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A product-service system using requirement analysis and knowledge management technologies

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Abstract

Purpose – Product-service system (PSS) has been attracting attentions of global manufacturing to providing high-value added services in addition to their traditional product development and manufacturing business. For this reason, it is of great importance to research PSS. The purpose of this paper is to establish a systematic strategy and a system tool for PSS design.

Design/methodology/approach – A requirement-driven product-service system (RdPPS) is developed using requirements analysis and knowledge management technologies. A framework is proposed to support RdPPS by providing tools and methods for requirement analysis and processing, formalization of PSS by ontology-based knowledge representation, reasoning method for PSS solution finding, and solution optimizing and assessing. Finally, the design support strategies for RdPPS are investigated to demonstrate the usability and functioning of the developed system.

Findings – Many conventional design methods did not consider the influence of customer requirements (CRs) during the planning phase of PSS design. Moreover, a broader range of knowledge is required to PSS design, since both products and services are considered.

Research limitations/implications – This research provides a solid foundation for PSS, and promotes an effective means for PSS design.

Originality/value – A RdPSS is presented. CRs are considered during the design phase of PSS as well as both product and service knowledge.

Keywords Product-service system, Aerospace manufacturing, Knowledge technology, Ontology-based representation, Requirement analysis

Paper type Research paper

1. Introduction

The challenges in global competition and environmental problems have been intensified since the last decade. Manufacturing enterprises are recognizing that offering high-value services in addition to products is more important than just providing the physical products (Zhu *et al.*, 2012). As a result, new concepts such as the product-service system (PSS), which is defined as consisting of tangible product

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and intangible services designed and combined so that they jointly are capable of fulfilling specific customer need (Tischner *et al.*, 2002), have been attracting much attention.

In the conventional design methods, there is lack of relationship between physical product and services in the early design phase. Moreover, those methods are usually set up based on the product structure and functional requirements (FRs). The obtained solutions only meet the function of product, without considering the functions of services and the customer requirements (CRs) for services.

As point out in modern mechanical manufacturing industry, enterprise production activities seriously depend on knowledge, which are mainly obtained from previous projects and cases. Compare to product design, a broader range of knowledge is required to PSS design, so both products and services are considered. However, there are no uniform standard packages, access interface, and open architecture as supports, the operation mechanism of knowledge-based PSS is not yet clear. It is difficult to provide methods and tools to support PSS design.

This research aims to develop a requirement-driven product-service system (RdPSS) using requirements analysis and knowledge management technologies, which could be used as a decision-making support tool to offer a means of supporting decision making for PSS design and meet the specific CRs. The framework is proposed to support RdPPS by providing tools and methods for requirement analysis and processing, formalization of PSS by ontology-based knowledge representation, reasoning method for PSS solution finding, and solution optimizing and assessing. Finally, the design support strategies for RdPPS are investigated to demonstrate the usability and functioning of the developed system.

The next section reviews relevant concepts and previous related research in order to provide the rationale of the research objectives. In Section 3, a PSS design methodology is proposed. The main body of this paper contains four key technologies for enabling the proposed PSS. A real case is then described to demonstrate the usability and functioning of the developed system. Finally, conclusions from the research are summarized and further work is discussed.

2. Literature review

PSS was first proposed by Goedkoop *et al.* (1999), which is described as a system of products, services, networks of players', and supporting infrastructure that continuously strives to be competitive, satisfying customer needs, and having a lower environmental impact than traditional business models. In addition to the view of Goedkoop, some similar concepts were proposed, e.g., technical PSS (Aurich and Fuchs, 2004), industrial PSS (Rese *et al.*, 2009), service/product engineering (Sakao *et al.*, 2009), functional products or total care products (Alonso-Rasgado and Thompson 2006), functional sales (Lindahl *et al.*, 2006; Sundin and Bras, 2005), and service-oriented manufacturing (Sun *et al.*, 2008). The following sub-sections will introduce the previous research works and the limitations related to this project.

2.1 PSS

The concept of PSS has been proposed to better exploit the potential benefits of integrating product development with related services. The systematic and scientific framework for configuration and modeling PSS has been investigated in recent years. Lee (2003) proposed an integrated manufacturing framework for the manufacturing and recycling of electronic products. Komoto *et al.* (2005) developed a product lifecycle simulation method to quantitatively analyze PSS. Aurich *et al.* (2006) introduced the concept and the framework of PSS-based PLM, through which lifecycle activities can be systematically considered in an integrated manner. Becker *et al.* (2010) proposed a concept model, which combines service providers with customers as co-creators of value taking place in PSS. Zhu *et al.* (2011) proposed a PSS framework from the aspects of both hardware and software for CNC machine tool. Sakao and Shimomura (2007) and Sakao *et al.* (2009) introduced the concept of service engineering as a new discipline for PSS design, and implemented a computer-aided design tool called service explorer.

The design process of PSS has also been explored in recent years. One common approach is given as follows (Tischner and Vezzoli, 2009; Muller and Stark, 2010; Aurich and Fuchs, 2004):

1. Customer analysis: in this phase, designers acquire the CRs, and then the FRs, and engineering characteristics (ECs) of product and service are identified by analyzing the CRs. The relationships between CRs, FRs, and ECs can be modeled by the mapping relationships.
2. PSS conceptual design: based on the identified CRs, FRs, and ECs, the conceptual ideas of PSS are generated with, for example, case-based reasoning, and knowledge reasoning. The most semantically similar conceptual ideas will be determined as the reference ideas for the specific CRs.
3. PSS detailed design: after evaluating the reference ideas, designers deploy each selected PSS idea to a detailed structure. Then detailed specifications of entities to realize PSS ideas are defined.

In conclusion, the researches about PSS are vast in range, including market investigation, design, manufacturing, sale, and recycle. The researches cover nearly the whole production and operation management. Although many engineering technologies and methods of product and service have been applied in the field of PSS, most researchers only focussed on the definition, architecture, organization, and implementation mechanism of PSS, only a few reported the PSS design with considering whether the results can satisfy the specific CRs and the implementation technology of PSS design approach.

