An Effective Resource Matching Scheme Based on a Novel Unified Descriptive Model for Modern Manufacturing Industry Systems

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Abstract: In order to effectively solve the problem of heterogeneous design/manufacturing/service resources and isolation in the whole lifecycle and realize unified description of design/manufacturing/service resources and resource sharing across subjects and stages, this paper proposes a hierarchical and modularized ontology-based resource-unified descriptive model, according to the characteristics of design/manufacturing/service resources. We analyze all kinds of properties of the resources, design a specific descriptive model of ontology, function, and service, ensure the consistency and independence of resource descriptions, and use the OWL (Web Ontology Language) ontology descriptive language and Protégé tools to verify. Then, based on the unified descriptive model, a resource matching method based on multi-level tags is proposed, which matches the task request with the resources in the resource library, selects the resources that meet the task request, and guarantees the resource sharing across subjects and stages. The resource matching work first performs task description and decomposition, and uses information entropy and rough set theory to sort the importance of subtasks, then uses the semantic similarity algorithm to complete multi-level tags’ matching. Finally, two examples are used to prove the feasibility and effectiveness of the experiment.

Keywords: the whole lifecycle; ontology modeling; multi-level tags; resource matching

1. Introduction

1.1. Research Background and Significance

With the rapid development of science and technology, the global manufacturing industry has been promoted to transform and upgrade in the direction of intelligence, service, and customization. Resource sharing among modern enterprises has become a hotspot in academia and industry, and the whole lifecycle management of resources has attracted attention from all walks of life. The resources are massive, heterogeneous, and independent, and the data sources, structures, and forms of different enterprises are different, which hinders data sharing. Therefore, it is particularly important to pay attention to the effective utilization of resources from the perspective of the whole lifecycle. At present, many different types of resources cannot be managed and utilized efficiently due to geographical location, differences in description, platform usage, and other reasons. The hierarchical and modularized unified description of resources in the design/manufacturing/service stage is an important basis for realizing unified resource management and resource matching. With the development of semantic description technology, the establishment of a unified description model for design/manufacturing/service resources is conducive to the realization of unified resource management, the resource sharing across subjects and stages, and to achieve the effect of unified description, accurate discovery, and efficient utilization of resources.
1.2. State-of-the-Art Research

At present, the research on resource unification and integrity modeling technology has achieved certain research results, but most of the current research objects are manufacturing resources. Xu et al. proposed a three-stage resource semantic description mechanism based on the cloud manufacturing platform, “framework establishment-framework acquisition-resource description”, and designed a service discovery algorithm [1]. On the premise of ensuring the heterogeneity and independence of manufacturing resources, Gao et al. built a hierarchical and modularized description framework for manufactured resources, and a web-based service encapsulation method is proposed to achieve service description and virtualized encapsulation of manufacturing resources [2]. Huang realized the unified description of manufacturing resources by adopting ontology with conceptual hierarchy and logical reasoning for semantic modeling, and considering the lifecycle dimension of manufacturing resources, the aggregated granularity dimension, and the dimension of comprehensive evaluation [3]. Chen et al. proposed a hierarchical environmental video semantic model that explicitly expresses the dynamic changes of resources. The model defines the hierarchical structure of environmental video semantics and the hierarchical expression of data through the three change-oriented domains (feature domain-behavioral process domain-result domain). Based on this, the perception and understanding of multi-stage tasks in the whole lifecycle are completed [4]. Guo et al. proposed an energy-efficient multi-source temporal data aggregation model called MSTDA (Multi-Source Temporal Data Aggregation model) in WSNs (Wireless Sensor Networks) and a data prediction algorithm based on an improved BP neural network with PSO (Particle Swarm Optimization), which helps to find out potential laws according to historical datasets and is deployed at both the base station (BS) and the node [5]. Wang et al. proposed a novel dynamic network data replication scheme based on the historical access record and proactive deletion, which dynamically handle data replication issues [6].

For resource matching problems, Bi proposed a semantic-based matching method for manufacturing cloud services to the matching requirements of a single cloud service. Based on the cloud service structure model, the semantic similarity between service requirements and cloud services was calculated. At the same time, a matching method of task requirement decomposition and composite service based on task relevancy was proposed [7]. Xiao et al. proposed a decision-making method for manufacturing resource matching based on multi-dimensional fusion. On the basis of integrating the multi-dimensional information of cloud manufacturing resources, the matching ability is analyzed by using the hybrid collaborative filtering (HCF) algorithm. Then, the functional attributes, reliability and preference information, are used to actively match the manufacturing resources, so as to realize the matching decision of manufacturing resources with accurate quality, stable service, and maximum efficiency [8]. Hu et al. proposed a combined system based on task complexity and evaluation of the service, which was analyzed and verified using the Artificial Bee Colony (ABC) algorithm. The experimental results further verify the feasibility and effectiveness of this method [9]. Yuan et al. proposed a QoS system with six objectives, listed the calculation expressions of QoS under different composition structures, and established a mathematical model of CMFG (Cloud Manufacturing). The optimization problem of the service portfolio is analyzed by using the grey relational analytical method, and this can improve the resource utilization and user’s perception of the CMFG [10]. He et al. proposed a new approach based on the Multi-Modal Semantic Association Rule (MMSAR) to fuse keywords and visual features automatically for web image retrieval, which not only remarkably improves the retrieval precision, but also has a fast response time [11]. Huang et al. proposed a novel Baseline Data-based Verifiable Trust Evaluation (BD-VTE) scheme to guarantee credibility at a low cost, and it can be used for trust assessment [12]. Xia et al. proposed an Adaptive Real-Time GTS (Guaranteed Time Slot) Allocation Scheme (ART-GAS) to provide differentiated services for devices with different priorities, which guarantees data transmissions for time-sensitive and high-traffic devices [13].
This paper proposes a hierarchical and modular ontology-based resource-unified descriptive model and a matching method based on multi-level tags, which can effectively solve the design/manufacturing/service resource differences and the problem of isolation in the whole lifecycle, realize resource unification and integrity modeling and the resource sharing across subjects and stages, and achieve the effect of integrated efficiency and continuous quality improvement across subjects and stages.

