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Product Development-Oriented Knowledge Service: Status Review, Framework, and Solutions

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ABSTRACT The product development knowledge stored in manufacturing firms can be obtained and re-used to assist the development engineers in new product development and facilitate the use of knowledge resources, which in turn enhances the quality and reduces the time-cost of product innovation. This study presents a knowledge service integrated framework for product development, which is refined from the literature and supported by practice needs. The proposed integrated framework is supported by four pillars of work, namely, how to represent knowledge exactly, the model of knowledge integration, the method of knowledge recommendation, and the mechanism and performance evaluation of knowledge service. A demonstration of a gantry crane design is provided to show the effectiveness and benefit of the proposed integrated framework and technology solutions. Finally, we offer some pointers for future research.

INDEX TERMS Knowledge reuse framework, knowledge representation, knowledge sharing, knowledge recommendation, product development.

I. INTRODUCTION

Manufacturers face increasing pressure to compete on improving product quality while satisfying the time to develop new products for the marketplace. Hence, the intangible asset of knowledge has deemed as a means of gaining competitive advantage over competition [1]. New manufacturing models and information technology are constantly promoting the industrial economy to become a knowledge economy. As the practice of product-service system pervades, knowledge service has become a useful and valuable tool for the manufacturing industry [2], [3]. Under intense competition, the manufacturing sector is facing more challenges than before; enterprises should focus on their core competitiveness to design and develop new products and services to meet market demand. Knowledge has become the core value and source of product innovation for a manufacturer. In the past decade, some enterprises have proposed and built knowledge service platforms to organize and manage the knowledge resources for sharing and reuse in product upgrades and new product development. Specifically, the software product lines and product lines in enterprises also seek to reuse knowledge and other assets between the products [4].

As knowledge resources grow, the efficiency of knowledge reuse should be considered to improve the service capacity of knowledge [5]. In a traditional manufacturing enterprise, it is difficult for engineers to acquire knowledge quickly and accurately when completing their work, which seriously affects product design quality and design progress [6]. By using a knowledge service system, engineers can obtain knowledge through knowledge retrieval, and knowledge recommender methods. This slew of activities is also the process of knowledge transfer, knowledge acquisition, and knowledge creation in product development [7]. Knowledge can be viewed as structured information, which depends on many variables including the purpose of the

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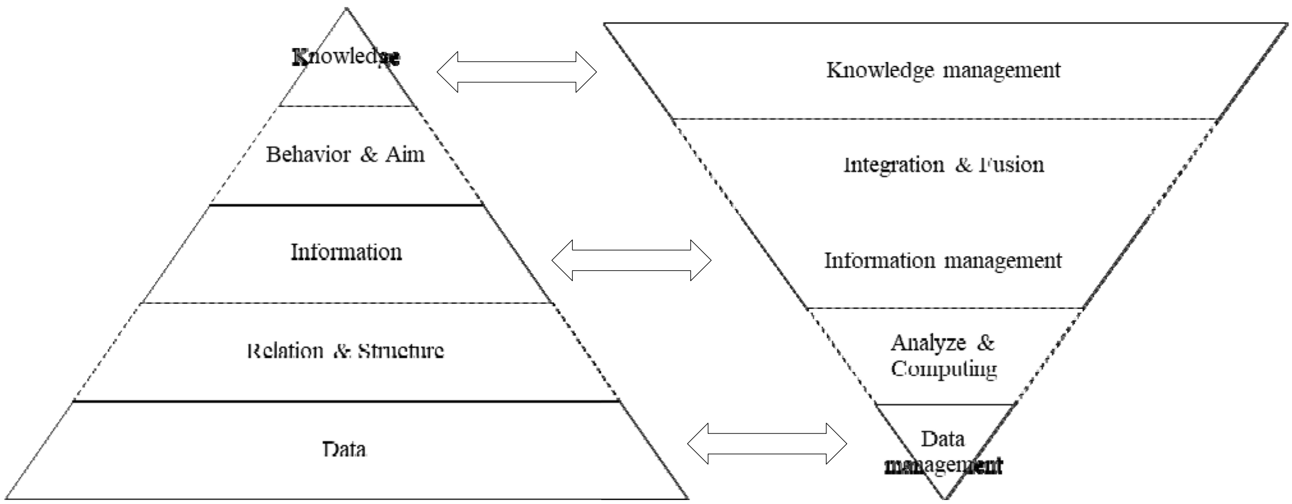

FIGURE 1. Level structure of knowledge management.

product design, the rules that design behaviors follow, the stage of the product design, and the organization. To better understand the information, the data should be well structured and organized for designers to reuse [8]. Knowledge management extends information and data management by considering information and data in context (see Figure 1). Manufacturing enterprises have much rich data and documents which could be represented and shared as knowledge to support product development. Using knowledge management methods, manufacturing enterprises can transfer valuable data and information to knowledge, which can be shared in collaborative development teams, and be used to improve the development efficiency of engineers.

In recent years, many researchers have committed to studying knowledge recommendation to help the engineers obtain the requisite knowledge conveniently and efficiently in product development [14]. To address the challenge described above, an acceptable and feasible knowledge management method and system which contains active knowledge sharing and knowledge recommendation should be proposed and validated. This can shorten product development time-cost and improve competitiveness through effective knowledge sharing methods [15].

Typically, engineers in the product development process spend about 80% of their time on relevant knowledge search and review [16]. Therefore, it is critical to conduct knowledge service speedily to shorten the time-cost, and then speed up the product development and improve product quality.

According to the academic research trends and the industry needs in practices, the framework in this study should be proposed based on the perspective of the product lifecycle, and defined to integrate with three aspects:

- To reuse different types of knowledge, the uniform knowledge representation and integration methods are proposed to effectively represent and model knowledge resources in product development stages.
- To shorten the knowledge acquisition time-cost for engineers, knowledge can be actively provided to the engineers by the knowledge recommendation method.
- To improve the performance of the knowledge service system continuously, this work can consider the performance evaluation method for the knowledge service system.

The rest of the article is set as follows. Section 2 briefly describes the current state of research. Section 3 proposes an integrated framework of knowledge service for product development. The detailed structure of the key techniques and solutions for knowledge service is developed and given in Section 4. Section 5 provides a demonstration of the gantry crane design to show the feasibility and potential of the knowledge service integrated framework and methods. Section 6 summarizes the conclusion and offers some future perspectives.

II. CURRENT RESEARCH STATUS

A. KNOWLEDGE CLASSIFICATION AND REPRESENTATION

1) CLASSIFICATION OF KNOWLEDGE

Two knowledge classification methods exist in the product development field. One classification method defines knowledge as explicit and tacit knowledge [17]. In addition, the knowledge set contains four types including the know-what, know-why, know-how, know-who according to the Organization for Economic Co-operation and Development (OECD) [18].

Normally, explicit knowledge, which comes from engineering and technical documents, algorithms, and databases. It mainly contains design information, engineering drawings, standard specifications, product manuals, and is generally formed in a structured, semi-structured model, such as product model files, 3D design files, and Word/Excel files. Tacit knowledge, which may come from experience, skills, and implicit rules, is difficult to code and structure but it is important in creating new value for a product. Tacit knowledge

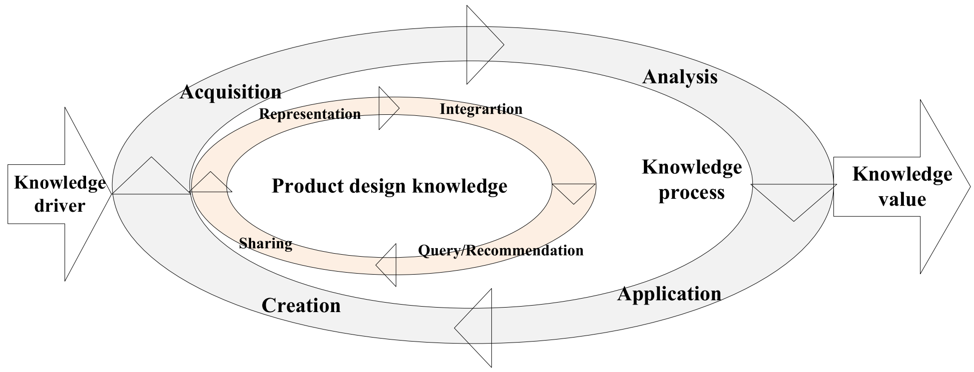

FIGURE 2. Knowledge management process.

is the intangible property of product developers or a design team. The engineers would take a long time to internalize this form of knowledge to learn new skills and gain new experience. It is difficult to represent or share this know-how knowledge with others. Unfortunately, tacit knowledge would be also lost with the departure of an engineer from a team.

The OECD sets knowledge as four types which are valuable and helpful to a knowledge-based organization; the details are as follows [18].

- Know-what refers to factual information. In the process of product development, engineers depend on this type of knowledge to complete their work;
- Know-why refers to the principles and laws of nature. This type of knowledge mainly contains the theory of product development and process design in manufacturing industries;
- Know-how refers to the experience or skills of an engineer to do something. Generally, this kind of knowledge can be used in market judgment calls and decision-making;
- Know-who knowledge refers to the information about who knows what and how to do what. It can provide the social relationships which link knowledge to experts.

2) METHODS OF KNOWLEDGE REPRESENTATION

Knowledge representation can be divided into two methods. One method focuses on describing and explaining an entity. This method is mainly based on predicate logic [19], production rules [20], description logic [21], [22], exchange protocol [23], and case-based [24]. These forms have the features of simple-form, strong-reasoning, and easy-maintenance. Another method focuses on the concept of knowledge and the relationship between the knowledge entities. The use of graph theory in knowledge representation is a representative of such methods. This method is based on semantic network [25], concept map [26], ontology [27], semantic web [28]–[30], and topic map [31]. This kind of knowledge representation method can describe the complex semantic relations among knowledge resources and has strong knowledge reasoning and understanding capabilities.

