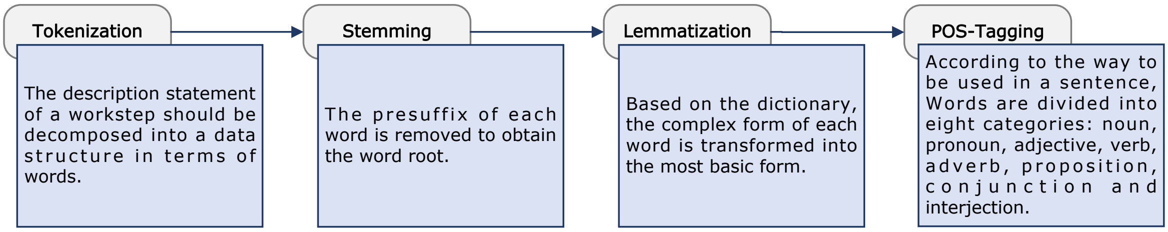


Figure 4: The steps of corpus preprocessing

After the corpus preprocessing of the process document, each workstep description can be broke up into a data set containing words and phrases. Regular expression matching, with the characteristics of high efficiency and high accuracy, is used for the extraction of elements for workstep events. The implementation process of element extraction is shown in Fig. 5.

The specific implementation steps are as follows:

1. The assembly workstep contents are obtained after preprocessing. At this time, each word in the content of the workstep is processed to remove additional information such as tense changes, and the type of each word has been defined.

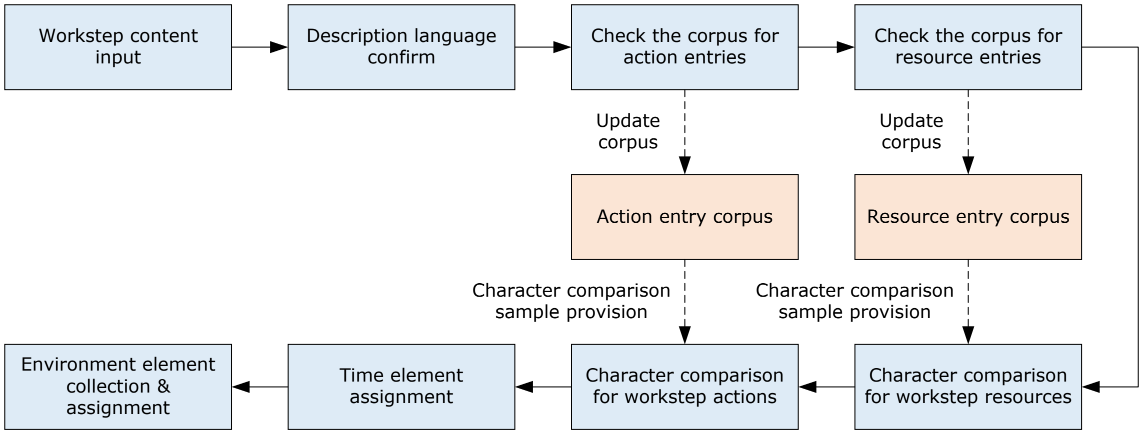


Figure 5: The steps of element extraction for assembly workstep contents.

2. The description language of the workstep content is confirmed in this step. With different language, different corpora should be used in subsequent processing, and language issues should also be considered in preprocessing. In this manuscript, English is chosen to be the descriptive language for workstep contents and corpora to verify the method proposed.
3. The corpus of the assembly actions should be confirmed that whether there is something to be updated. Generally, the assembly actions that may occur in the workshop are recorded in the action corpus, such as move, install, fix, et al. If no new assembly method is introduced in the assembly workshop, the corpus will not be updated in general.
4. The corpus of the assembly resources should also be confirmed then. The corpus should be updated to add the name or number of the new entry when assembly resource items, such as materials, tools, equipment, et al., enter the assembly workshop.
5. Compare each entry in the assembly resource corpus with the content of workstep to find the same entry. The assembly resources corresponding to the entries should be associated with the assembly workstep. Meanwhile, the quantity of assembly resources, especially materials, can be extracted by the current quantitative adjective before the words representing resource entries.
6. Similarly, the actions in the assembly workstep can also be obtained by comparing the action corpus with the contents of the workstep one by one.
7. The element of time corresponds to the time information in the design the execution of the assembly workstep. The adding time of assembly process can be obtained from the current system time. On the other hand, the starting and ending times of the assembly process can be obtained during the execution of the task.
8. The environment information corresponding to the assembly workstep can also be collected and transmitted during the execution of the task by appropriate sensor networks, which is not the focus of this manuscript.