2. Materials and Methods
2.1. Design/Manufacturing/Service Resource Classification and Descriptive Framework

2.1.1. Classification of Design/Manufacturing/Service Resources

The range of design/manufacturing/service resources is very broad, and design/manufacturing/service resources have the characteristics of mass, heterogeneity, and independence. Considering that the follow-up work is to establish a unified descriptive model and resource matching for these resources, effective resource classification is a necessary premise of establishing the descriptive framework. This section proposes efficient and detailed classification of design/manufacturing/service resources.

Resources are the core of the whole lifecycle of products, and all services are inseparable from the support of resources. According to the current research status [14,15], resources were divided into two categories: hard resources and soft resources. Hard resources refer to all the physical hardware resources directly related to the design/manufacturing/service processes involved in the product’s lifecycle, such as equipment, material, etc. Soft resources refer to the non-hardware resources involved in the product’s lifecycle, which ensure the normal operation of the design/manufacturing/service processes, such as software, data, technical, etc. The disordered tree of design/manufacturing/service resource classification is shown in Figure 1. Due to the wide range and variety of resources involved in design/manufacturing/service resources, limited by space, the figure does not list them all. The smaller the granularity of classification, the lower the complexity of resource description, the easier the unified description of design/manufacturing/service resources, and the higher the efficiency of resource matching and sharing.

Figure 1. The disordered tree of design/manufacturing/service resource classification.

2.1.2. Design/Manufacturing/Service Resource Descriptive Framework

Design/manufacturing/service resources have the characteristics of mass, heterogeneity, independence, etc. If there is no unified descriptive framework to accurately describe them, it will lead to problems such as redundancy of information and lack of data. Therefore, a unified descriptive framework is needed to model resources. In order to describe resources uniformly and ensure full autonomy of resources, this section proposes a bottom-up unified descriptive framework with modular and hierarchical features, as shown in Figure 2.
This section presents a hierarchical and modularized ontology-based resource-unified description model, which represents precise instances without logical reasoning ability. Each part of the descriptive model realizes the standardized expression of resources, so that resources can be mapped to the cloud resource library, which is convenient for unified management of resources. Relevant resource classes are gathered together to form a resource library, which provides support for subsequent web services, matching services, and resource sharing across subjects and stages.

### 2.2. Ontology-Based Resource Unified Description Model

The unified descriptive model is an important foundation for subsequent resource matching and sharing. Unified modeling of design/manufacturing/service resources realizes the standardized expression of resources, so that resources can be mapped to the cloud resource library, which is convenient for unified management of resources. This section presents a hierarchical and modularized ontology-based resource-unified descriptive model, in modern manufacturing industry systems, using it to uniformly describe resources across subjects and stages. For example, using this model can uniformly describe a screw from a lathe and an engine, respectively, then using resource matching can match a suitable screw for another aircraft screw manufacturing task.

#### 2.2.1. Design/Manufacturing/Service Resource Modeling Method

As is known from the current state of research [16,17], the current popular resource modeling methods include object-oriented modeling and ontology modeling.

Object-oriented modeling is to decompose a transaction into various objects, and the purpose of creating an object is not to complete a step. Its essence is abstract, and it advocates constructing the system from the inherent things in the objective world, and modeling directly from the problem. It is often used in software systems’ development and precise instances without logical reasoning ability.

Ontology modeling studies the specific existence and composition of the objective world, mainly about the normative definition and description of a certain domain model. It usually refers to the relationship between concepts and the relationship of individuals and concepts, and the application of ontology is mainly in data modeling and construction of a knowledge base, paying more attention to the integrity of knowledge. In software...
development, ontology models do not specifically refer to the creation of elements, but they describe a fact. Based on description logic, it has automatic reasoning ability.

From the point of modeling, object-oriented modeling is only modeling the software’s structure, while ontology modeling is a set of strict knowledge modeling based on logic, which has rich expressive ability. In addition, object-oriented modeling does not have strict model-theoretic semantics, while the ontology modeling based on description logic has this advantage, and it can automatically check semantic consistency and automatically reason to discover implicit knowledge. Based on the above analysis and the characteristics of design/manufacturing/service resources (mass, heterogeneity, independence), ontology modeling, compared with object-oriented modeling methods, can overcome the defects of expression and facilitate subsequent resource matching and sharing. Therefore, this paper adopts the ontology-based modeling method when constructing the unified descriptive model of resources.

2.2.2. Establishment of the Unified Description Model of Resources

Due to the wide range of design/manufacturing/service resources, different types of resources have different attributes, and the description is quite different. Considering that a resource may be used in different stages, one-to-many correspondence between the resources is used in the design/manufacturing/service stages and ontology/function/service information, so that the resource attributes in design/manufacturing/service stages can be comprehensively analyzed. The resources are described respectively through the three attribute sets of ontology, function, and service, and a unified descriptive model will be established. The set of ontology information includes a set of static properties, a set of dynamic properties, and a set of parameters for performance. The set of functional information includes a set of functional capabilities and a resource-assisted set. The set of service information includes a set of service properties and a set of provider’s descriptions.