B. KNOWLEDGE ACQUISITION AND REUSE

1) KNOWLEDGE SHARING IN PRODUCT DEVELOPMENT

In recent years, knowledge-sharing methods are widely used in various fields to provide effective ways for knowledge reuse and innovation. Zhang *et al.*

With the development of the product lifecycle, the knowledge management of a manufacturing enterprise includes customer information, product development, production files, and product delivery and service. The knowledge in product design and development stage contains mostly the design method, design rule, factual knowledge, design principle, product model, design process knowledge, domain expert knowledge, and product design cases [9]. Knowledge-driven enterprises need to integrate the knowledge process into the product development stage.

As shown in Figure 2, the knowledge management process is provided to explain the knowledge lifecycle for product design. In the outer loop of Figure 2, the knowledge process contains knowledge creation, knowledge acquisition, knowledge analysis and knowledge application [10]. The inner loop of Figure 2 shows the product design knowledge process, which includes knowledge representation, integration, query, recommendation and sharing. The start of this loop is knowledge representation. The knowledge is managed and stored by a unified model, and then according to the business demands, this knowledge would be provided to engineers in a suitable form. The engineers can obtain knowledge through knowledge retrieval and knowledge recommendation methods. With these two loops, knowledge can be transferred and shared when engineers work on their product development tasks.

A valuable knowledge reuse system can support users to reform and upgrade their products by improving product quality and time taken. Since the product development stage involves much knowledge, it is one of the most knowledge-intensive processes in an enterprise [8]. Knowledge storage, sharing and application provide vital and helpful support for product development and upgrades [11]. Product development knowledge includes the various types of product data, product development tools, product

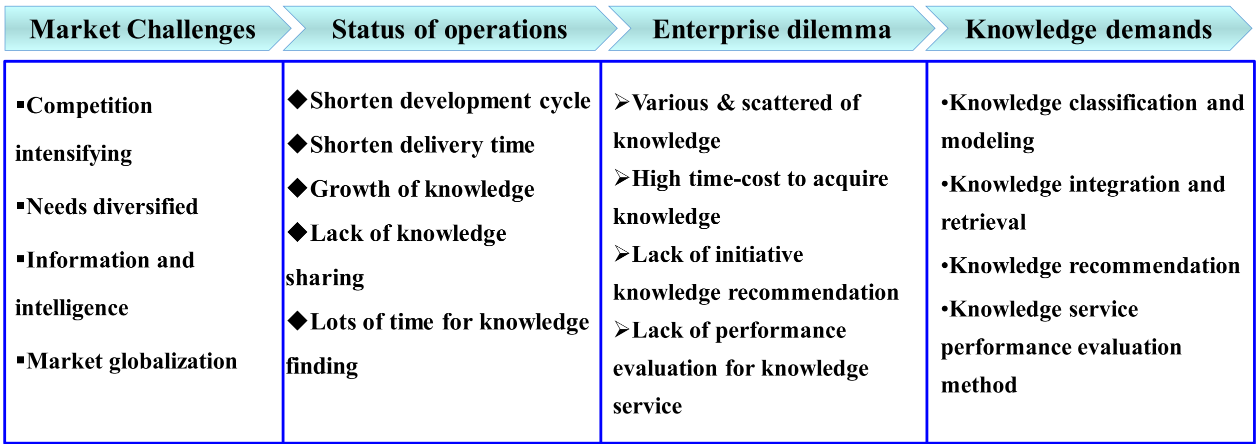

FIGURE 3. **Mapping from manufacturing firm demands to knowledge service demands.**

development and design document/cases as well as other support aspects.

Manufacturing firms increasingly face challenges from the market, including competition, market globalization, information and intelligence. During the product development stage, firms have to improve their efficiency to shorten the development cycle and delivery time. Meanwhile, product development engineers also encounter some issues, including the growth of knowledge, difficulty in knowledge sharing, and a high time cost for knowledge discovery. As shown in Figures 3, to cope with these challenges, a knowledge service framework should be provided to handle the issues of knowledge representation, knowledge sharing and reuse in product development. The proposed framework can meet the knowledge demands of an enterprise including knowledge classification and representation, knowledge sharing and recommendation to identify and transfer the knowledge in product development. At the same time, engineers need to learn a lot and to work with their team for years before becoming domain experts [12]. Specifically in the manufacturing industry, firms are trying to increase their investment in intangible asset management, e.g. knowledge management, which has become a trend [13].

[32] present a novel approach to support the decision-making process, which combines knowledge maps and knowledge navigation. Chen [33] presents a systematic approach to developing a knowledge integration and sharing mechanism for collaborative molding product design and process development. Cupek *et al.* [34] present a novel information model to provide solutions for manufacturing execution system. Bradfield and Gao [35] propose an ontology-based methodology to solve knowledge transfer issues in the new product development of a multi-national environment. Zhen *et al.* [36] proposes a novel distributed knowledge sharing model for spreading and sharing knowledge among engineers in collaborative product development teams. Chungoora *et al.* [37] present a novel concept in their article, based on the Model Driven Architecture (MDA). To best integrate heterogeneous product knowledge, Wu *et al.* [5] present an ontology-based knowledge integration method to help time-saving problems for product development. Xu *et al.* [38] propose a product modeling framework based on interaction feature pairs.

On the product lifecycles, the research of a knowledge sharing framework and method focuses on the socialization mechanisms of the product development teams, product-service system development (PSS), product supply chain management and outsourcing projects of the software product. Chen *et al.* [39] attempt to develop a part affordance-based approach for externalizing and capturing detailed design knowledge for effective reuse. Lawson *et al.* [40] propose and test a theoretical model of the impact of formal and informal socialization mechanisms on the level of knowledge sharing within inter-organizational product development projects and the subsequent effect on the buying firm's performance. Akhavan *et al.* [41] provide a method for selecting the NPD project team members, which maximizes the expertise level of team members and at the same time, optimize knowledge sharing in the enterprise. Chirumalla *et al.* [42] work stems from the findings of two research projects from the aerospace industry. They note that the development of profitable PSS relies on the development of strong and weak ties across the supply network. Gan [43] presents a conceptual framework to implement knowledge sharing for closed-loop supply chain management (CLSC), to improve the CLSC members' performance. Maleszka [44] considers a personalized document retrieval system that gathers information about user interests, determines the user's profile and helps the user to obtain the relevant documents.

2) KNOWLEDGE RECOMMENDATION MODEL

As knowledge recommendation technology gains more traction from academe and industry, an important research field of product development knowledge acquisition and reuse can be the focus on the knowledge recommender method [45], [46]. Our paper intentionally finds and reviews

TABLE 1. State of current research.

Research content		Existing solution	Shortcoming
Framework	Mode & Process	PDKM; Knowledge acquisition; KMS	Lack product design knowledge service framework and processes in a new network environment.
Knowledge representation and sharing methods	Modeling	Ontology, Classification	Lack method for beneficial product design, and simultaneously complete representative product design process.
	Integration	Ontology	Lack knowledge integration method according to different sources of knowledge source.
	Sharing	Knowledge retrieval	Lack perspective of knowledge demanders and providers.
Knowledge recommendation methods	Based on task	Information recommendation based on workflow	Lack research based on task in product design.
	Based on interest	Tracking information for interest	Lack research based on interest in product design.
	Experts	Domain experts push	Lack perspective of knowledge service.

the current research status in this area. Zhen *et al.* [47] propose a novel distributed knowledge recommender system for collaborative teams. A method for the dynamic curation of manufacturing-related knowledge is proposed by Wood [48], based on the effect of a successive paradigm introduction on the network structure within manufacturing firms. Choi *et al.* [49] research present a hybrid online-product recommendation system that combines the implicit rating-based CF (collaborative filtering) and SPA (sequential pattern analysis) to improve the recommendation quality. Zhen *et al.* [50] present a knowledge recommendation model to support personal knowledge management in a collaborative work environment. Verma *et al.* [51] also propose a knowledge recommender system to support engineers to obtain knowledge. Yan *et al.* [52] propose a new knowledge recommendation approach by refining the contextual and the relationship of engineers. Su *et al.* [53] propose a framework of power grid knowledge recommendation and situation reasoning based on cloud computing and CEP (Complex Event Process). Mishra *et al.* [54] have developed a system that considers the sequential information present in Web navigation patterns, along with content information. Liu *et al.* [55] present an intelligent knowledge recommending approach for new product development based on workflow context matching. Song *et al.* [56] use Gantt charts to describe the time-sequence relationship in the knowledge recommendation process.

C. ANALYSIS OF CURRENT RESEARCH STATUS

Through analyzing the research works and the knowledge demands of manufacturing enterprises, recent research efforts mainly focus on the knowledge sharing and reusing. A few of them focus on the knowledge service area. Product development knowledge service needs a framework from a lifecycle view, including knowledge modeling, knowledge integration, knowledge recommender, and knowledge evaluation. Table 1 shows the state of current research. In Table 1, some factors (e.g. product lifecycle, knowledge service mechanism, and knowledge performance evaluation) need to be considered. Product development in the manufacturing industry, which has some new features, is the basis of this article.

However, with this analysis and earlier observations, prior studies primarily focus on the knowledge model and knowledge reuse, and few of them discuss how to organize and transfer knowledge in the product lifecycle. The current studies do not propose a systematic framework based on the product lifecycle. To bridge this gap in industrial development, this paper introduces a product lifecycle perspective framework for knowledge service to support knowledge-driven product development. The proposed framework seeks to provide a solution for the engineers to make decisions on their tasks. For this purpose, an XTM-based (XML Topic Map) knowledge model is proposed, the ontology-based knowledge integration and knowledge recommendation methods have also been developed. The performance evaluation method for knowledge service system is designed to improve the knowledge service system continuously. To show the benefits of the proposed framework, a demonstration of the knowledge service and technical analysis is given.