2.2 Limitations

Compared to the traditional design methods, the design objects of PSS are extended from single product to combination of product and service. Considering the complexity and diversity of the PSS design, two limitations are pointed out as follows:

1. The heterogeneity of design objects: it primarily refers to the heterogeneity, compositionality, and compatibility of design objects. In engineering practice, requirements of customers are not only limited to features of product, but also encompass the functions and results of service activities. However, as the two different types of objects of PSS, product, and service have typical characteristics of heterogeneity. It is result that many researches focus on the integration design of product and service, to satisfy the specific requirements and complete the engineering design tasks. Moreover, as a combination of product and service, some problems of matching the physical and intangible service should also be solved.

(2) The complexity of the process of design: including the interaction of design process, and the diversity of decision making. Considering that PSS is a combination of physical products and intangible services, there are interaction and association relationships existing between products and services in PSS, both influence factors of products and services should be considered in the design process. Therefore, beside of describing the product structures and service activities, knowledge of the interaction and integration relationships between products and services should also be systematically represent. However, product diversity and service diversity led to the diversity of PSS solutions, increasing the complexity of the process of design.

In view of the above-mentioned facts, two technical problems are studied in this research. First, how to realize the product and service integrated design by mapping the relationships among requirements, functions and characteristics of products and services. The other is how to develop a knowledge-based support system for PSS solutions generation.

3. The proposed methodology

In this research, a RdPSS will be developed using requirement analysis and knowledge management methodologies. The factors of CRs will be incorporated, and exert their significant impacts to the implementation and performance of RdPSS. A systematic decision-making approach will be used to identify the relative prioritization of ECs. By introducing ontology as domain knowledge base, an ontology-based knowledge representation framework will be developed for the representation and reuse of knowledge unambiguously, which realizes the knowledge originated from the current and previous service processes. A knowledge-based design support system is proposed, which is used to support the acquisition of PSS solutions design. The proposed PSS is web based, and will offer a means of supporting decision making for PSS solution finding. Figure 1 shows the framework of PSS design, which can be divided into four steps as explained below:

- Step 1. Requirements analysis: as shown in the middle of Figure 1, main tasks include acquiring the requirements from designers, manufacturers, service providers and customers, and identifying satisfactory ECs using requirements analysis methodologies. The redundant ECs will be reduced, and the weightings of reduced ECs will be defined accurately. The requirement management here is seen as one of the functional modules of the proposed PSS.
- Step 2. Ontology-based knowledge representation: as shown in the bottom of Figure 1, ontologies are built to represent, accumulate and store knowledge and experience generated during product and service design activities. Ontology-based knowledge representation is proposed to collect and formalize existing design cases and store them as formalized knowledge cases in the knowledge repository.
- Step 3. Knowledge reasoning: the knowledge-based method is used here to help and support engineers for PSS solution finding. When the required PSS activities are identified and formalized by referring to the predefined ontology, the formalized PSS will be reasoned in the knowledge repository to find semantically similar PSS cases.

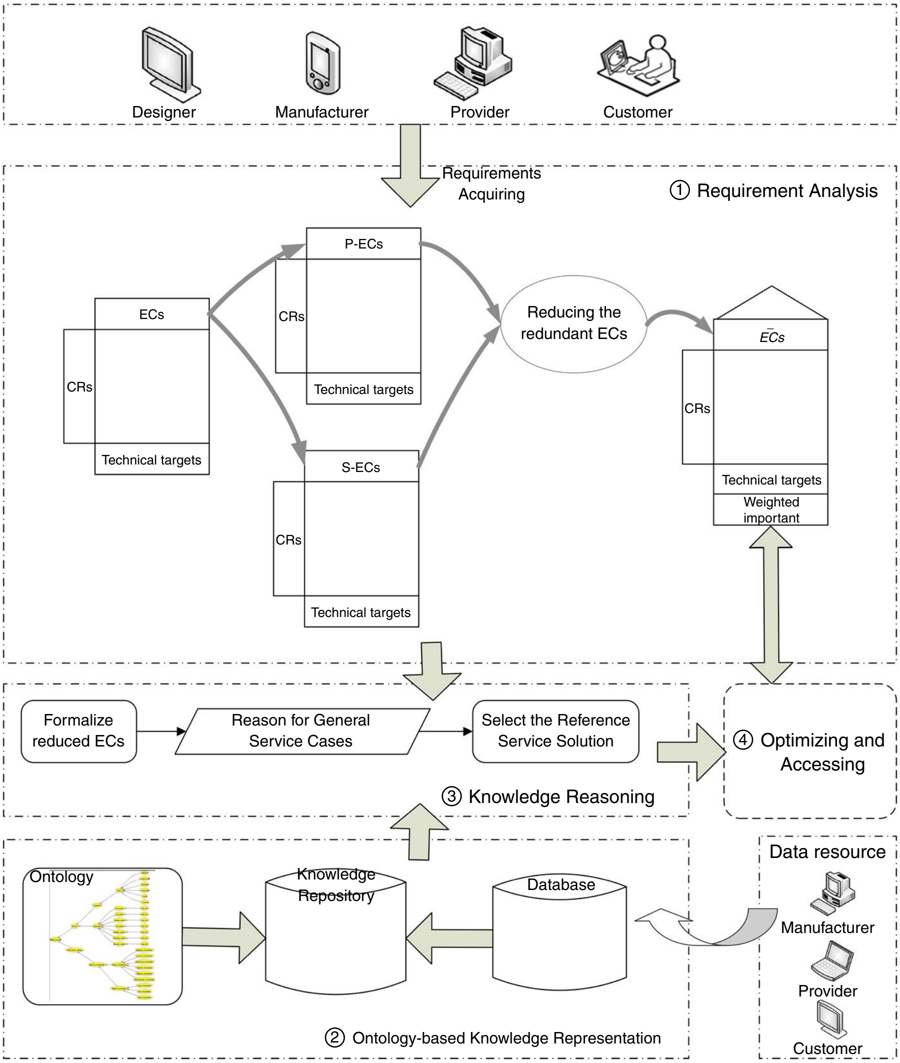

Figure 1.
Framework of PSS design

- Step 4. Optimizing and assessing: when the reference solutions are determined, some factors have been considered to evaluate whether these solutions are viable. An algorithm has been developed and described to calculate the overall performance of a reference solution by considering the evaluation criteria. The higher the score a solution gets, the more possibility that the solution will be chosen.