A unified descriptive model RP was built for design/manufacturing/service resources, which is represented as follows:

\[
RP = \{\text{Rid, RCon, RFunc, RQos}\}
\]

where Rid is the resource id, RCon is the model of ontological resource information, RFunc is the model of functional resource information, and RQos \cite{18,19} is the model of service resource information.

(1) The model of ontological resource information, RCon, is expressed as a set:

\[
\text{RCon} = \{\text{RB, RD, RPar}\}
\]

where, \(\text{RB} = \{\text{RNam, Rtype, RLoc, RMaker, RUse, Others}\}\)

\(\text{RD} = \{\text{RState, RFault, Others}\}\)

\(\text{RPar} = \{\text{MaxR, RangS, PP, Roug, PA, OverL}\}\)

RCon includes a set of static properties (RB), a set of dynamic properties (RD), and a set of parameters for performance (RPar).

- Set of static properties (RB): All static information of the resource, including name (RNam), type (Rtype), geographic location (RLoc), manufacturer (RMaker), usage (RUse), and other supplementary information (Others).

- Set of dynamic properties (RD): All dynamic information of resources, including current state (RState), current fault (RFault), and other supplementary information (Others).

- Set of parameters for performance (RPar): The technical parameter’s information involved in the whole process. Taking a CNC machine tool as an example, this set includes the maximum machining size (MaxR), the maximum feed speed (RangS), the machining accuracy (PP), the surface roughness (Roug), the number of axes (PA), the workbench load (OverL), etc.
(2) The model of functional resource information, RFunc, is expressed as a set:

\[
\text{RFunc} = \{\text{Func}_A, \text{RAtt}\}
\]

where, \(\text{Func}_A = \{\text{FunId}, \text{FuncTyp}, \text{Input, Output, FuncDem, FuncCra, Others}\}\)

\(\text{RAtt} = \{\text{RelDes, Rely, Relyed}\}\)

RFunc includes a set of functional capabilities (FuncA) and a resource-assisted set (RAtt).

Set of functional capabilities (FuncA): The manufacturing capability and processing function of resources, including functional number (FunId), functional type (FuncTyp), input and output (Input, Output), functional preconditions (FuncDem), processing technology (FuncCra), and other supplementary information (Others).

Resource-assisted set (RAtt): The interdependence between resources. For example, the CNC machine tool is associated with the CNC system, and the CNC system is an auxiliary resource for manufacturing machine tools. It includes dependency description (RelDes), auxiliary party (Rely), and assisted party (Relyed).

(3) The model of service resource information, RQos, is expressed as a set:

\[
\text{RQos} = \{\text{SAtt, SPro}\}
\]

where, \(\text{SAtt} = \{\text{STime, Scost, SQua, Ssat, Others}\}\)

\(\text{SPro} = \{\text{PId, PName, PDesc, PLoc, PTel, PEmail, PUrl}\}\)

RQos includes a set of service properties (SAtt) and a set of provider’s descriptions (SPro).

Set of service properties (SAtt): All basic information of the service stage, including service time (STime), cost (yuan) (SCost), quality (range of use years) (SQua), reputation (customer favorable rate) (Ssat), and additional supplementary information (Others).

Set of provider’s descriptions (SPro): All descriptive information of the resource provider, including provider’s identifier (PId), the name of the organization to which the resource belongs (PName), provider’s descriptive information (PDesc), provider’s geographic location (PLoc), contact phone number (PTel), contact email address (PEmail), and website link (PUrl).

2.2.3. The Instance of Unified Description Model

Common ontology editing tools [20] include OntoEdit, OILed, and Protégé. Among them, Protégé is a knowledge-based editor, which is written by java. Although the tool itself cannot realize reasoning, it has strong extensibility, and plug-ins can be inserted to extend some special functions, such as reasoning, questioning, XML (Extensible Markup Language) transformation, etc. It also supports multiple inheritance, provides basic functions of ontology construction, and has clear module division. Therefore, this paper adopted Protégé to construct the unified descriptive model of design/manufacturing/service resources. The ontological diagram of the descriptive model is shown in Figure 3.

At present, many ontology modeling languages have appeared. The traditional ontology modeling languages include Ontolingua, OKBC, OCML, FLogic, and LOOM. The web-oriented modeling languages include DAML, XML, and OWL. The OWL (Web Ontology Language) modeling language is a language for defining and instantiating ontologies. Unlike XML schema, it is knowledge representation, not a message, and it supports reasoning. The research in this paper requires that the modeling language has strong expressive ability, internal logic, and reasoning functions, and the sharing of resources requires the modeling language to be compatible with W3C (World Wide Web Consortium) to a certain extent. After screening, OWL can meet the above requirements, so this paper used OWL to formally describe the unified descriptive model of design/manufacturing/service resources.