III. KNOWLEDGE SERVICE FRAMEWORK OF PRODUCT DEVELOPMENT

A. KNOWLEDGE DEMANDS IN PRODUCT DEVELOPMENT

Knowledge service is a demand-oriented framework and system. One of the most important topics in this field is how to structure the mapping relationship among the knowledge resources, development engineers and knowledge demands. Manufacturing companies mainly focus on high time-cost for designers to acquire knowledge and low knowledge integration. Based on these challenges, the knowledge demands of the proposed framework could be divided into three dimensions: knowledge representation, knowledge acquisition, and knowledge matching between knowledge resources and demands.

(1) Knowledge representation: There are many sources of knowledge in the product design process. Some come from the development engineers' experience, and some come from the completed projects. These types of knowledge are stored in the systems in various forms, which require users to design a unified representation method to make knowledge sharing and transfer more efficient. Therefore, a knowledge service

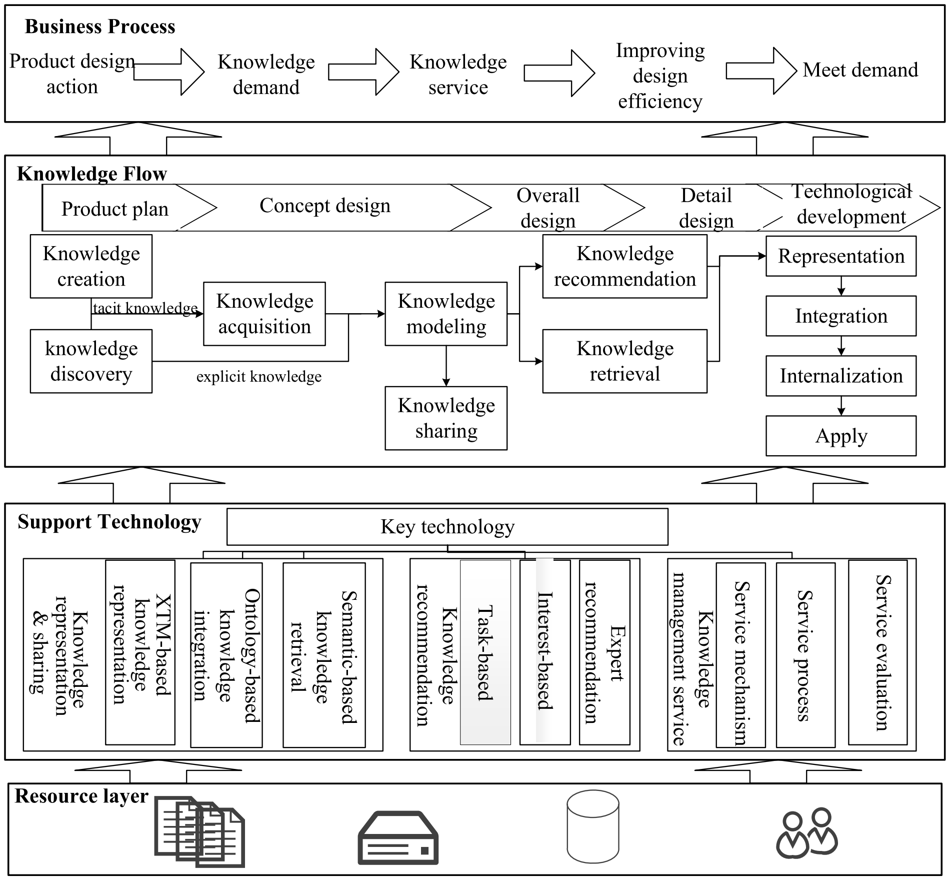

FIGURE 4. Layer structure of product development knowledge service.

system should have the ability to deal with heterogeneous knowledge.

(2) Knowledge acquisition: When engineers receive a product development task, they can acquire decision-making knowledge through a knowledge service system supported by knowledge retrieval and knowledge sharing method. The way that the engineers acquire knowledge resources can be determined by their professional skills, educational background, and personal preferences. Knowledge acquisition contains knowledge retrieval and knowledge recommendation to meet the specific and potential knowledge demands of the product development engineers.

(3) Knowledge matching: Knowledge service seeks to establish the mapping relationship between the knowledge demands and the knowledge resources, and then it can provide solution for the problem in the actual development processes. The different knowledge demands can be refined from development processes, by computing the similarity between knowledge demands and resources, a knowledge service system would provide knowledge resources to support product development. Therefore, the computation of the matching degree between the knowledge resources and demands is key to knowledge service.

B. LAYER STRUCTURE OF FRAMEWORK

Knowledge service requires collaboration between the engineers to help them take advantage of existing explicit knowledge and tacit knowledge to develop products that meet the needs of the market and customers. To achieve that goal, a four layer structure of the knowledge service system is proposed including the business process layer, the knowledge flow layer, the support technology layer and the resource layer, as shown in Figure 4.

C. KNOWLEDGE SERVICE MAPPING PROCESS FOR PRODUCT DEVELOPMENT

The knowledge service process for product development is provided in Figure 5. It can be seen as the matching process between knowledge service demanders and knowledge service providers. As shown in Figure 5, when engineers accept a product development task, there will be a mapping link created between the service demanders and service providers. Knowledge service demanders obtain and publish their knowledge services through the knowledge service platform and acquire the knowledge service retrieval and recommendation according to the knowledge demands.

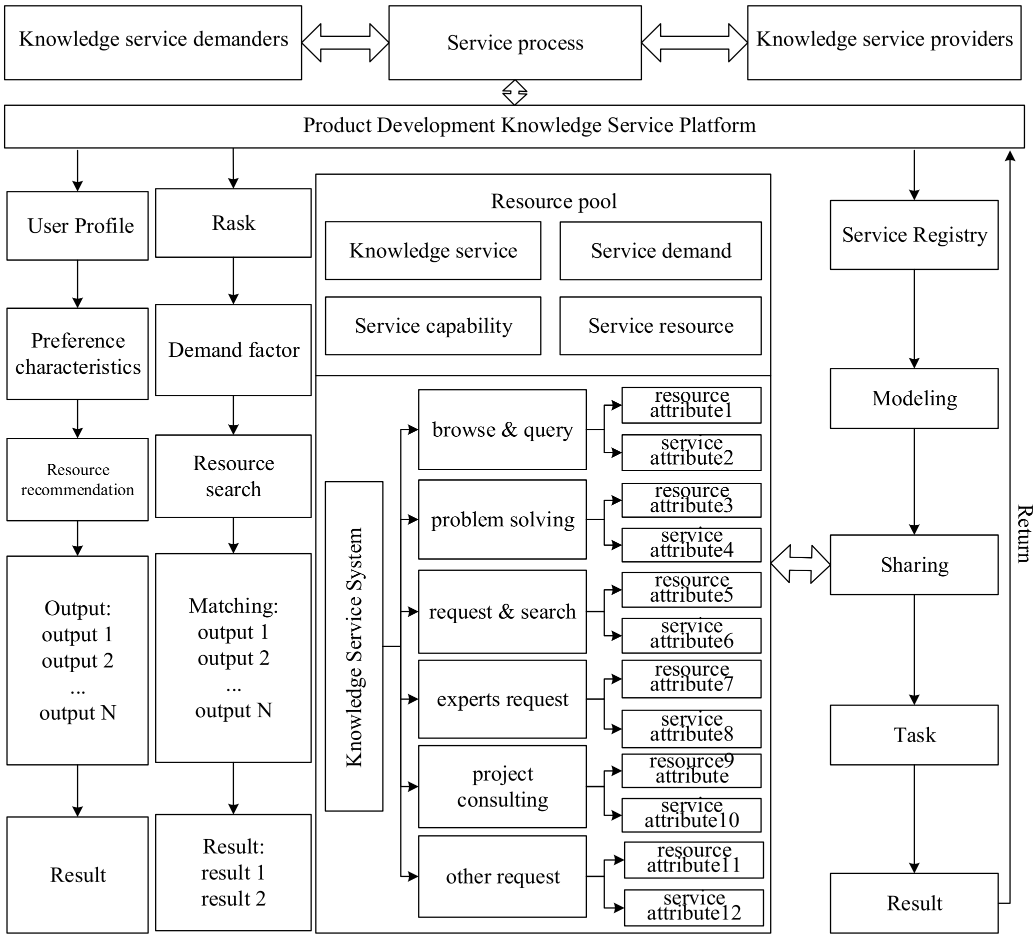

FIGURE 5. Knowledge service process for product development.

The knowledge resources stored in a service resource pool would be provided by the service providers, which consist of knowledge service, service capability, and knowledge service resource. The service resource pool can be mapped to knowledge service demands.

- Knowledge service demanders are engineers who receive a product development task. The knowledge demands generally consist of knowledge retrieval demands and knowledge recommendation demands;
- For the knowledge service providers, they should complete the actions including service registration, service resource modeling, service resource sharing, and service search;
- The knowledge service demanders would create the service demand after receiving the development tasks, and obtain the knowledge resources by knowledge retrieval and recommendation;
- The main contents of product development knowledge service consist of knowledge browsing and inquiry, product development problem solving, product development document request, domain expert knowledge request, and project consultation.

D. PRODUCT DEVELOPMENT KNOWLEDGE SERVICE SYSTEM

The knowledge service system of product development is formed from five modules. The details of each module and the relationship between each other are shown in Figure 6.

(1) The module on knowledge representation contains knowledge classification, knowledge resource request and the formal representation of knowledge resource.

(2) The module on knowledge integration and sharing consists of the customization of knowledge request, knowledge integration and knowledge retrieval.

(3) The module on knowledge recommendation contains three recommendation methods including knowledge recommendation based on design task, knowledge recommendation based on engineers' interests, and expert knowledge recommendation.

(4) Through the knowledge service mechanism, the knowledge demands of an engineer can be mapped to the service sources. According to the demands of the knowledge service demanders, the knowledge service providers can provide the matched services.