Four key techniques/methods have been used in the proposed PSS, i.e., first, how to determine the weightings of ECs by analyzing the requirements; second, how to represent the PSS activities and the relationships between them by predefined ontology; third, how to reuse the knowledge which are collected from previous PSS cases, and use the knowledge reasoning method to find the similar generally cases in the knowledge repository; and fourth, how to assess the reference PSS solution and find the optimal solution for the specific requirements. The techniques and methods used in the four steps are further explained in the following sections.

4. Requirements analysis (Step 1)

It is not easy to identify satisfactory ECs, since the information in the early stage of PSS planning is subjective, qualitative, and even uncertain to engineers. Therefore, we used requirement analysis technologies to acquire voices of customer, identify general requirements and the relationships among these requirements, transfer CRs to ECs, and determine the final important rating of ECs. Each EC will be used as an evaluation index to evaluate and assess the reference service solutions. As a well-known planning and problem-solving methodology, quality function deployment (QFD) is used to support PSS design in this research. The procedure, starting from requirements acquiring to the prioritization stage, is described as follows:

1. Acquire customer voices or requirements from customers and market: the mentioned requirements here include internal requirements and external requirements. The internal requirements consist of the requirements emerged during different phases of product lifecycle, e.g., design, manufacturing, usage, disposal. The external requirements are not only customers' requirements, but also providers' and partners' requirements. The methods of acquiring the requirements are mainly by survey, interview, and internal reports.
2. Develop ECs from CRs based on house of quality (HoQ) model in QFD: HoQ model is primarily used to describe the relationships between and within CRs and ECs. After acquiring the CRs, the FRs will be identified by analyzing the CRs. Then, the FRs in the functional domain will be translated into ECs using QFD approach, including product-related ECs (P-ECs) and service-related ECs (S-ECs). A set of ECs candidates will be determined, some of the ECs candidates may be redundant, and the conflict relationships between the ECs candidates may also exist. Therefore, the further selection from the ECs candidates is essential.
3. Reduce the redundant ECs: to identify the most important characteristics and remove the unnecessary ones in the EC set. Rough set theory as a relatively intelligent knowledge discover tool is used to evaluate the important of ECs, reduce the number of redundant ECs, and seek the minimum subset of ECs. The new EC set produced by attribute reduction, can fully characterize the knowledge. The redundant ECs can be thought of as a sufficient set of ECs.
4. Determine the relative weightings between CRs and the reduced ECs: a relationship between CRs and ECs is defined as "a decision matrix." A decision matrix is created combining the result of the computation with calculated CRs. QFD method is used to obtain the importance weights of ECs based on CRs and relationships modeled in the HoQ. In order to accurately define the importance weights of ECs, the inter-dependency relationships between CRs and ECs (including P-ECs and S-ECs), the inter-dependency relationships between P-ECs and S-ECs, and the inner-dependency relationships among these three clusters should also be taken into consideration in QFD analysis.

(5) Calculate the overall weight of each ECs: to define the importance weights of ECs accurately, analytic network process (ANP) method is used to form a network considering the interactions at different levels. Moreover, the relative weights of each EC will be calculated by ANP method.

(6) Determine the final important rating of ECs: the final weights of ECs are obtained based on QFD and HoQ. The technical targets of ECs are also determined. The most important ECs will be formalized by referring to a set of predefined ontology, and reasoned in the knowledge repository of the proposed PSS to find semantically similar generalized MRO service cases. The technical targets will be used to evaluate and assess the reference service solution and find the optimal solution for the specific requirements.

5. Knowledge representation (Step 2)

5.1 A knowledge-based design support system

It is identified that knowledge, which is critical to the company's business, is not systematically managed. Although members of staff recognize the value and importance of their knowledge from previous design cases, there is a lack of method to reuse it to solve current design problems. It is also found that there is a lack of systematic method to evaluate PSS solutions which currently depend on individuals' experience. In this paper, the proposed knowledge-based design support system is developed to solve the problem that knowledge could not be identified and reused easily during product and service design activities (see Figure 2). This system includes PSS design workspace and knowledge base. A PSS model is designed in the PSS design workspace, which could be used to identify the concealed knowledge items within activities from each phase of product design and service process development. The knowledge base consists of knowledge obtained from the previous PSS and product/service cases, which are collected from various sources including different information systems and functional departments.

To reuse the knowledge appeared in the product and service design activities, a body of formally represented knowledge is described based on a conceptualization: the objects, concepts, and other entities that are assumed to exist in the product and service design activities and the relationships that hold among them (Genesereth and Nilsson, 1987).

The ontology techniques are introduced in this study to model the identified knowledge. The term ontology is used to mean a specification of a conceptualization, which is viewed as a formal explicit description of concepts in a domain of discourse concepts (sometimes calls classes), properties of each concept describing various features and attributes of the concept (properties), and restrictions on slots (sometimes called role restrictions). An ontology together with a set of individual instances of classes constitutes a knowledge base.

PSS domain ontology is developed to collect and formalize previous PSS/service cases, and store them as generalized knowledge into the knowledge base in this research. The predefined ontologies can represent the semantic information and relationships between functional modules and process modules, as well as the relationship information between them. The solution for ontology management is shown in Figure 3, which mainly involves ontology defining and modeling, and semantic similarity evaluation, which is explained further below.