In order to better illustrate the unified descriptive model of design/manufacturing/service resources [21], the following takes a certain type of CNC (Computer Numerical Control) machine tool as an example, and part of the core code of its OWL descriptive document is shown in Figure 4.
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2.3. Multi-Level Matching of Tasks and Resources

According to the content of the previous section, the design/manufacturing/service resources are stored in the resource library according to the unified descriptive model. How to use these resources to achieve the effect of subsequent resource sharing, so that the resource matching technology is based on the existing technical foundation, is proposed in [22,23]. Matching between task and resource is the key technology to realize resource sharing, and it is also the focus of this paper. A matching system based on multi-level tags is proposed. First, the preparations for resource matching are carried out, including the description of the task, the decomposition of the task, and the importance ranking of the task. Then, a calculation method with improved semantic similarity based on text keywords is proposed, and finally, the multi-level matching is designed according to the calculation method with improved semantic similarity. In this way, it can effectively complete the matching of tasks and resources, realize the selection of resources, and facilitate resource sharing. For example, for a battery manufacturing task, it can match the resources that best meet the needs of the manufacturing task from the many resources in the resource library.

2.3.1. Preparations for Resource Matching

The preparatory work for resource matching includes the description of the task, the decomposition of the task, and the importance ranking of the task. Task description is
an important prerequisite for resource matching. An accurate and reasonable description of tasks can help us to accurately find resources with a high matching degree in the resource library. Task decomposition is an important basis for resource matching. Tasks are decomposed into subtasks with appropriate granularity, and complex manufacturing tasks are completed with resources matched by subtasks. The importance ranking of the tasks is the premise of resource matching optimization. Ranking the importance of subtasks after task decomposition can further improve the processing efficiency of resource matching, and can effectively deal with the complexity of collaborative design/ manufacturing/service tasks and the uncertainty of tasks’ information.

I. The description of the task

The premise of matching suitable resources is to reasonably and accurately describe the task. According to the characteristics of the task and the unified descriptive model of resources, this paper describes the task from three aspects: task ontology, task function, and task service.

1. Information of task ontology, including the static attribute set, dynamic attribute set, and performance parameter set. The static attribute set includes the name of the OEM part, manufacturer, etc., the dynamic attribute set includes the current state, faulty information, etc., and the performance parameter set includes the size and material of the OEM part.

2. Information of task function, including the set of function capability and the resource-assisted set. The set of function capability includes functional number, input and output, etc., and the resource-assisted set refers to the interdependence between tasks, including dependency description, auxiliary party, and assisted party.

3. Information of task service, including the set of service attributes and the descriptive set of providers. The set of service attributes includes service time, cost, satisfied information, etc., and the descriptive set of providers includes the provider’s name, descriptive information, contact number, geographic location, and so on.

II. The decomposition of the task

The decomposition of the task is an important basis for resource matching. Tasks are decomposed into subtasks with appropriate granularity, and complex manufacturing tasks are completed with resources matched by subtasks. According to the characteristics of the tasks, the following principles based on the existing research on task decomposition are proposed [24]:

1. Principle of special priority: some tasks with special requirements are not divided, such as tasks with special requirements of customers.

2. Principle of standard priority: the tasks involved in national standards or industry standards are not decomposed, such as conventional standard parts.

3. Principle of progressive priority: in order to ensure that the granularity of subtasks is appropriate, tasks are decomposed layer-by-layer from the top to the bottom according to the execution order, until the decomposed subtasks can be independently completed by a single resource, and no further decomposition is continued.

4. Principle of independent priority: the subtasks are loosely coupled and do not interfere with each other, which ensures that subtasks can be executed in parallel and reduces operating costs.

The total demand task was decomposed according to the above principles, and the specific steps of decomposition are shown in Figure 5.

III. The importance ranking of subtasks

The importance ranking of subtasks is the premise of resource matching optimization, which can effectively deal with the complexity of design/ manufacturing/service tasks and the uncertainty of tasks’ information. According to the existing technology [25,26], a method of sorting the importance of design/ manufacturing/service subtasks using the theory of entropy of information...
and rough set theory was adopted. The schematic diagram of the specific process is shown in Figure 6:

1. According to the rough set theory, the variable parameters are assumed, the decision attributes are determined and graded based on the entropy of information, and the corresponding conditional attributes and decision attributes are obtained.
2. Define the dependency of decision attributes and condition attributes, then use equivalence relation to remove some conditional attributes.
3. Calculate the weights of attributes according to rough set theory, then calculate the importance of subtasks and normalize them to obtain the importance ranking of subtasks.

![Flow chart of decomposition.](figure5)

Figure 5. Flow chart of decomposition.

![Schematic diagram of the importance ranking process.](figure6)

Figure 6. Schematic diagram of the importance ranking process.
2.3.2. Calculation Method of Semantic Similarity between Tasks and Resources

The key technology of resource matching is to accurately calculate the similarity between tasks and resources in the descriptive text [27–29]. If the similarity between the subtask and the resource in the descriptive text exceeds a certain threshold, it can be determined that the two are matched. In practical scenarios, the issuers of tasks usually use short and refined texts when describing tasks, and can convert the original tasks into more sophisticated subtasks through the resource preparation work (task description, task decomposition, and task importance ranking) in Section 3.1, while the states of subtasks’ descriptions are suitable for semantic similarity computation. According to this feature, an improved calculation method of semantic similarity based on text keywords is proposed [30]. The specific steps are as follows:

Step 1: Text preprocessing, through the system of Chinese and English segmentations, tag and classify the parts of speech of the words in the text, and filter the useless stopped words in the text.

Step 2: Extract keywords, and calculate the weight of keywords, \( K_i \), according to Equation (1) for keywords that are not filtered in the text.

\[
f_{n_i} = \frac{wn_i}{wn_{total}}
\]

\[
\text{weight}_i = \text{pos}_i \cdot f_{n_i}
\]

where \( wn_i \) represents the times that the keyword \( K_i \) appears in the text, and \( wn_{total} \) represents the times that the text appears in all keywords. \( pos_i \) represents the part-of-speech value, where noun weight \( \alpha_1 = 0.4 \), verb weight \( \alpha_2 = 0.2 \), numeral weight \( \alpha_3 = 0.2 \), adverb weight \( \alpha_4 = 0.1 \), and adjective weight \( \alpha_5 = 0.1 \).