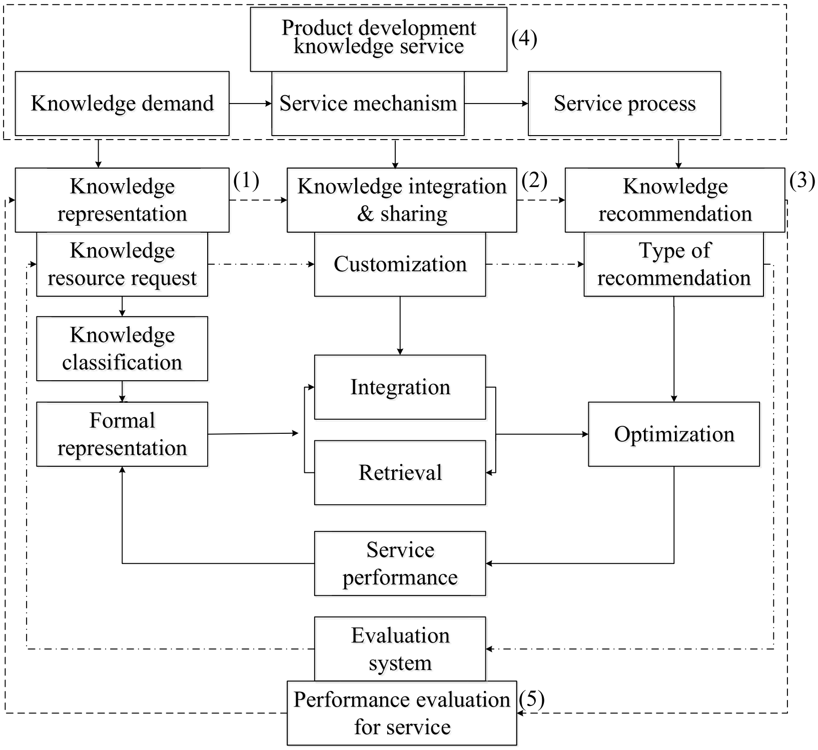

FIGURE 6. Product development knowledge service system.

(5) The performance evaluation for service can improve the operation and service capability of a knowledge service system.

E. FRAMEWORK OF KNOWLEDGE SERVICE FOR PRODUCT DEVELOPMENT

As shown in Figure 7, the proposed knowledge service framework has five sub-processes, namely,

(1) The product development process can be divided into five stages as shown in Figure 7. The proposed framework in this study supports the activities in the concept design stage.

(2) The sub-process of knowledge process has the core modules of the proposed framework: knowledge representation, knowledge sharing, and knowledge recommendation and evaluation.

(3) In the sub-process of operation, some support technologies for the core module are provided. To construct the knowledge model, the knowledge resources are defined as four types (as shown in Figure 7). The XTM-based (XML Topic Maps) method can be used for knowledge representation. For the knowledge integration and sharing module, the ontology-based method can be used for knowledge integration and the semantics-based method can be used for knowledge retrieval. The knowledge recommendation module, which has three types of knowledge should be actively provided to the engineers. The fuzzy comprehensive evaluation method can be used to evaluate knowledge service performance.

(4) The supporting process comprises the process on how to realize the main functions belonging to the core modules.

(5) The product development knowledge service system is the support platform for engineers. The interface of this system can acquire the knowledge demands and map it to the knowledge service resources. It also contains the stakeholders of the system, service mechanism, and service processes.

IV. SUPPORTING TECHNOLOGIES FOR PROPOSED FRAMEWORK

A. XTM KNOWLEDGE REPRESENTATION MODEL

According to the definition provided by the OECD, knowledge in this paper is divided into four types [18]. The know-what knowledge mainly contains documents, specifications and database. The know-why knowledge consists of the product concepts, design specifications, customer requirements, domain knowledge, and feasibility reports. The know-how knowledge generally contains the simulation model, engineering forms, skills, and the know-how of individuals, design principles and procedures. The know-who knowledge contains the domain experts, customers, organizational routines and organizational culture.

To reuse these four categories of knowledge, this paper designs an XTM-based representation model to effectively model and represent knowledge in the different product development stages. The XTM is a standard for the

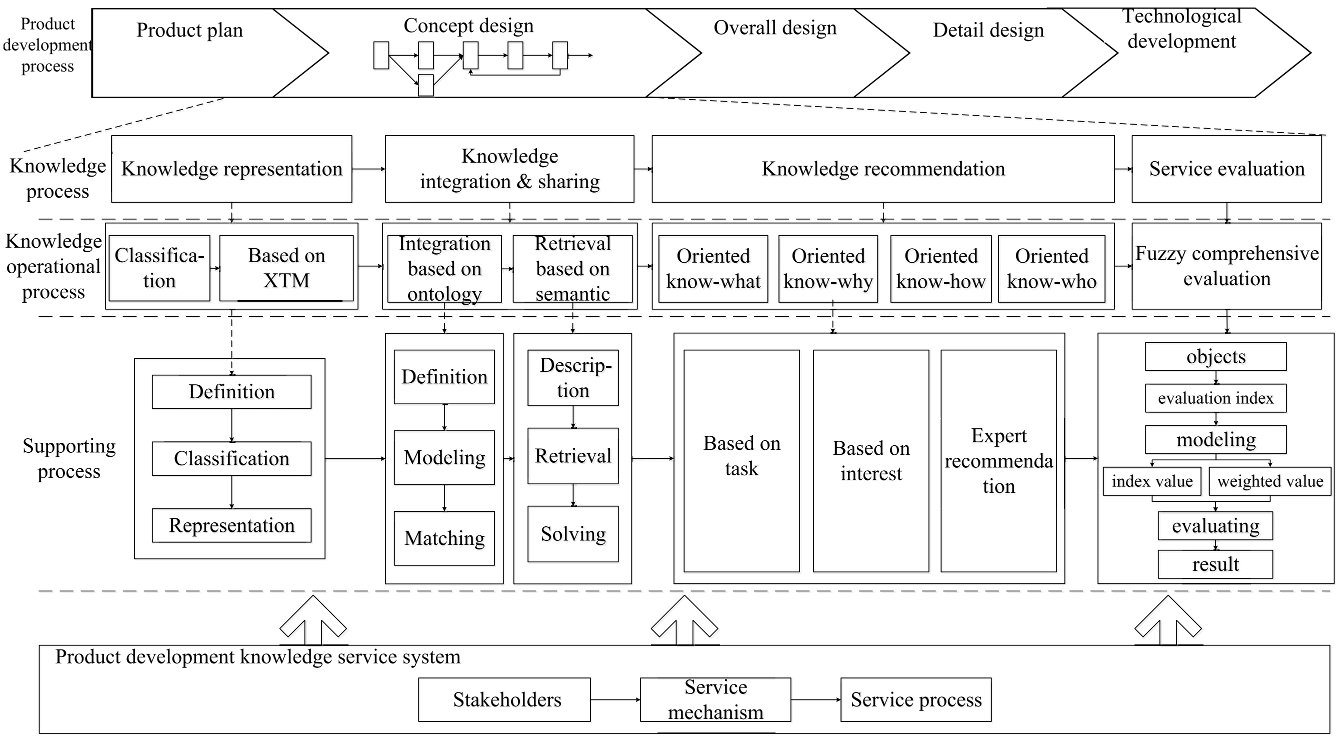

FIGURE 7. Framework for product development knowledge service.

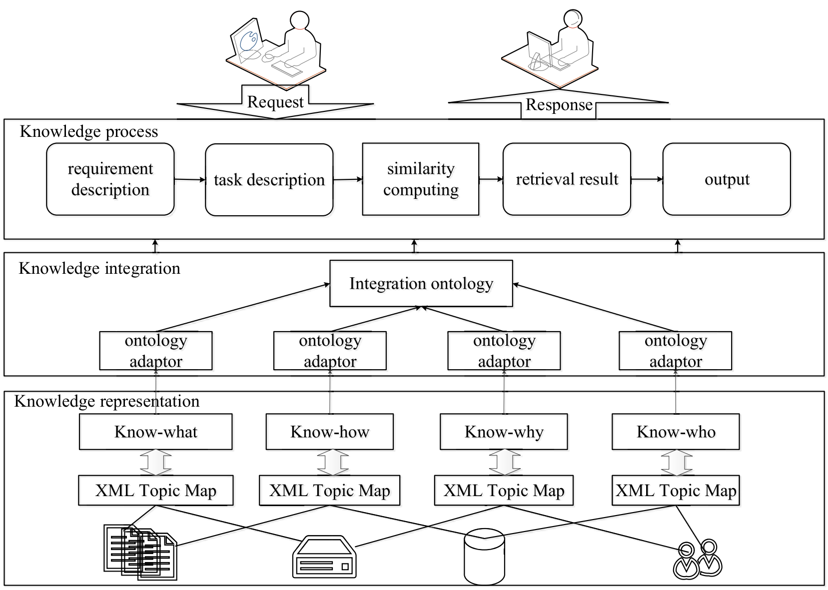

FIGURE 8. Knowledge representation model for product development.

representation and exchange of knowledge with an emphasis on the information finding method [13]. As shown in Figure 8, the proposed model has three layers: knowledge process, knowledge integration and knowledge representation. The knowledge process contains the process of knowledge sharing from requirement description to knowledge output responding to the engineers' request. The integration ontology in knowledge integration layer contains an integration ontology and four knowledge ontologies. In the knowledge representation layer, the model is designed according to XTM to create and map the knowledge resources.

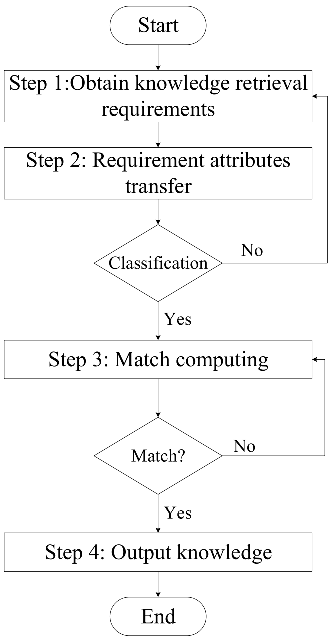

FIGURE 9. Process of knowledge sharing for product development.