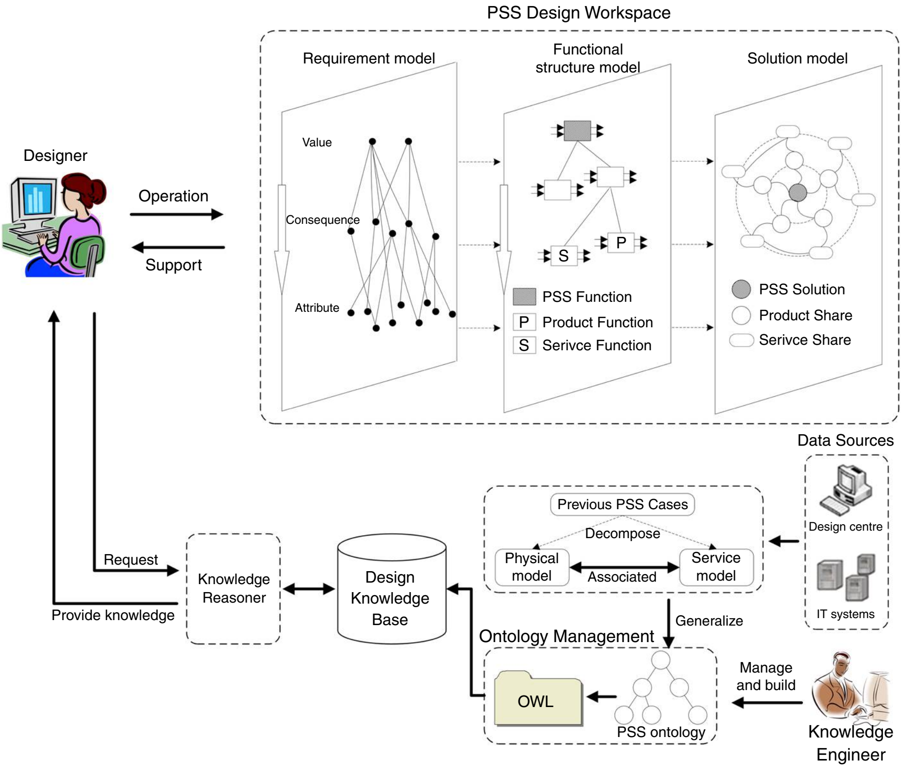

Figure 2.
A concept sketch of knowledge-based design support system

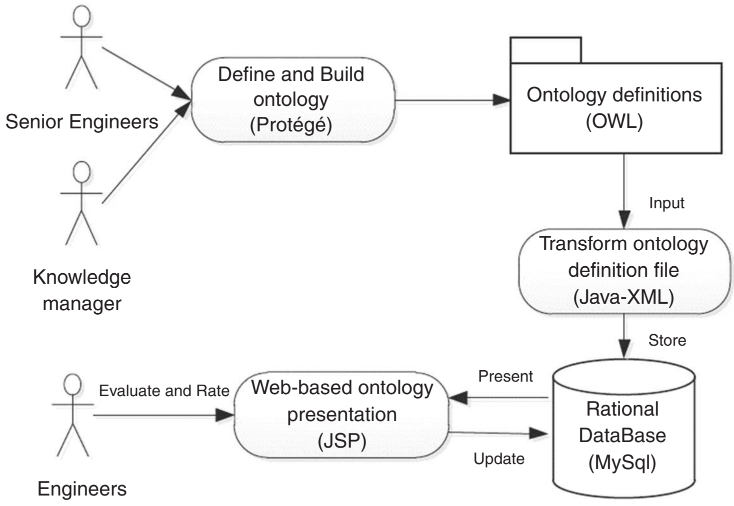

Figure 3.
Solution for ontology management

5.1.1 Ontology definition and modeling. The concepts used in the design processes will be defined by knowledge managers and senior engineers (see Figure 3). The mentioned concepts here involve two parts, i.e., the predefined part and extended part. The former can be considered as general engineering concepts, which is normally in higher level of abstraction. The latter means the specific concepts, which is used in the company and generated based on the predefined concepts.

Suppose that the formalization of ontology can be described as: O = (S, I, P, RS). Where O represents the ontology; S represents the collection of all concepts, each concept in S can be regarded as a class, and the class is inherited by subclass that represent concepts that are more specific than the superclass; I represents the instances of the class; P represents properties of classes and instances; RS represents the relationship between two concepts, i.e., part_of, has_part, sibling_of, attribute_of, has_attribute, instance_of, has_instance, and so on. Protégé is adopted as an ontology editor to formalize predefined ontology in computer language, which was developed by Stanford University and used in the academic area for ontology development (Bradfield and Gao, 2007). By using the tool, the ontology is formalized with object web language (OWL) specifications.

Physically it is stored in an extended mark-up language (XML) file, as shown in Figure 3. As a language for defining and instantiating web ontology, OWL is used to describe the concepts and relationships that are inherent in web documents and applications (Ebrahimipour *et al.*, 2010). Compared to other languages and standards, such as XML and resource definition language (RDF), OWL has more facilities for expressing meaning and semantics (Smith *et al.*, 2004). Then, the ontology definition file is processed and transformed using Java technologies. The transformed ontology will be stored in a rational database, and be used with other parts of the system.

5.1.2 Evaluation of semantic similarities of concepts. The main aim is to evaluate and rate semantic similarities between concepts. The rated ontology will be used in the knowledge repository management, and used to find the solutions and support decision making in other parts of the system. The evaluating and rating work will be conducted by engineers in the related departments (see Figure 3). The rules of evaluation and rating are described below, which are carried out in two tasks: first, evaluate and rate semantic similarities between the parent concept and its child concepts; and second, evaluate and rate semantic similarities between sibling concepts.

Figure 4 represents hierarchically ontological definition of a group of concepts. The higher of levels a concept stays in, the more general semantic meaning it represents. While in lower level, the semantic meaning of a concept is more specific.