Step 3: Calculate the semantic distance, \( \text{Dis}(R, S_j) \). The semantic distance between tasks and resources is the sum of their keyword weights, and the semantic distance is calculated according to Equation (2).

\[
\text{Dis}(R, S_j) = \sum_{i=1}^{n} \text{weight}_i
\]

where \( R \) represents subtask request and \( S_j \) represents the \( j \)-th resource in the resource library.

Step 4: Calculate the semantic similarity, \( \text{Sim}(R, S_j) \). The semantic similarity and the semantic distance are in an inverse relationship, and the semantic similarity is calculated according to Equation (3).

\[
\text{Sim}(R, S_j) = 1 - \text{Dis}(R, S_j)
\]

In addition, for the semantic similarity problem of the numerical interval, this paper proposes a similarity calculation method for the numerical interval. Let the numerical interval of a certain task \( A \in [a_{\text{min}}, a_{\text{max}}] \), and the numerical interval of a certain attribute of a certain resource \( B \in [b_{\text{min}}, b_{\text{max}}] \), then the similarity, \( \text{ValSim}(A, B) \), formula between them is:

\[
\text{ValSim}(A, B) = \begin{cases} 1 & \text{if } A \cap B = A \text{ or } A \cap B = B \\ \frac{\min(a_{\text{max}}, b_{\text{max}}) - \max(a_{\text{min}}, b_{\text{min}})}{a_{\text{max}} - a_{\text{min}}} & \text{if } A \cap B = C \text{ and } C \subseteq A \\ 0 & \text{if } A \cap B = \emptyset \end{cases}
\]

2.3.3. Matching of Resources Based on Multi-Level Tags

The description model of tasks and resources is a tree structure descriptive model based on sets and composed of multi-level elements. When resource matching is required, this feature and the existing technology [31–33] can be used to calculate the semantic similarity of elements at all levels. When the semantic similarity of all the corresponding elements of the task and the resource exceeds the threshold, it can be considered that the task and the resource are successfully matched. Based on this, the element attributes of the task description and the resource-unified description model are constructed as
multi-level tags. The matching of multi-level tags includes five levels: (1) the match of basic information, (2) the match of functional matching, (3) the match of manufacturing capability, (4) the match of service constraints, and (5) comprehensive match. The process of specific matching is shown in Figure 7.

![Flow chart of matching based on multi-level tags.](image)

**Figure 7.** Flow chart of matching based on multi-level tags.

I. The match of basic information

The match of basic information mainly measures the similarity of basic information between tasks and candidate resources [34–36], where basic information mainly includes resource name, resource location, resource manufacturer, etc. The attribute set of basic information is generally a phrase composed of unordered text keywords. The semantic similarity between the task, \( R \), and the \( j \)-th resource, \( Sim(R, S_j) \), is calculated by Equation (4), and the matching degree of basic information is obtained as \( \text{Match}(R, S_j)_{\text{BasicInf}} \):

\[
\text{Match}(R, S_j)_{\text{BasicInf}} = \sum_{i=1}^{n} \omega_i Sim(R, S_{ji})
\]  

(6)

where \( R \) represents the request of the subtask, \( S_j \) represents the \( j \)-th resource in the set of candidate resources, \( \omega_i \) represents the corresponding weight of the basic information \((0 < \omega_i < 1, \sum_{i=1}^{n} \omega_i = 1)\), \( n \) represents the number of basic information, and \( S_{ji} \) represents the \( i \)-th basic information of the \( j \)-th resource in the set of candidate resources. The matching of basic information algorithm is designed as follows:

1. Initialization: determine the basic informational matching threshold, \( \beta_{label1} \), the set of selected resources, \( E = \emptyset \), and initialize the matching degree between the basic information of the task and the resource: \( \text{Match}(R, S)_{\text{BasicInf}} = 0 \).
2. According to Equation (6), calculate the matching degree, \( \text{Match}(R, S_j)_{\text{BasicInf}} \), between task \( R \) and candidate resource \( S_j \); then, if \( \text{Match}(R, S_j)_{\text{BasicInf}} > \beta_{label1} \), \( E = \{S_j\} \cup E \), \( \text{Match}(R, S)_{\text{BasicInf}} = \left\{\text{Match}(R, S_j)_{\text{BasicInf}}\right\} \cup \text{Match}(R, S)_{\text{BasicInf}} \).
3. \( j = j + 1 \), and continue to execute Step (2) until \( j \leq m \) (\( m \) represents the number of resources in the candidate set).
4. After the execution, the resource candidate set \( E \) and the matching degree of the corresponding basic information, \( \text{Match}(R, S)_{\text{BasicInf}} \), are returned, and the next level will continue.
II. The match of functional information

The match of functional information refers to matching the functional information in tasks and resources. The functional attribute is generally a phrase consisting of unordered text keywords, and the matching of functional information mainly includes input matching, output matching, preconditional matching, and effect matching. Input and output matching, respectively, refer to the information required for task execution and the output after the task is completed, preconditional matching refers to the logical conditions required for execution, and effect matching refers to the effect after the successful execution of the task.