B. KNOWLEDGE SHARING PROCESS

According to the knowledge requirements of the engineers, the system extracts and transforms the features of the requirements, determines the category of the knowledge requirements, then matches the knowledge requirements and the knowledge ontology, before providing the results to the engineers. The steps of knowledge sharing, shown in Figure 9, are as follows:

Step 1: To gather the knowledge requirements of the engineers, we describe the requirements information with three dimensions to form a dataset;

Step 2: To extract and transform the requirements to form a feature matrix, and determine the type of required knowledge based on the matrix;

Step 3: To identify the required knowledge type, we obtain the similarity between the knowledge requirements and the knowledge ontology, and find the knowledge resources with high similarity;

Step 4: Sort the retrieval results through a similarity computation and the degree of preference of the knowledge requirements to find the knowledge content that is most similar to the requirements and provide it to the engineers.

C. KNOWLEDGE RECOMMENDATION METHOD

The knowledge resources can be mapped to the engineers through the knowledge recommender processes and technologies. Once an engineer receives a task, the engineer can also obtain the related knowledge in the meantime. Figure 10 provides the knowledge recommendation process. The engineers login to the knowledge service system through the application interface. On the user side, each user has a profile to record the user's information. The user features can be extracted from the user profile. At the system side, the knowledge service system will generate the usage recordings and usage history of the engineers. Based on the user features and usage history, the appropriate knowledge would be recommended to the engineers to help their development tasks. The recommendation steps are as follows:

Step 1: Extract and analyze the usage recording to generate user feature values.

Step 2: Analyze the product development tasks and map the user features to the knowledge ontology.

Step 3: Obtain the value from the user features to the knowledge ontologies, and classify the matching results according to the similarity.

Step 4: Generate the knowledge recommendation results, and present them to the engineers.

D. PERFORMANCE EVALUATION FOR KNOWLEDGE SERVICE

There are two dimensions that should be considered when evaluating the performance of knowledge service for product development. First, the evaluation content related to the engineers mainly contains knowledge representation, knowledge integration, knowledge sharing, and knowledge recommendation. Second, from the perspective of the information system, the performance of knowledge service and the system should be considered also.

Therefore, the evaluation index chosen in this paper is divided into two parts: knowledge service content and knowledge service system. The evaluation index of the knowledge service content is developed from four aspects: knowledge representation (B_1B$_1$), knowledge integration (B_2B$_2$), knowledge sharing (B_3B$_3$), and knowledge recommendation (B_4). The knowledge service can be evaluated from knowledge service (B_5) and knowledge service system (B_6). The specific decomposition is shown in Table 2.

Performance evaluation often involves subjective judgment, which may lead to fuzzy and uncertain information. Thus, it is a typical natural language-oriented multi-factor evaluation problem. The fuzzy-based evaluation method developed in the literature [57]–[59] is considered to be effective for conducting the performance evaluation with fuzzy semantics provided by the knowledge service users. Here, as the performance evaluation method is not the main focus of this study, we will not describe the detail. The performance evaluation can improve the performance of the knowledge service system, as well as provide potential benefits to manufacturing firms.

V. PROPOSED FRAMEWORK APPLICATION

Firm S specializes in gantry crane design. It has a long history of providing crane design services. The core business of this firm is in engineering and technology consulting, gantry crane design and development, and the evaluation of reliability and safety technology of the product. Due to the long product design lead time and the development cycle, the crane industry is facing the challenge of an industrial

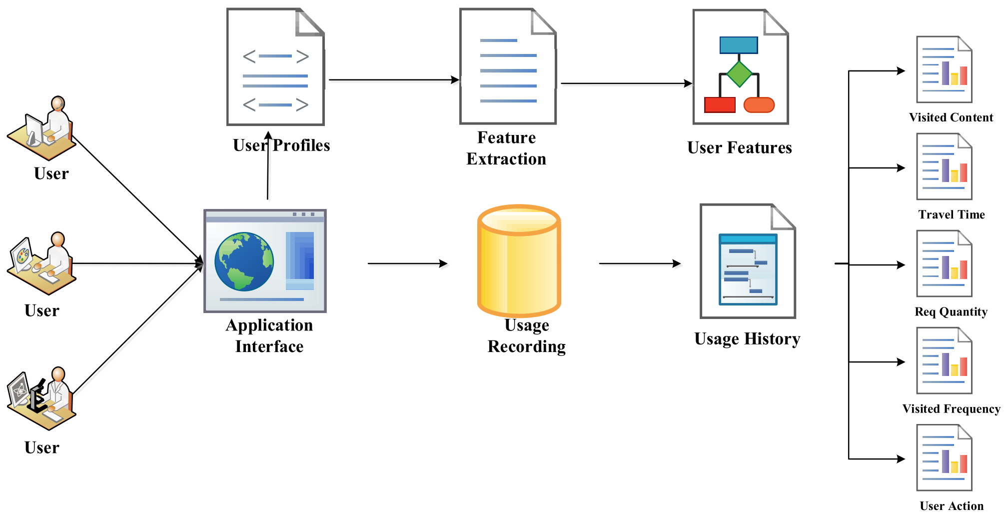

FIGURE 10. Knowledge recommendation process.

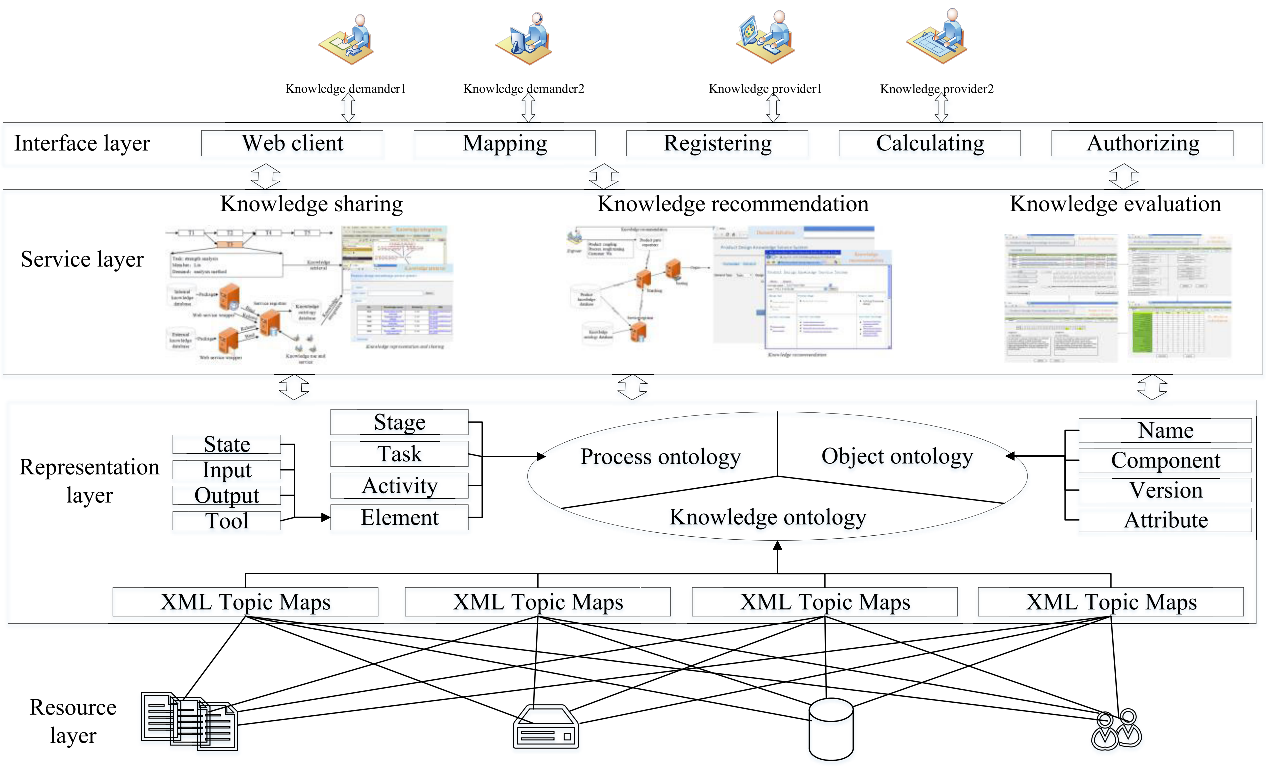

FIGURE 11. System functional architecture of knowledge service system.

upgrade to overcome the difficulty of global market competition, shorten the product delivery time cost, and increase the level of customization. According to the challenge described, one of the problems that should be considered is how to reuse the valuable knowledge buried in a distributed development environment. It lacks a knowledge transfer and sharing network for the product development engineers making it difficult to acquire and reuse the knowledge. It also fails to collaborate with an external organization. Therefore, firm S plans to design and implement the knowledge service system to solve the problems mentioned.

A. SYSTEM FUNCTIONAL ARCHITECTURE FOR KNOWLEDGE SERVICE SYSTEM

The system functional architecture of the proposed knowledge service system is provided in Figure 11, which contains

TABLE 2. Evaluation index for knowledge service.

Objective	First level indicator	Second level indicator
Evaluation index for knowledge service	Knowledge representation (B_1)	Comprehensibility（B_{11}）
		Accept complexity（B_{12}）
		Usability（B_{13}）
	Knowledge integration (B_2)	Coverage（B_{21}）
		Degree of Integration（B_{22}）
		Complexity（B_{23}）
	Knowledge sharing (B_3)	Retrieval matched-degree（B_{31}）
		Availability（B_{32}）
		Retrieval complexity（B_{33}）
	Knowledge recommendation (B_4)	Matched-degree of knowledge and task（B_{41}）
		Conformity of knowledge and interest（B_{42}）
		Matched-degree of expert（B_{43}）
	Knowledge service(B_5)	Reliability（B_{51}）
		Service level（B_{52}）
		Individuality（B_{53}）
	Knowledge service system (B_6)	Response（B_{61}）
		Reaction velocity（B_{62}）
		Resource（B_{63}）
		User involvement（B_{64}）
		Safety（B_{65}）

four layers: knowledge resource layer, knowledge representation layer, knowledge service, and interface layer. The resource layer contains various knowledge resources, like project documents, product models, support tool information, domain expert information and maintenance data. In the representation layer, different knowledge resources are structured and represented by the XTM-based method. There are three core modules in the service layer: knowledge sharing module, knowledge recommendation module and knowledge evaluation module. The knowledge demanders and providers communicate with the system through the interface layer, which includes the web client, mapping, registering, computing and authorization. The knowledge service system is developed on the java server pages and the safety analysis is conducted.