Suppose that S represents a set of services: $S = \{S_1, S_2, S_3, \ldots, S_n\}$, where S_1 consists of a set of service activities and their functions. P represents a set of processes of service: $P = \{P_1, P_2, P_3, \ldots, P_n\}$. F represents a set of function of service: $F = \{F_1, F_2, F_3, \ldots, F_n\}$. SP represents the sub-process of service, P_1 consists of $\{SP_{11}, SP_{12}, SP_{13}, \ldots, SP_{1n}\}$. P_1 is the parent of SP_{11} and SP_{12}, S_1 is the parent of P_1 and F_1, P_1 and F_1 are siblings. The relationships are described as: $SP_{11} \in P_1$; $SP_{12} \in P_1$ and $P_1 \in S_1$; $F_1 \in S_1$. Figure 5 represents hierarchically ontological definition of a group of concepts. The higher of levels a concept stays in, the more general semantic meaning it represents. And the semantic meaning of a concept is more specific in lower levels.

```
<?xml version="1.0"?>
<rdf:RDF
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
       …
  xml:base="http://www.owl-ontologies.com/Ontology1320411757.owl">
  <owl:Ontology rdf:about=""/>
  <owl:Class rdf:ID="Service">
    <rdfs:subClassOf>
      <owl:Class rdf:ID="MRO_service"/>
    </rdfs:subClassOf>
  </owl:Class>
  <owl:Class rdf:about="#Product">
    <rdfs:subClassOf rdf:resource="#MRO_service"/>
  </owl:Class>
  <owl:Class rdf:about="#Resource">
    <rdfs:subClassOf rdf:resource="#MRO_service"/>
  </owl:Class>
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    <rdfs:subClassOf rdf:resource="#MRO_service"/>
  </owl:Class> <owl:Class rdf:ID="Component">
    <rdfs:subClassOf>
      <owl:Class rdf:ID="Product"/>
    </rdfs:subClassOf>
  </owl:Class>
   <owl:Class rdf:about="#Subsystem">
    <rdfs:subClassOf rdf:resource="#Product"/>
  </owl:Class>
  …

 </rdf:RDF>

<!-- Created with Protege (with OWL Plugin 3.4.7, Build 620)
http://protege.stanford.edu -->
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Figure 4.
Snippet of the XML file

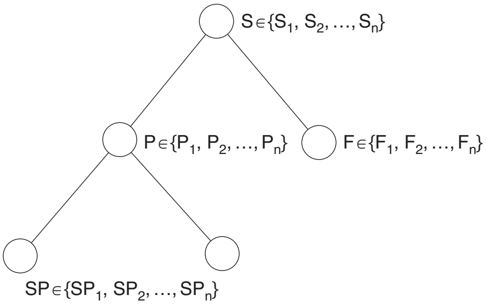


Figure 5.
Comparison of semantic meanings between concepts

Suppose that the number of engineers who are going to evaluate and rate the similarities between concepts is m. Each engineer will be given the credibility by the knowledge manager according to their engineering experience, which is represented as $C = \{C1, C2, C3, \ldots, Cm\}$, more experienced engineers have higher credibility. Taking an example of calculate the semantic similarity between S_1 and P_1. The final result of semantic similarity Sim (S1, P1) can be represented as follows:

$$Sim(S_1, P_1) = \frac{\sum_{i=1}^{m} C_i \times Sim(S_1, P_1)_i}{\sum_{i=1}^{m} C_i} \tag{1}$$

The similarity of the sibling classes (F_1 and P_2) can be represented as the following equation:

$$Sim(F_1, P_2) = \left\{ \begin{array}{l} \frac{\sum_{i=1}^{m} C_i \times Sim(F_1,S_1)_i}{\sum_{i=1}^{m} C_i} \times \frac{\sum_{i=1}^{m} C_i \times Sim(S_1,P)_i}{\sum_{i=1}^{m} C_i} \\ \times \frac{\sum_{i=1}^{m} C_i \times Sim(P,S_2)_i}{\sum_{i=1}^{m} C_i} \times \frac{\sum_{i=1}^{m} C_i \times Sim(S_2,P_2)_i}{\sum_{i=1}^{m} C_i} \end{array} \right\} \tag{2}$$

5.2 Ontology-based knowledge representation

To represent, accumulate and store knowledge and experience generated during the design activities, an ontology-based knowledge representation framework has been proposed to collect and formalize PSS cases from engineers' everyday work and store them as formalized knowledge in the knowledge repository, as shown in Figure 6.

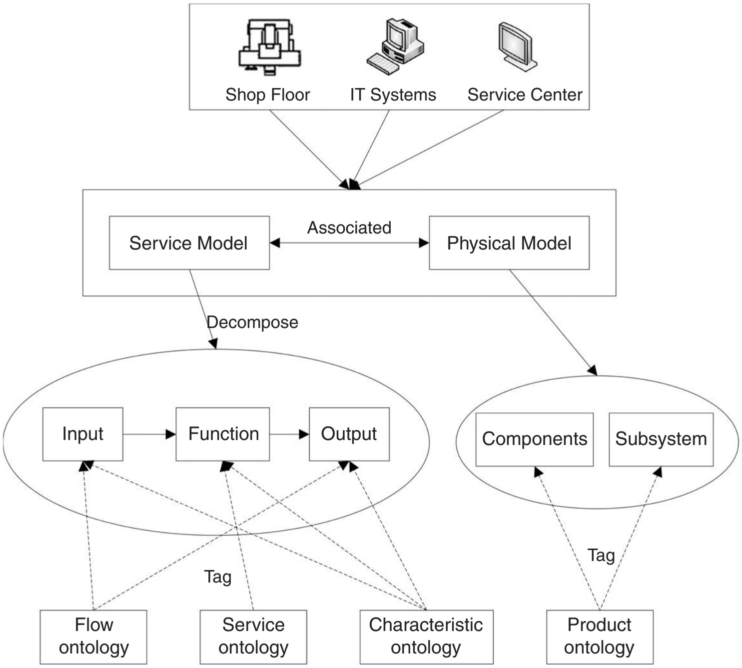


Figure 6.
Ontology-based knowledge representation

The proposed system is developed for the reuse of knowledge unambiguously, which realizes the knowledge originated from the design activities and conducted design activities. In this system, previous design cases are collected from various sources including different information systems and functional departments. The PSS design activities can be synthesized in two models: the service model and physical model. The service model describes the functions of service activities as well as the service processes, which can be further decomposed into an input-function-output model. The physical consists of components and design documents, and describes the places where services occur. The predefined ontology can be used to tag each element of the functional model and physical model, and then the whole design activities with tagged semantic meaning can be stored in the knowledge repository. As depicted in Figure 5, the input and output flows are tagged with flow ontology and the effective characteristics that matters in the functional model. The function is tagged with concepts of service ontology to denote its semantic meaning of functionally. The component is tagged with product ontology to denote the components where service occurs. The knowledge representation method will be applied to enable the proposed PSS that can provide users with various functions that are searching, sharing, and reusing information in the distributed environments.