The functional matching algorithm is the same as the matching algorithm of basic information. The matching degree of functional information between the task R and the j-th resource, \( \text{Match}(R, S_j) \)_{\text{IOPE}} is:

\[
\text{Match}(R, S_j)_{\text{IOPE}} = \theta_1 \text{Match}(R, S_j)_{\text{input}} + \theta_2 \text{Match}(R, S_j)_{\text{output}}
+ \theta_3 \text{Match}(R, S_j)_{\text{pre}} + \theta_4 \text{Match}(R, S_j)_{\text{effect}}
\]

(7)

where \( \text{Match}(R, S_j)_{\text{input}} \), \( \text{Match}(R, S_j)_{\text{output}} \), \( \text{Match}(R, S_j)_{\text{pre}} \), and \( \text{Match}(R, S_j)_{\text{effect}} \) respectively, refer to the degree of input matching, output matching, preconditional matching, and effect matching calculated by Equation (6) (their calculational methods are the same as the calculational process of basic information matching degree, which will not be repeated here), and \( \theta_1, \theta_2, \theta_3, \) and \( \theta_4 \) represent the weight of each matching attribute (\( \sum_{i=1}^{4} \theta_i = 1 \)).

If the task is successfully matched with the resources in the selected resources, that is \( \text{Match}(R, S_j)_{\text{IOPE}} > \beta_{\text{label2}} \) (\( \beta_{\text{label2}} \) refers to the threshold of matching functional information), the successful matched resource will be put into the set of selected resources, and if the match fails, it will be removed from the set of selected resources. Then, the next level of matching is performed. If the set of selected resources is empty at the end of the match, the multi-level match fails, and no suitable resource is selected.

III. The match of manufacturing capability

The match of manufacturing capability refers to matching the parametric sets and dependencies of tasks and resources. The parametric set generally includes size, shape, precision, etc. The dependency refers to the description of the interdependence among resources, such as the relationship between the CNC machine tool and the CNC system, and the CNC system is an auxiliary resource for manufacturing machine tools. Parametric and dependency sets are generally unordered phrases of text keywords.

The match of manufacturing capability is the same as the matching algorithm of basic information. The match of manufacturing capability between the task R and the j-th resource, \( \text{Match}(R, S_j) \)_{\text{CapaInf'}} is:

\[
\text{Match}(R, S_j)_{\text{CapaInf'}} = \gamma_1 \text{Match}(R, S_j)_{\text{para}} + \gamma_2 \text{Match}(R, S_j)_{\text{rely}}
\]

(8)

where \( \text{Match}(R, S_j)_{\text{para}} \) and \( \text{Match}(R, S_j)_{\text{rely}} \) respectively, refer to the matching degree of the parametric set and dependency relationship calculated by Equation (6) (their calculational methods are the same as the calculational process of basic informational matching degree, which will not be repeated here), and \( \gamma_1 \) and \( \gamma_2 \) represent the weight of each matching attribute (\( \sum_{j=1}^{2} \gamma_i = 1 \)).

If the task is successfully matched with the resources in the candidate resources, that is \( \text{Match}(R, S_j)_{\text{CapaInf'}} > \beta_{\text{label3}} \) (\( \beta_{\text{label3}} \) refers to the threshold for matching the manufacturing capacity), the successfully matched resources are put into the set of selected resource, and if the match fails, they are deleted from the selected resources. Then, the next level of matching is performed. If the set of selected resources is empty at the end of the match, the multi-level match fails, and no suitable resource is selected.
IV. The match of service constraints

The match of service constraints refers to matching the evaluation information of tasks and resources [37,38]. The set of evaluation attributes includes four parts: time, quality, cost, and credibility. Let the acceptable time, quality, cost, and credibility intervals of the task be \( T_{\text{task}}, Q_{\text{task}}, C_{\text{task}}, \) and \( Cr_{\text{task}} \), and let the functional information, the manufacturing capability, and the service constraints. During the matching process, the functional information, manufacturing capability, and service constraints are further filtered. The comprehensive matching calculation is performed. If the selected resource is empty at the end of the match, the multi-level match fails, and no suitable resource is selected.

If the task is successfully matched with the resources in the candidate resources, that is \( \text{Match}(R, S_i)_{\text{SerCons}} > \beta_{\text{label4}} \) (\( \beta_{\text{label4}} \) refers to the threshold for matching the service constraints), the successfully matched resource is put into the set of selected resources, and if the matching fails, it is deleted from the selected resource. Then, the next level of matching is performed. If the selected resource is empty at the end of the match, the multi-level match fails, and no suitable resource is selected.

V. Comprehensive matching

There may still be a large number of design/manufacturing/service resources that meet the conditions through the four levels of matching [39–41]. In order to obtain more accurate resources to provide services, the resource set \( E \) that has been selected through the four levels of matching \([39–41]\) is refined. In order to obtain more accurate resources to provide services, the resource set \( E \) that has been selected through the four levels of matching \([39–41]\) is refined. In order to obtain more accurate resources to provide services, the resource set \( E \) that has been selected through the four levels of matching \([39–41]\) is refined. In order to obtain more accurate resources to provide services, the resource set \( E \) that has been selected through the four levels of matching \([39–41]\) is refined. In order to obtain more accurate resources to provide services, the resource set \( E \) that has been selected through the four levels of matching \([39–41]\) is refined.