B. DEMONSTRATION OF THE PROPOSED APPROACH

The focal company has received a project to design an 800t gantry crane, which needs to be delivered on time in accordance to the contractual agreement. The gantry crane design tasks can be divided into general design, structural design, mechanical system design, electrical system design and safety protection device design in the design stage (see Figure 12). The mechanical system design, taken as an example, can be divided into upper/lower trolley lifting structure design, upper and lower trolley operation structure design, crane operation system design, maintenance crane design, elevator design and lubrication system design. During the design and development of the gantry crane, the engineers have different knowledge demands in various stages of the product development practice. Based on the proposed framework, the engineers generally can obtain knowledge through the knowledge service system. They can also evaluate the knowledge service used to increase the availability of the knowledge service system.

The business process mainly describes the knowledge flow from the product design task to meet the knowledge demand. It mainly contains the activities of product design, knowledge demands, knowledge services, improving product design efficiency, and ultimately meeting the knowledge demands. Through the proposed methods and framework of knowledge service, the knowledge service system can meet the knowledge demands, complete product design and enhance customer satisfaction.

Knowledge flow points to how the knowledge is transferred and shared in the product development processes. It can be divided into stages and activities in which the engineers have various knowledge requirements. Then the knowledge resources would be represented and integrated according to the engineers' demands. The knowledge demands of the engineers can be satisfied by knowledge retrieval and knowledge recommendation. The engineers also can evaluate the performance of the matched service after using the knowledge resources, which can upgrade the quality of the knowledge service system.

The support technology of this framework contains three key technologies, namely, knowledge representation and sharing, knowledge recommendation, and knowledge management service. To realize knowledge representation and sharing, it can be used by knowledge representation based on XTM (XML Topic Maps), knowledge integration based on ontology and knowledge retrieval based on semantics technology. To realize knowledge recommendation, it can be used by the method based on task, interest and expert recommendation. To realize knowledge service, the key technology can be divided into three sub-processes: knowledge service mechanism, service process and service evaluation. Knowledge resources are the data and information existing in the databases or systems.

1) KNOWLEDGE REPRESENTATION FOR GANTRY CRANE DESIGN

The software Protégé software 4.3 (build 304) is used to model the design ontologies of the 800t gantry crane. As shown in Figure 13, the ontology for the gantry crane design contains three dimensions including knowledge object, knowledge source, and knowledge form. Knowledge source dimension acquires knowledge defined from the stage of the product lifecycle. This kind of knowledge generally is used by engineers according to their roles in the product lifecycle. That means product design engineers would obtain design knowledge, product service providers would obtain service knowledge. As shown in Figure 13(a), ProductLifeCycle comprises several subclasses namely, *market_survey,*

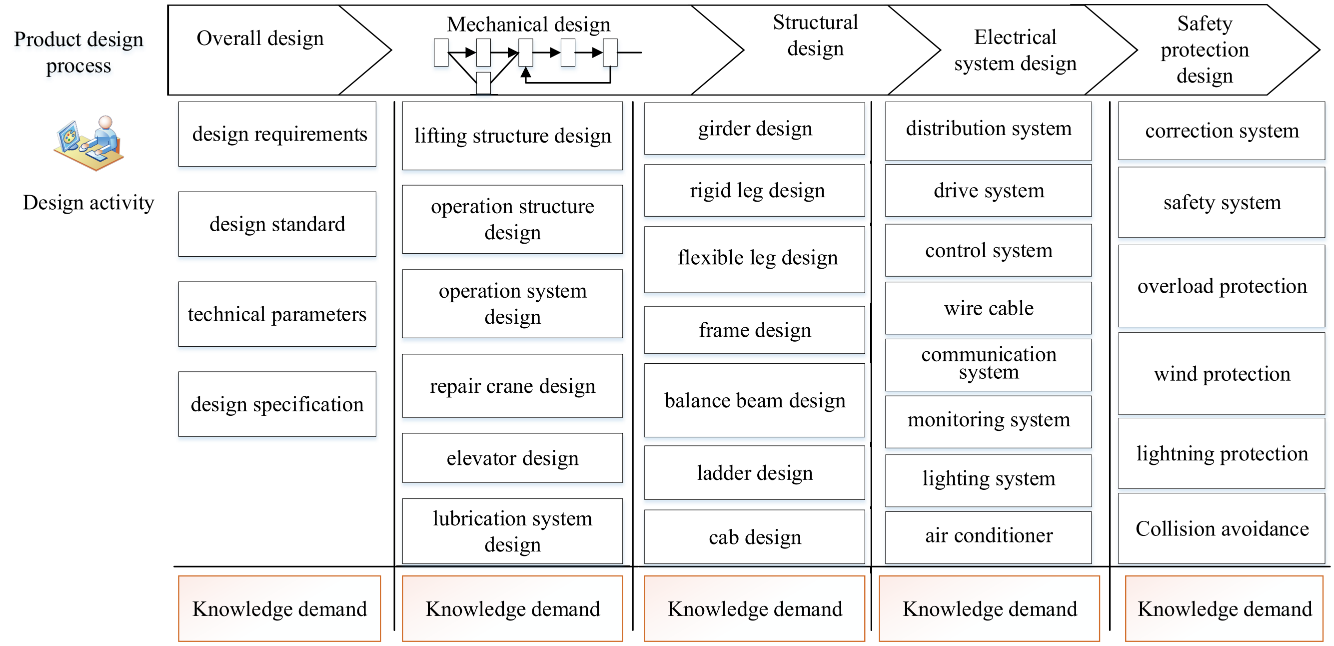

FIGURE 12. Design process of the gantry crane.

product_service, product_assembly, product_development, product_manufacturing, and product_sale.

2) APPLICATION SCENARIOS AND DEMONSTRATION FOR KNOWLEDGE SHARING

During the product development process, engineers need to obtain knowledge to support their development work. Knowledge retrieval can be used as a conventional choice to review and browse related knowledge resources. The knowledge service can also provide a recommender mode to help an engineer to acquire knowledge.

As shown in Figure 14, during the 800t gantry crane design process, a product development engineer starts to browse and obtain knowledge based on the task at hand. There are different design tasks T1, T2, T3 based on the workflow. The engineer gets the assigned design task T3 after logging in to the system, which is the strength analysis of the parts of the trolley in the mechanical system design part. After receiving the design task, the knowledge demands of "common analysis methods of the strength of parts" are generated. The engineer retrieves and learns the knowledge resources in the knowledge repository according to the design task. At the system side, the matched knowledge resources would be determined by the similarity algorithm and provided to the engineer. This closes the loop for the knowledge retrieval process. For the detail of the knowledge sharing process in product development, the reference [5] can provide further description.

The Knowledge object dimension defines knowledge to describe the designed product object. Knowledge objects can be divided into two categories: design object and design process as shown in Figure 13(b). Design object knowledge refers to the support knowledge: *product_ID, part_ID, object_properties, design_teams. Design process knowledge includes design_part_family, production_family, design_activities, design_stage, design_task and process_elements.*

The Knowledge form describes the model of the knowledge resource, which includes know-what, know - why, know-how and know-who knowledge, as shown in Figures 13(c). When an engineer accepts a task and encounters a problem in structure design, this engineer can acquire the knowledge resources from the *Structure* form. It consists of five subclasses: *CAD_Model, CAE_Simulation, Photograph, Product_Drawing, and Sketch.* Further, each subclass can also be divided into subclass.

The ontologies shown above describe the knowledge from three dimensions. To represent knowledge sources uniformly, it is necessary to model an integrated ontology for supporting new product development. In this work, an OWL ontology that integrates the three dimensions is structed by Protégé software 4.3, as shown in Figure 13(d).

Using the method described, knowledge is classified as four types. Once logged into the system, the engineers would get a design task. Then the knowledge requirement is generated. After obtaining the similarity between the requirements and the knowledge resources, the engineers would receive the recommended knowledge list to support their design work.