6. Knowledge reasoning for solution finding (Step 3)

The reasoning method is critical to finding reference solutions for PSS conceptual design. One of the most important steps in the reasoning method is to analyze semantic similarities between formalized PSS design cases and generalized design cases stored in the knowledge repository.

The similarity between concepts of PSS is calculated as the similarity between semantic expressions of concepts. As mentioned in Section 5.1.1, domain ontology is developed to represent the semantic information and relationships between modules.

The similarity between concepts of target PSS model and reference PSS case can be calculated with the following equation:

$$\begin{aligned}\mathrm{Sim}(C_T,\ C_B) &= \mathrm{Sim}(P_T,\ P_B)\times \mathrm{Sim}(F_T,\ F_B)\\ &= \sum_{1}^{n}\mathrm{Sim}(SP_{1nT},\ SP_{1nB})\times\sum_{1}^{m}\mathrm{Sim}(SF_{1mT},\ SF_{1mB})\end{aligned}$$

where $\mathrm{Sim}(C_T, C_B)$ represents the similarity between concepts of target PSS model C_T and reference PSS case C_B which is stored in knowledge base. $\mathrm{Sim}(P_T, P_B)$ represents the similarity between concepts of physical contained in C_T and C_B. $\mathrm{Sim}(F_T, F_B)$ represents the similarity between concepts of services contained in C_T and C_B. Sim (SP_{1nT}, SP_{1nB}) represents the similarity between concepts of characteristic of physical contained in target PSS concept model C_T and reference PSS case C_B. $\mathrm{Sim}(SF_{1mT}$, $SF_{1mB})$ represents the similarity between concepts of element of service model contained in target PSS concept model C_T and reference PSS case C_B. The EDR electronic dictionary method is used in this paper to calculate the distance between vocabularies in the ontology (2001), which provides the relations among basic vocabularies. Each concept is basically described with "verb (predicate) + noun (object)." Then, the similarity between concepts can be calculated as following.

$\mathrm{Sim}(C_T,\ C_B) = \left\{\mathrm{dist}(ObjSP_T, ObjSP_B) + \mathrm{dist}(PreSP_T,\ PreSP_B)\right\} \times \left\{\mathrm{dist}(ObjSF_T,\ ObjSF_B) + \mathrm{dist}(PreSF_T,\ PreSF_B)\right\}$ Therefore, the most semantically similar PSS solutions will be generated by the above reasoning method.

7. Optimizing and assessing (Step 4)

When the reference PSS solutions are determined, it is important for engineers to evaluate whether these solutions are viable. There are some factors to be considered when a solution has been proposed, including development time, development cost, development risk, and functional compatibility. These factors are critical to the success of the service activity. Without consideration of these factors, even if a solution is technically perfect it may still lead to failure of the project as a whole.

For each reference solution generated from methods described above, its development time, cost, and risk are reviewed using information/knowledge acquired from related systems or technical documents. The values of these factors are compared with the original requirements for development time, cost, and risk which are identified by requirement analysis, and also with other alternative reference solutions. As to functional compatibility, it means the extent to which and how much the reference solution meets the original requirements. The reduced ECs which are identified by requirement analysis will be considered as important factors to evaluate and access the functional compatibility.

With the help of knowledge base of the developed system, engineers can find knowledge regarding development time, development cost, and development risk of the specific service task. An algorithm has been developed and described below to calculate the overall performance of a reference solution by considering those solution evaluation criteria. The higher the score a solution gets, the more the possibility that the solution is chosen. The formula below is used to calculate the impact (CI) of a reference solution:

$$CI = \sum_{j=1}^{\mathrm{n}} \left\{ wc_j \times \left[\alpha\left(\frac{T_j'}{T_j}\right) + \beta\left(\frac{CT_j'}{CT_j}\right) + \gamma\left(\frac{R_j'}{R_j}\right) \right] \right\} + \sum_{i=1}^{m} \left(wf_i + \frac{EC_i'}{EC_i} \right) \qquad (3)$$