The comprehensive matching algorithm is as follows:

(1) Initialization: determine the comprehensive matching threshold, \( \beta_{\text{sum}} \), the final set of selected resources, \( E = \emptyset \), and the comprehensive matching degree between tasks and resources: \( \text{Match}(R, S)_{\text{sum}} = 0 \).
VI. AHP to determine comprehensive matching weight

This section deals with the weight problem in the comprehensive matching of multi-level tags’ matching. Each level of matching corresponds to multiple subtask attributes, and each subtask has different requirements. Therefore, it is necessary to determine the proportion of each level of matching according to the importance of different levels of matching. Here, the tomographic analysis method solves this problem [42,43].

The Analytic Hierarchy Process (AHP) can treat the research object as a system, and make decisions according to the thinking methods of decomposition, comparison, judgment, and synthesis. Moreover, this method is simple and practical, requires less quantitative data and information, and can process practical problems that many traditional optimization techniques cannot address. Not only does it work in situations that are uncertain and subjective, it also allows experience, insight, and intuition to be applied in a logical way. Specific steps are as follows:

1. Build a hierarchical model

The establishment of the AHP is shown in Figure 8. The target layer: the importance of matching at all levels, the middle layer: matching at all levels, and the bottom layer: the influencing factors of matching at each level.

![Figure 8. Schematic diagram of the hierarchical structure.](image)

2. Constructing the matrix of importance of comparative judgment

The relative importance scale is determined, as shown in Table 1.

| Scale   | Meaning                      |
|---------|------------------------------|
| 1       | Equally important            |
| 3       | Slightly important           |
| 5       | Strongly important           |
| 7       | Very important               |
| 9       | Absolutely important         |
| 2, 4, 6, 8 | Between two adjacent judgments |

Table 1. Meaning of the relative importance scale.
Let the judgmental matrix be $A$, and the relative weight $a_{ij}$, where $a_{ij}$ is the degree of importance relative to the previous factor. A comparison matrix is obtained, 

$$A = (a_{ij})_{n \times n} = \begin{pmatrix}
a_{11} & \cdots & a_{1n} \\
\vdots & \ddots & \vdots \\
a_{n1} & \cdots & a_{nn}
\end{pmatrix}$$

where $n$ is the order of the comparison matrix; that is, the matching series. Calculate the judgmental matrix:

$$A = \begin{pmatrix}
1 & 1/3 & 1/5 & 1/5 \\
3 & 1 & 1/3 & 1/5 \\
3 & 3 & 1 & 1/3 \\
5 & 5 & 3 & 1
\end{pmatrix}$$

(3) Calculate the weight of the indicator

According to the method of summation, first, the judgmental matrix is normalized: $a_{ij} = \frac{a_{ij}}{\sum_{i}a_{ij}}$, the normalized matrix is obtained, and then $A$ is added row-by-row, and the normalized vector of weight is obtained: $\zeta = 0.062, 0.123, 0.275, 0.540^T$. Considering the space problem, the maximum eigenvalue and the consistency test of the matrix will not be written.

3. Results

This section takes the chassis’ design and manufacturing task of a certain brand of new energy vehicles as an example to describe and introduce the calculation process of subtask importance ranking and resource matching in detail, and verifies the feasibility and effectiveness of the method. This dataset comes from related companies in the research group; at the same time, the experimental content has been partially applied to the project integration platform.

3.1. Ranking of the Importance of Subtasks

According to the description and decomposition of tasks in Section 2.3.1, five subtasks of the automobile chassis design and manufacturing were obtained: frame (T1), suspension (T2), steering system (T3), brake (T4), and battery (T5). Using the entropy of information and rough set theory to rank the importance of design/manufacturing/service subtasks, the importance ranking of the five subtasks was obtained, as shown in Table 2.

| Subtasks | T1   | T2   | T3   | T4   | T5   |
|----------|------|------|------|------|------|
| Importance | 0.159 | 0.193 | 0.210 | 0.184 | 0.254 |

It can be seen from Table 2 that the battery (T5) is of the highest importance, which also reflects from one aspect that the design and manufacture of batteries is an indispensable part of the development of new energy vehicles. As it grows, the market for new energy batteries in the future will be immeasurable.

3.2. Match of Resources

Aiming at the process of battery production, taking the task of manufacturing a battery temperature sensor as an example [44,45], the request, R, of manufacturing a temperature sensor of a battery is explained: $R = \{\text{BasicInfo}: \{\text{name: battery temperature sensor, location: Shanghai, manufacturer: Honeywell}\}, \text{IOPE}: \{\text{input: high and low temperature resistance and bushing, output: battery temperature sensor, preconditions: \{1. appearance is standard, 2. weight is not more than 7.5 g, 3. insulation resistance is greater than 10 MQ/500 V\}, effect: \{1. lifespan is not less than 6 years, 2. error in output voltage is not more than 0.02 v\}\}, \text{CapalInf}: \{\text{parameters: \{1. size: 120 mm, 2. weight: 0.1 g, 3. frequency: 140 Hz\}}\}$.
The match of basic information

Matching the basic information of the resource library with the task request, set $\beta_{\text{label}1} = 0.8$, weight $\omega_i = \{0.6, 0.2, 0.2\}$, calculated by Equation (6), there were six candidate resources in the resource library that met the threshold requirements, namely $S_1$, $S_2$, $S_3$, $S_4$, $S_5$, and $S_6$. The corresponding matching degree was $\text{Match}(R,S)_{\text{BasicInf}} = \{0.845, 0.879, 0.846, 0.969, 0.981, 0.893\}$, and the candidate set of resources was $E_1 = \{S_1, S_2, S_3, S_4, S_5, S_6\}$.