3) APPLICATION SCENARIOS AND DEMONSTRATION FOR PROCESS OF KNOWLEDGE RECOMMENDATION

To shorten the construction period, a large amount of outfitting work needs to be completed in advance. To reduce the weight of the gantry crane and improve the performance and

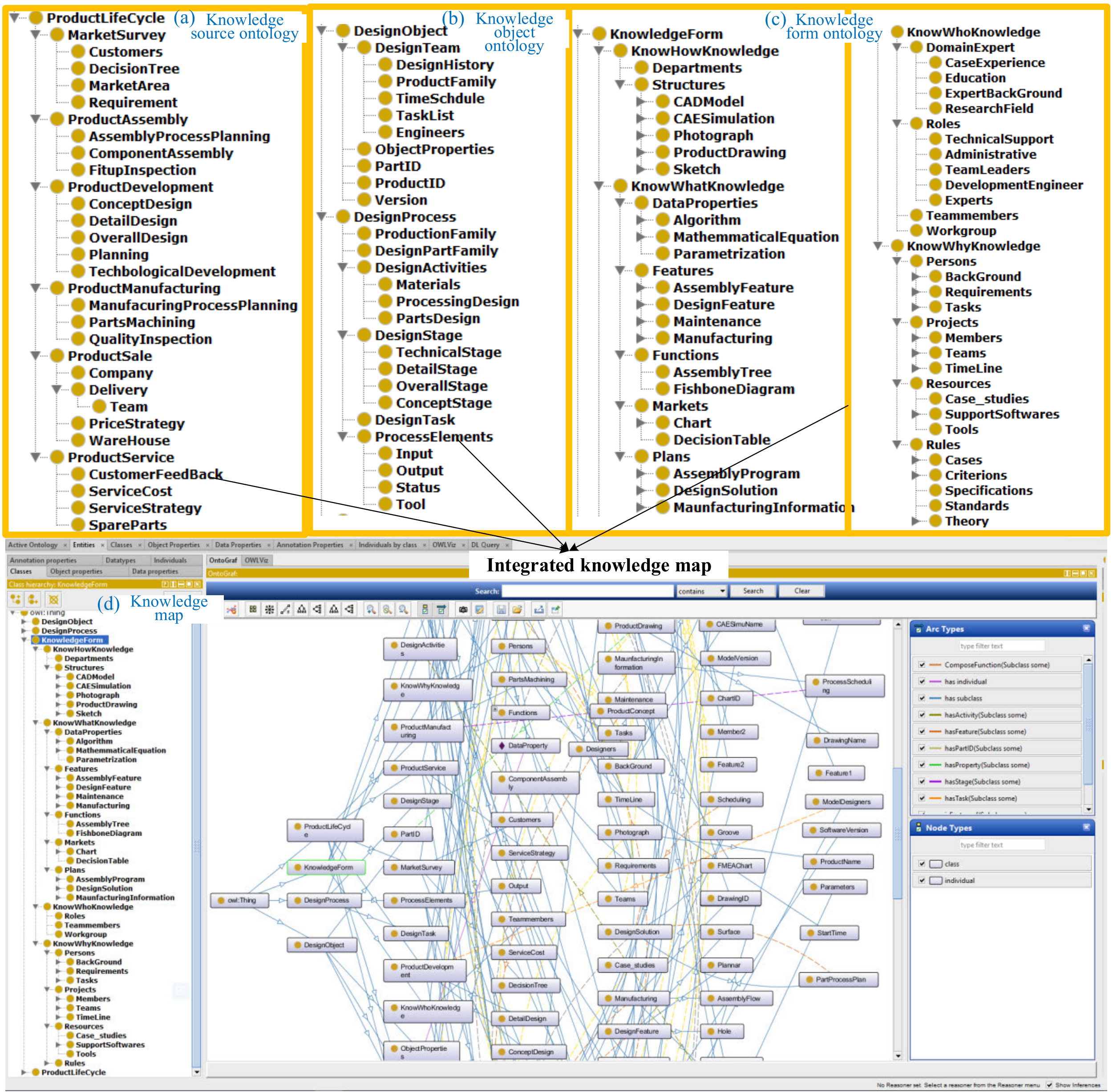

FIGURE 13. Construction of ontology-based knowledge map. (a) Knowledge source ontology, (b) knowledge object ontology and (c) knowledge form ontology integrated into (d) the knowledge map.

reliability of the gantry crane, the newer technologies and newer materials are used in product development.

The record of knowledge reuse in the design process of the trolley on the 800t crane is selected. The knowledge reuse log records are divided into two dimensions, including product design knowledge and design tasks. The design knowledge model contains knowledge objects, design processes, and design objects.

As shown in Figure 15, an engineer is assigned to the design task of ''intensity analysis of the trolley parts'' in the gantry crane mechanical system design. The design purpose is to lower the cost of the trolley on the 800t gantry crane while saving materials. At the same time, the knowledge service system receives the knowledge requirement and determines that it is a design task-based knowledge recommendation. Then the system provides the matched knowledge resource to the engineer based on the recommender rules. Similarly, if the engineer chooses the interest-based mode or expert-based knowledge recommendation mode, the system would provide the appropriate knowledge resources to the engineer according to the knowledge requirements. For the detail of the knowledge recommendation process in product development, the reference [65] can provide further description.

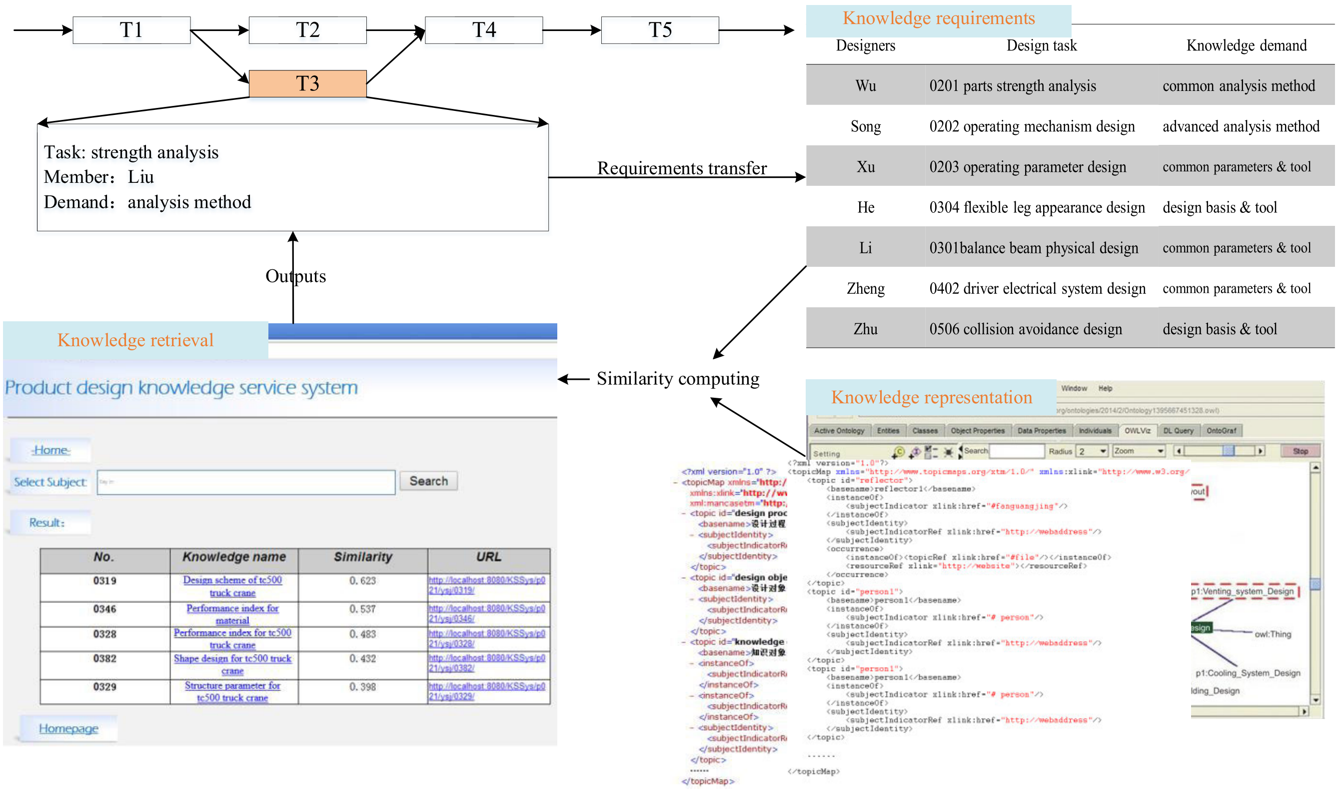

FIGURE 14. Application scenarios and demonstration of knowledge representation and sharing.

4) APPLICATION SCENARIOS AND DEMONSTRATION OF PROCESS OF KNOWLEDGE SERVICE AND EVALUATION

The knowledge service system needs to be continuously improved with its operation. With the accumulation of knowledge, the engineers' knowledge demands also change with time and type of projects. For the long-term development of the system, the performance evaluation of knowledge service system is also necessary and helpful.

As shown in Figure 16, the evaluation criteria for knowledge service is divided into knowledge representation, knowledge integration, knowledge sharing, knowledge recommendation, knowledge service and service platform. After completing the knowledge service matching, the user can receive the knowledge resources to learn and support the product development. Then, the evaluation is conducted, the user's suggestions and measures become a part of the knowledge resources of the knowledge management service platform. The knowledge content is constantly updated following the user's requirements. Therefore, the knowledge service platform will also be continuously improved.

C. EXPERIMENTAL EVALUATION

1) TECHNICAL BENEFITS

In Section 2, some of the currently published frameworks and methods have been summarized and discussed. To compare the potential benefits of this proposed framework, Table 3 compares the proposed and existing approaches. In Table 3, the key technologies for comparison contain knowledge representation, knowledge integration, knowledge recommendation, knowledge service, and service evaluation. Prior studies primarily focus on one or two key technologies for a knowledge service system, seldom provide a comprehensive framework from the product lifecycle perspective. The knowledge service framework proposed in this paper provides a systematic knowledge reuse solution from a product lifecycle perspective.