4 ELEMENT REASONING OF WORKSTEP EVENT

The process documents may not contain the names of all the resources associated with the assembly worksteps, leading to the incompleteness of assembly workstep elements. To deal with this problem, it is necessary to construct an expert system for workstep event elements reasoning, as shown in Fig. 6

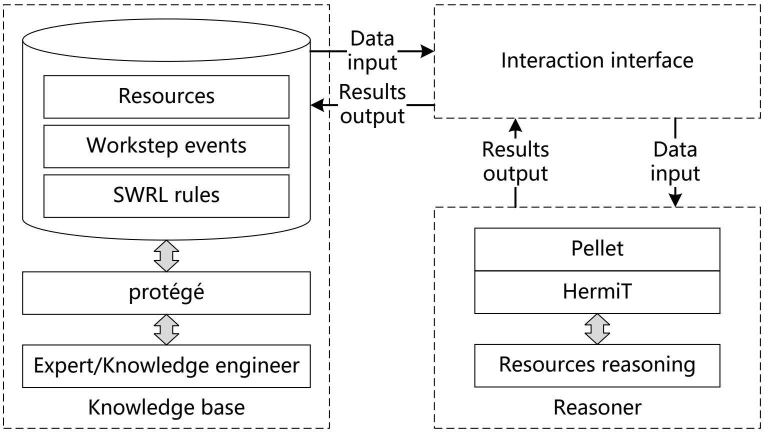


Figure 6: The expert system for workstep event elements reasoning

The rules used in reasoning are mainly derived from the knowledge in the assembly workshop, mainly including the following aspects:

- The use of some assembly resources requires the support of other resources. For example, if welding equipment is needed, appropriate welding consumables must be required.
- Certain operations require equipment or tools supports. For example, if heavier materials are to be transported, logistics equipment like carts, AGVs, or cranes are necessary under their respective applicable conditions.
- The locations of the execution of assembly operations are determined by the resources associated with the operations in some cases. For example, if a workstep requires a fixed specialized frock, the location where the workstep is executed will depend on the location of the frock.

The reasoning rules of assembly resources are mainly used to establish a connection between assembly workstep and resources that are not directly reflected in the content of the workstep. These rules are the experience and knowledge summarized by experts and assembly operators in the field of assembly in long-term production practice. SWRL is used in this manuscript to model these rules. SWRL is an OWL rule description language developed on the basis of rule markup language. The purpose of SWRL is to drive the combination of rules and OWL knowledge base and enhance the deductive reasoning ability of OWL knowledge base. SWRL rules can work with ontology reasoning engines as part of the ontology.

Each rule can be expressed using SWRL and applied to ontology reasoning. According to the SWRL syntax, OWL semantics can be abstracted into tuples in the form of formulas with a method of data type mapping [3], as shown in Eq. (2).

$$I = (R, EC, ER, L, S, LV) \tag{2}$$

Thereinto, R stands for a group of resources. LV stands for a group of literal values in R. EC stands for the mapping between classes and data types along with the mapping between R and LV. ER stands for the mapping of binary relation between properties and R. L stands for the mapping between typed literal and elements in LV. S stands for the mapping between individual name and elements in EC.