(b) The match of functional information

For the candidate set of selected resources, $E_1$, and the request, the match of functional information was performed, set $\beta_{\text{label}2} = 0.7$, the weight of IOPE $\theta_i = \{0.5, 0.1, 0.2, 0.2\}$, and the matching degree was calculated between $E_1$ and request $\text{Match}(R,S)_{\text{IOPE}} = \{0.764, 0.589, 0.782, 0.961, 0.976, 0.896\}$ by Equation (7), where $\text{Match}(R,S)_{\text{IOPE}} < \beta_{\text{label}2}$ and $S_2$ did not meet the matching requirements, so the set of resource candidates at this time was $E_2 = \{S_1, S_3, S_4, S_5, S_6\}$.

(c) The match of manufacturing capability

On the basis of the previous level of matching, the candidate set of selected resources, $E_2$, and the request were matched to the manufacturing capacity, set $\beta_{\text{label}3} = 0.8$, the weight of the manufacturing capacity was $\gamma_i = \{0.6, 0.4\}$, and the matching degree between $E_2$ and the request was calculated by Equation (8). The matching degree of service constraint $\text{Match}(R,S)_{\text{CapaInf}} = \{0.849, 0.885, 0.982, 0.811, 0.764\}$, and $\text{Match}(R,S_6)_{\text{CapaInf}} < \beta_{\text{label}3}$, and $S_6$ did not meet the matching requirements, so the set of resource candidates at this time was $E_3 = \{S_1, S_3, S_4, S_5\}$.

(d) The match of service constraints

On the basis of the previous level of matching, the candidate set of selected resources, $E_3$, and the request were matched with the service constraints, set $\beta_{\text{label}4} = 0.9$, the weight of the service constraints was $\delta_i = \{0.2, 0.2, 0.3, 0.3\}$, and the matching degree between $E_3$ and the request was calculated by Equation (9). The matching degree of service constraints $\text{Match}(R,S)_{\text{SerCons}} = \{0.902, 0.885, 0.992, 0.918\}$, $\text{Match}(R,S_3)_{\text{CapaInf}} < \beta_{\text{label}4}$, and $S_3$ did not meet the matching requirements, so the set of resource candidates at this time was $E_4 = \{S_1, S_4, S_5\}$.

(e) Comprehensive match

According to the AHP method in Section 2.3.3, the weight of the comprehensive matching was determined as $\zeta_i = \{0.062, 0.123, 0.275, 0.540\}$. On the basis of the four levels of matching presented above, the candidate set of selected resources, $E_4$, was comprehensively matched, set $\beta_{\text{Sum}} = 0.9$, and the comprehensive matching degree of the resource candidate set was calculated by Equation (14). $\text{Match}(R,S)_{\text{Sum}} = \{0.854, 0.984, 0.874\}$ and $\text{Match}(R,S_1)_{\text{Sum}} < \beta_{\text{Sum}}$, $\text{Match}(R,S_4)_{\text{Sum}} < \beta_{\text{Sum}}$, and $S_1$ and $S_4$ did not meet the matching requirements, so the final candidate set of resources was $E_5 = \{S_4\}$. The matching degree results of the task for manufacturing a battery temperature sensor are shown in Table 3.
Table 3. Results of the task for manufacturing a battery temperature sensor that matches the resource $S_4$.

| Matching Series                        | Matching Content | The Matching Result of Task R and Resource $S_4$ |
|----------------------------------------|------------------|-----------------------------------------------|
|                                        |                  | Matching Degree | Overall Match |
| The match of basic information         | Basic information| 0.969           | 0.969         |
| The match of functional information    | Input            | 1               |
|                                        | Output           | 1               |
|                                        | Preconditions    | 0.924           |
|                                        | Effect           | 0.881           |
| The match of manufacturing capability  | Parametric set   | 0.971           | 0.98          |
|                                        | Dependencies     | 0.998           |
| The match of service constraint        | Time             | 0.986           |
|                                        | Quality          | 0.987           |
|                                        | Cost             | 0.997           |
|                                        | Credibility      | 0.994           |
| Comprehensive match                    | The match of basic information | 0.969 |
|                                        | The match of functional information | 0.96 |
|                                        | The match of manufacturing capability | 0.982 |
|                                        | The match of service constraint | 0.992 |
|                                        |                  |                 |

Summarizing the above, it can be concluded that the resource $S_4$ best-matched the task of the battery temperature sensor.

4. Conclusions

Resources are the core of the whole lifecycle of products, and all services are inseparable from the support of resources, in order to allow resources to be used as quickly and efficiently as possible to the greatest extent. According to the characteristics of mass, heterogeneity, and independence of resources, this paper constructed a hierarchical and modularized unified descriptive model for design/manufacturing/service resources, and the specific descriptive models of ontology, function, and service were respectively proposed. An example based on OWL language and the Protégé tool verified the model, which proved its feasibility and effectiveness. In order to realize the subsequent resource sharing across subjects and stages, this paper first proposed a series of matching preparations, including task description, task decomposition, and subtask sorting, and then proposed the matching method of resources based on multi-level tags, including basic information, functional information, manufacturing capability, service constraints, and comprehensive matching, where the matching weights were determined by AHP. Finally, an instance was used to verify the effectiveness of the matching method with multi-level tags.

This paper is part of the research on resource sharing, and further work needs to be carried out in the future, mainly including: (1) Resource matching should not only satisfy static capabilities, but also have dynamic capabilities. (2) On the basis of current research, an efficient composition technology should be designed. (3) Experiments with more simulated datasets are needed [46], along with (4) improvements in the generalizability of the model [47,48].

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