At present, knowledge service has a very important role in enterprise management. It is also an essential research field in knowledge management. The proposed framework can meet the knowledge demands in the product development process. Engineers can avoid the potential waste of time and resources by obtaining the required knowledge service through time-saving. Applying a thorough theoretical analysis and a demonstration of the gantry crane design, the proposed framework is better for the following reasons:

- A new framework with product lifecycle view of knowledge service has been proposed to support product development.
- The study presents a uniform knowledge representation method to model knowledge resources and integrates the

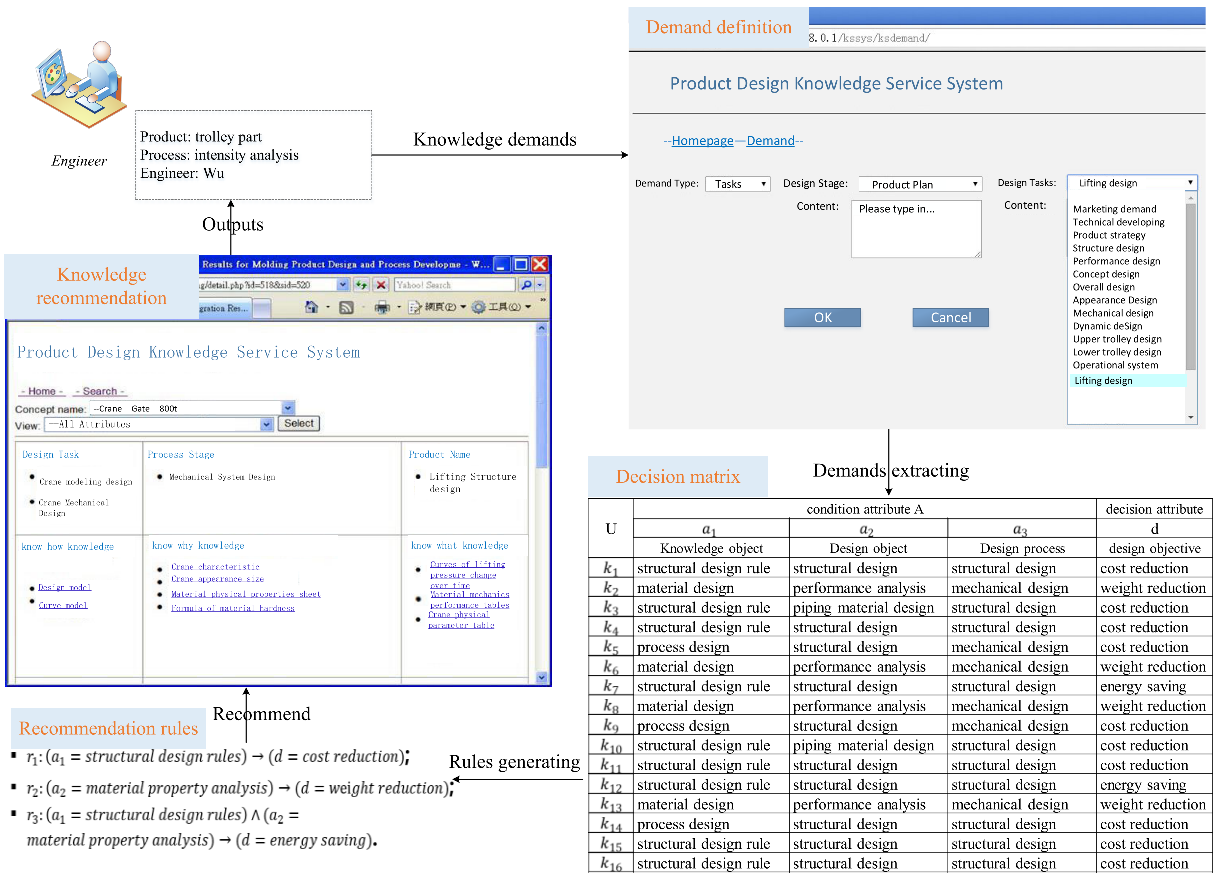

FIGURE 15. Application scenarios and demonstration of knowledge recommendation.

TABLE 3. Comparison between proposed and former approaches.

Knowledge service lifecycle	Brandt [60]	Chen [33]	Bernard [61]	Mountney [62]	Martin [63]	Shaw [64]	*This paper*
Knowledge representation	√	√		√	√	√	√
Knowledge integration	√	√	√	√	√		√
Knowledge recommendation			√		√	√	√
Service evaluation							√
Demonstration example	Product design	Mold product	Foodservice	Internet	Engine	Mechanical product	Manufacturing (Gantry crane)

* *"√" denotes that the framework has the key technology*

mapping relationship between knowledge demands and knowledge resources.

- The study provides a knowledge recommendation method to reduce the time-cost of knowledge browsing in product development.
- A performance evaluation method is proposed in this study to enhance the knowledge service process and quality continuously.

2) PERFORMANCE OF PROPOSED APPROACH

We design an experiment to compare the performance of the proposed framework against the traditional knowledge acquisition process. The traditional knowledge acquisition process uses the product data system. The survey is conducted in the gantry crane design enterprise. The interviewed objects work on the team of marketing, structural design, mechanical system design, electrical system design, and IT support. From the

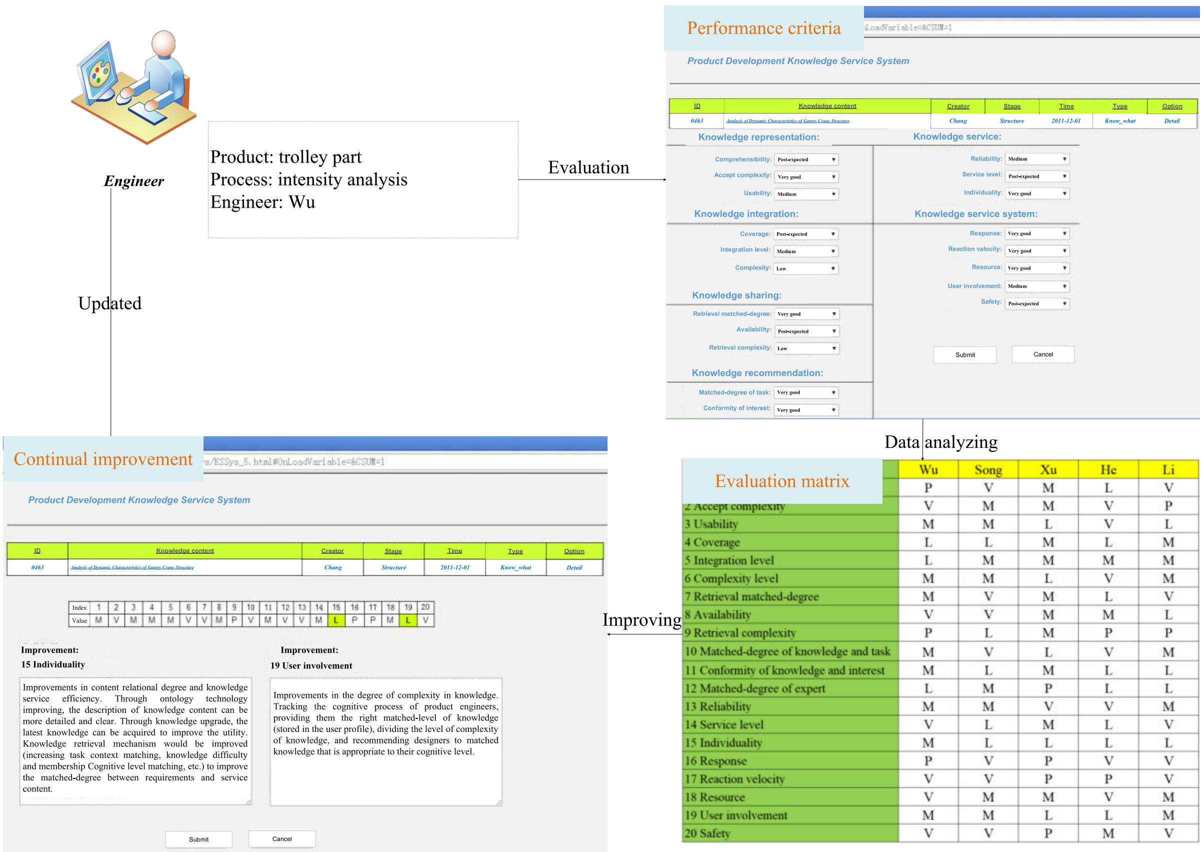

FIGURE 16. Application scenarios and demonstration of knowledge service and evaluation.

TABLE 4. Benefits of the proposed approach.

Comparison	User retrieval time (%)	Utilization (%)	Number of changes
Traditional process	17%	20%	25
Proposed approach	6%	56%	15

* *User retrieval time = time to obtain knowledge/product design time*

survey, around 20% of the product design requires new design solutions. In other words, almost 80% of product design can be obtained from the knowledge repository. Table 4 shows the benefits of the proposed knowledge service system, including the time to obtain knowledge, the knowledge utilization rate and the number of design changes. As shown in Table 4, the time to obtain knowledge for the proposed approach is less than the traditional process. The user retrieval time for engineers is 6% with the proposed approach, and it is 17% in the traditional process. Moreover, the knowledge utilization rate of the traditional approach is less than 30%, and it can reach up to 60% with the proposed framework. The number of changes decreases from 25 to 15, which means the times need to be modified during product design.

VI. CONCLUSION AND FUTURE PERSPECTIVES

This paper proposes an integrated framework which is supported by four pillars of work including the XTM-based knowledge representation, the ontology-based knowledge integration, the task-based knowledge recommendation, and the performance evaluation of knowledge service. The proposed framework provides a lifecycle view of knowledge service. The demonstration of a gantry crane design shows the benefit of firms' implementation and potential of the proposed integrated framework and technology solutions.

The conclusion of this study can be summarized as follows:

- A five-layer framework is proposed from the product lifecycle perspective to help the engineers to gain knowledge, improve the efficiency of problem-solving and design, and reduce the design cost.
- The proposed knowledge service framework integrates the knowledge representation, knowledge integration, knowledge recommendation, and evaluation of knowledge service. It provides a closed-loop knowledge acquisition and reuse solution for enterprises.

- The demonstration of a gantry design shows that the proposed approach can support knowledge reuse during product development. To compare the performance of the proposed framework against the traditional knowledge acquisition process, an experiment is designed, and the proposed framework is better in time to obtain knowledge, the knowledge utilization rate and the number of design changes.

In the future, the potential studies related to this work can be conducted as follows:

(1) With the development of new information technologies, cloud computing, artificial intelligence, and machine learning have become new directions. The proposed system can call on these new information technologies furtherly.

(2) More empirical studies with various types of product development can be conducted to further extend the approach proposed in this paper.

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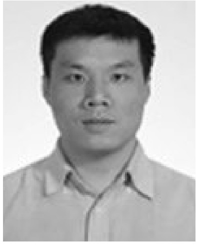

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