In editing, rules are made up of a series of atoms, which can be data functions $C(x)$, relational functions $P(x,y)$, or other built-in functions $(r, x1, x2, ...)$. Thereinto, C stands for classes in the ontology, while P stands for properties, including object properties and data properties. In addition, x and y are the corresponding variables, representing individuals and data values, respectively. Build-in functions are embedded in SWRL, in which r stands for functional relationships and x stands for variables with the functions of numeric calculation, string operation, comparison operation, Boolean operation, et al.

The reasoning process based on SWRL can be expressed by Eq. (3)

$$(\wedge_{i=1}^{n} Atom_i) \rightarrow (\wedge_{j=1}^{m} Atom_j) \tag{3}$$

SWRL consists of reasoning antecedents and reasoning consequents, which are made up of multiple atoms with the relationships of logical AND. When atoms of the reasoning antecedents are all true, reasoning consequents can be deduced. With the ontology reasoning engine Pellet [19] or HermiT [7], SWRL rules can be used for reasoning in the ontology of assembly events to establish the connections between workstep and other participating resources.

By this form of reasoning method, assembly workstep event elements that cannot be obtained in the process of information extraction can be reasoned out to further enrich the assembly workstep events. The standardization and semantic modeling of assembly process can be realized through the establishment of multiple assembly workstep events.

5 A CASE STUDY

As mentioned above, if there are thorough information classifications and listed relevant entries in the assembly process document, it is easy to obtain semantic information from the process document and complete the modeling of the assembly process. Otherwise, it is necessary to realize the modeling of the assembly process through the extraction and reasoning of the event elements of the assembly worksteps when dealing with the process document that contains only general process content description, which is the main research content of this manuscript. Therefore, this section proposes a case study depicting the semantic modeling process of worksteps oriented to assembly process content.

A typical gate value assembly process is analyzed as an example, among which a representative workstep in the assembly is used to reflect the whole process and verify the effectiveness of the method proposed. The original content, preprocessing result and element extraction result of this workstep are shown in Fig. 7.

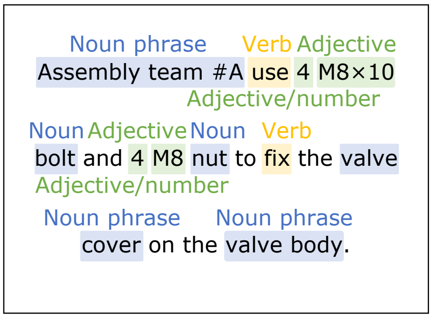
With element extraction, 5 objects and 1 action can be extracted and associated with the sample workstep. However, there are still some elements that are not directly reflected in the content of the sample workstep, which are also indispensable in the execution of the workstep. Continuing with the above sample workstep, the SWRL rules listed in Tab. 2 can be used to deduce the missing element of the workstep.

By reasoning with the rules listed in the table, the corresponding screwdriver, wrench and AGV trolley can be associated with the sample workstep, which are not directly reflected in the workstep content. With the constant updating of the rule base, all types of worksteps can be associated with additional elements through ontology reasoning, which ensures the integrity of assembly workstep models. For sample workstep, the finally established workstep model is shown in Fig. 8.

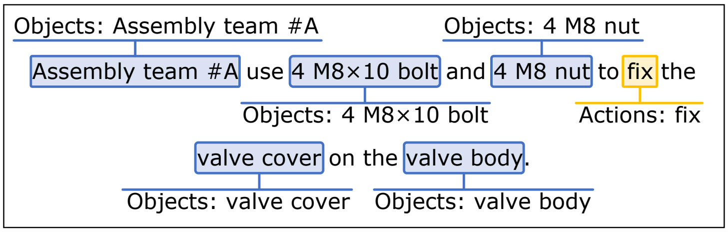
In this case, the elements of sample workstep is extracted and deduced. According to the processing results, the semantic modeling of the workstep is realized, providing an effective method for the semantic modeling and expression of assembly process.

Workstep number	Workstep content
......	......
15	Assembly team #A uses 4 M8×10 bolts and 4 M8 nuts to fix the valve cover on the valve body.
......	......