This formula takes all the four criteria into consideration. Parameters in this formula are explained as follows: integer j∈[1, n] is the number of components where service occurs; integer i∈[1, m] the number of reduced ECs; $\mathrm{wc_j}$ the relative importance of a component; $\mathrm{wf_j}$ the relative importance of a EC; T'_{j}, CT'_{j}, R'_{j}, EC'_{i} the developing time, cost, risk, and technical target of ECs of reference solution; T_j, CT_j, R_j, EC_{i} the development time, cost, risk, and technical target of ECs of the original requirement; and α, β, γ the coefficients of development time, cost and risk, where $\alpha + \beta + \gamma = 1$. Values of α, β, and γ are determined by designers according to the service project aims. For example, if the project is time sensitive, then α will be assigned a relatively larger value; if the project is cost sensitive then β will be assigned a relatively large value; or if the quality of the product is critical then γ will be assigned a larger value.

Relative importance of a component can be acquired by comparing with other components within the same domain, which has been described in above. The relative importance of an EC is calculated using the ANP method.

8. Case study

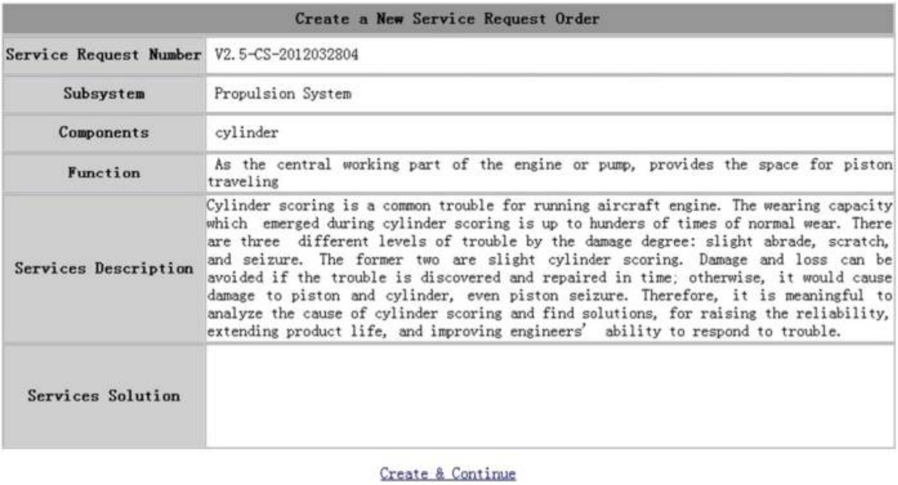
Application of the methodology has been partially displayed during the discussion of the methodology. The overview of the results and general process has been described in an intuitive way as below.

A three-tier web-based pilot system has been developed to implement the proposed methodology for PSS design. The prototype system is partly developed. Software tools involved in this prototype include MySQL as an infrastructure of data storage, Tomcat 6.0 as a web server and servlet container, Eclipse 3.3 as a multi-language software development environment, JavaServer Page as a Java technology to serve dynamically generated web pages, Protégé as an ontology editor and a knowledge acquisition system.

An industrial application is used in this project for demonstrating the usability and function of the proposed methodology. The example is a real case which happened in the service operation for an aircraft engine. The case study focusses on developing a knowledge-based support system for PSS design, and generating the PSS solutions to satisfy the specific CRs. The industrial example used in this research is an aircraft engine, which is a critical part of an aircraft. Cylinder scoring is a common trouble for running aircraft engine. The wearing capacity which emerged during cylinder scoring is up to hundreds of times of normal wear. There are three different levels of a problem by the damage degree: slight abrade, scratch, and seizure. The former two are slight cylinder scoring. Damage and loss can be avoided if the problem is discovered and repaired in time; otherwise, it would cause damage to piston and cylinder, even piston seizure. Therefore, it is meaningful to analyze the cause of cylinder scoring and find solutions, for increasing the reliability, extending product life, and improving engineers' ability to respond to the problem.

A new request service order is created while the requirement information is collected from the customers (the customers are especially refer to airlines), as shown in Figure 7. The order contains information such as service request number, subsystem, component, function, and service description. When the information is filled, the service request order can be created, and go to the next stage. The ECs can be identified by requirement analysis, such as the temperature of the cooling water, the inner surface finish and precision of the cylinder liner, cylinder liner taper and ovality, piston installation position, octane number, cylinder lubrication degree, water and lubricating oil temperature, flows of pump, blowing rate, fan belt firmness, fan installation position, cylinder liner outside wall scale, water level, and so on. After that, the FR model and physical structure model will be built, and uploaded into the system.

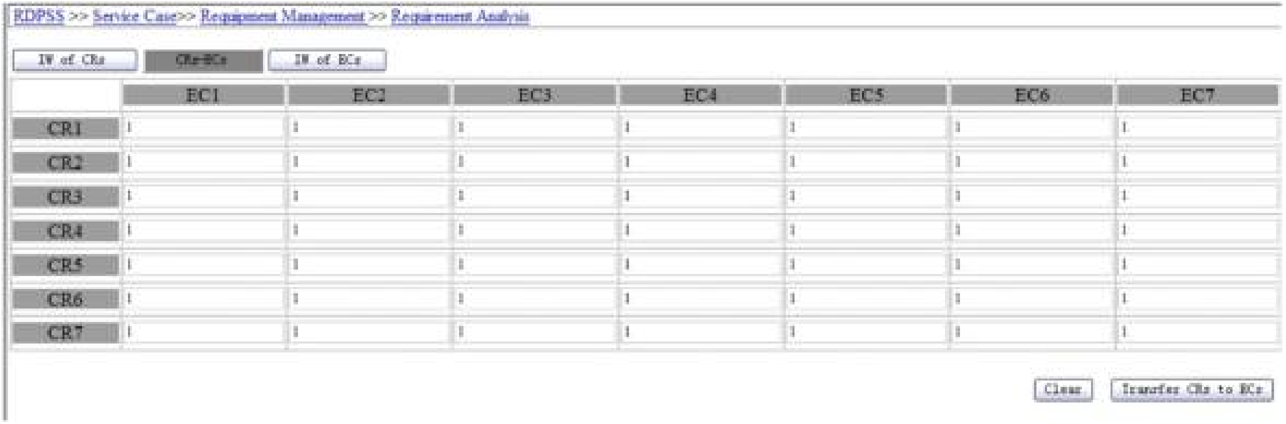
Once a service order has been created, the engineer assigned with this task will analyze the CRs, and obtain the accurate CRs. The CRs will be translated into ECs using QFD-enable method. Figure 8 is the interface of translating CRs



Create a New Service Request Order

Service Request Number	V2.5-CS-2012032804
Subsystem	Propulsion System
Components	cylinder
Function	As the central working part of the engine or pump, provides the space for piston traveling
Services Description	Cylinder scoring is a common trouble for running aircraft engine. The wearing capacity which emerged during cylinder scoring is up to hunders of times of normal wear. There are three different levels of trouble by the damage degree: slight abrade, scratch, and seizure. The former two are slight cylinder scoring. Damage and loss can be avoided if the trouble is discovered and repaired in time; otherwise, it would cause damage to piston and cylinder, even piston seizure. Therefore, it is meaningful to analyze the cause of cylinder scoring and find solutions, for raising the reliability, extending product life, and improving engineers' ability to respond to trouble.