(a) The original content of the sample workstep



(b) The preprocessing result of the sample workstep



(c) The element extraction result of the sample workstep

Figure 7: The (a) original content, (b) preprocessing result and (c) element extraction result of the sample workstep

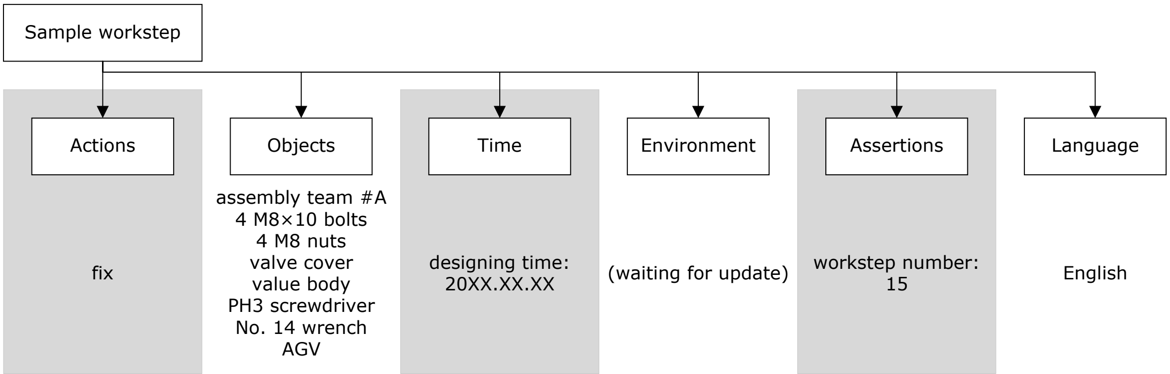


Figure 8: Sample assembly workstep modeling result

6 CONCLUSIONS

This research proposes an assembly process modeling method based on ontology technology in order to solve the problems of non-standard description and insufficient semantics. Firstly, assembly process is divided into worksteps, which correspond to the concept of event ontology as basic units. The elements of workstep events are analyzed under the premise of considering the characteristics of assembly process. Secondly, NLP technology is used to process assembly documents, further realize the transformation from human language to machine language, which constitutes a significant step of extraction of workstep event elements. In addition,

Logical description	*SWRL representation*
When fixing bolts with a nominal diameter greater than or equal to 8 mm, a PH3 screwdriver should be used to install.	$workstep(?ws) \cap hasbolt(?ws,?b) \cap hasnominaldiameter(?b,?nd) \cap swrlb : greaterThanOrEqual(?nd,8) \cap screwdriver(?sd) \cap hastype(?sd,?t) \cap swrlb : SameAs(?t,PH3) \rightarrow hastool(?ws,?sd)$
When fixing nuts with a nominal diameter equal to 8 mm, a No. 14 wrench should be used to install.	$workstep(?ws) \cap hasnut(?ws,?n) \cap hasnominaldiameter(?n,?nd) \cap swrlb : SameAs(?nd,8) \cap wrench(?w) \cap hasNo(?w,?no) \cap swrlb : SameAs(?no,14) \rightarrow hastool(?ws,?w)$
When the materials used in the workstep is not in the assembly station, a AGV should be used to transport.	$workstep(?ws) \cap haslocation(?ws,?l) \cap hasmaterial(?ws,?m) \cap hasposition(?m,?p) \cap swrlb : DifferentFrom(?l,?p) \cap AGV(?agv) \rightarrow hasAGV(?ws,?agv)$
When the tools used in the workstep is not in the assembly station, a AGV should be used to transport.	$workstep(?ws) \cap haslocation(?ws,?l) \cap hastool(?ws,?t) \cap hasposition(?t,?p) \cap swrlb : DifferentFrom(?l,?p) \cap AGV(?agv) \rightarrow hasAGV(?ws,?agv)$

Table 2: The explanation of the six-tuple of assembly workstep events

the workstep event is completed with ontology reasoning of non-intuitive assembly resources that are used for the worksteps as well.

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