Services Solution	

Figure 7.
Service order creation



RDPSS >> Service Case>> Requirement Management >> Requirement Analysis

	EC1	EC2	EC3	EC4	EC5	EC6	EC7
CR1	1	1	1	1	1	1	1
CR2	1	1	1	1	1	1	1
CR3	1	1	1	1	1	1	1
CR4	1	1	1	1	1	1	1
CR5	1	1	1	1	1	1	1
CR6	1	1	1	1	1	1	1
CR7	1	1	1	1	1	1	1

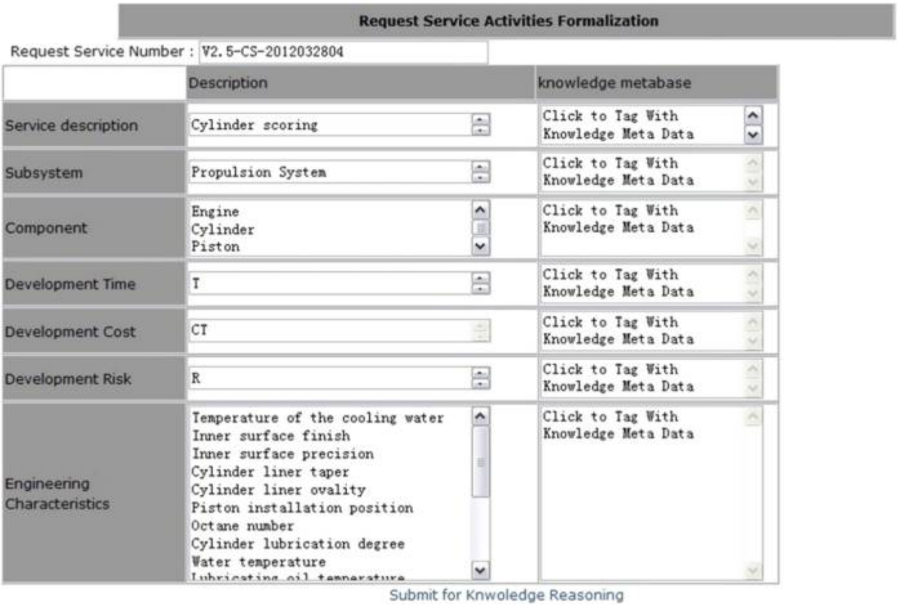
Figure 8.
Customer requirement management interface

into ECs. Then, a decision matrix is created combining the result of the computation with calculated CRs. The final weights of ECs are obtained by calculating the decision matrix maximum eigenvalue. The ECs will be used as evaluation index to evaluate and assess the reference service solution and find the optimal solutions for specific CRs.

Figure 9 shows the interface of the system for PSS model formalization with predefined ontology. The service activity can be decomposed into function, inputs, outputs, resources, constraints, relationships between service functions and service processes, each of them will be tagged with predefined ontology. The development time, cost, risk and characteristics of flows and functions that are considered as impact factors are also formalized with predefined ontology.

After selecting concepts for each part of the decomposed PSS model, the form needs to be submitted for knowledge reasoning. Figure 10 shows an overview of the system interface. This page shows the final stage of reasoning in the system to retrieve the most semantically similar cases as reference solutions. Clicking the hyperlink in the suggested solutions, a popup window will appear which presents the details of the solutions.

When the reference service solutions are retrieved, engineers should evaluate and assess the reference service solutions and find the optimal solutions for specific CRs. An evaluation index system is built to solve the problem that customers expect so that multiple targets obtain optimal performance in the given feasible region. The important ratings of evaluation index are calculated by QFD-enabled method. Figure 11 is the interface of the evaluation criteria. After importing the important ratings of the evaluation index, engineers can choose from the prioritized list of reference solutions by calculating the impacts of critical factors. Figure 12 is the result of the example processed in the knowledge-based PSS.

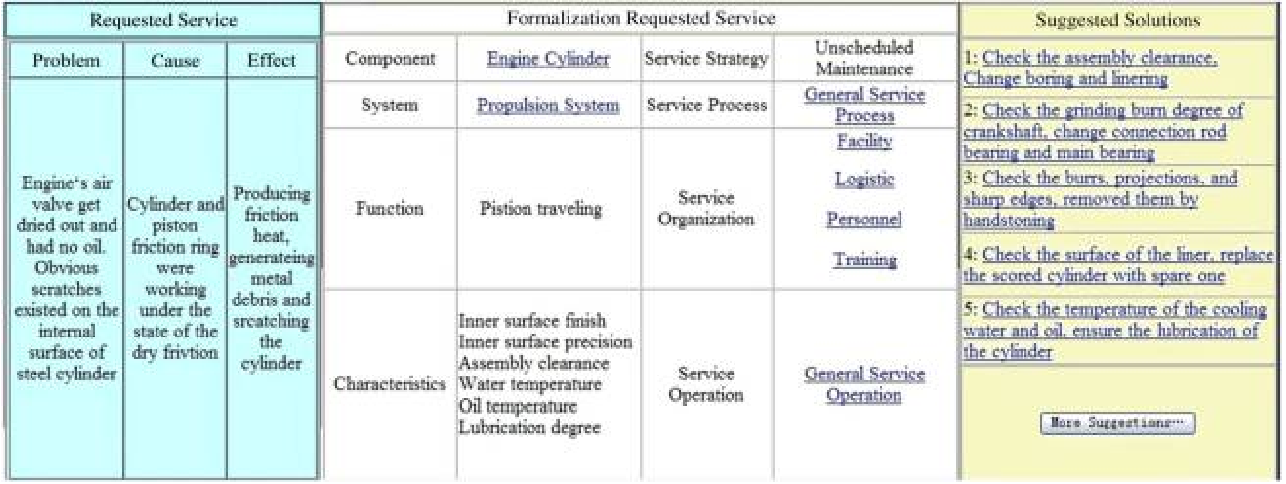


Request Service Activities Formalization

Request Service Number : V2.5-CS-2012032804

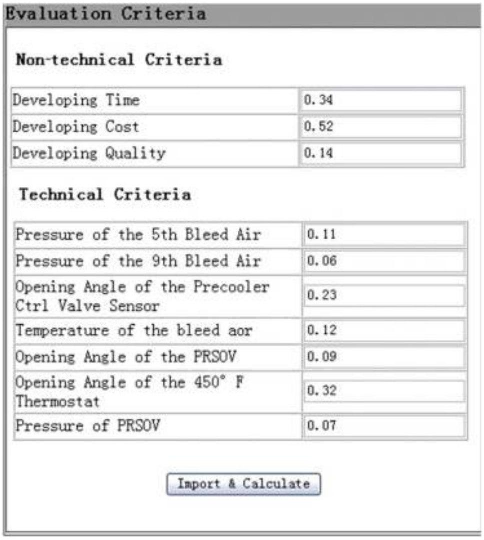
	Description	knowledge metabase
Service description	Cylinder scoring	Click to Tag With Knowledge Meta Data
Subsystem	Propulsion System	Click to Tag With Knowledge Meta Data
Component	Engine Cylinder Piston	Click to Tag With Knowledge Meta Data
Development Time	T	Click to Tag With Knowledge Meta Data
Development Cost	CT	Click to Tag With Knowledge Meta Data
Development Risk	R	Click to Tag With Knowledge Meta Data
Engineering Characteristics	Temperature of the cooling water Inner surface finish Inner surface precision Cylinder liner taper Cylinder liner ovality Piston installation position Octane number Cylinder lubrication degree Water temperature Lubricating oil temperature	Click to Tag With Knowledge Meta Data

Figure 9.
Requested service formalization



Requested Service			Formalization Requested Service				Suggested Solutions
Problem	Cause	Effect	Component	Engine Cylinder	Service Strategy	Unscheduled Maintenance	1: Check the assembly clearance. Change boring and linering
Engine's air valve get dried out and had no oil. Obvious scratches existed on the internal surface of steel cylinder	Cylinder and piston friction ring were working under the state of the dry frivtion	Producing friction heat, generateing metal debris and srcatching the cylinder	System	Propulsion System	Service Process	General Service Process	2: Check the grinding burn degree of crankshaft, change connection rod bearing and main bearing
			Function	Pistion traveling	Service Organization	Facility Logistic Personnel Training	3: Check the burrs, projections, and sharp edges, removed them by handstoning 4: Check the surface of the liner, replace the scored cylinder with spare one
			Characteristics	Inner surface finish Inner surface precision Assembly clearance Water temperature Oil temperature Lubrication degree	Service Operation	General Service Operation	5: Check the temperature of the cooling water and oil, ensure the lubrication of the cylinder More Suggestions···

Figure 10.
Reasoning results of the example processed in the knowledge system



Evaluation Criteria

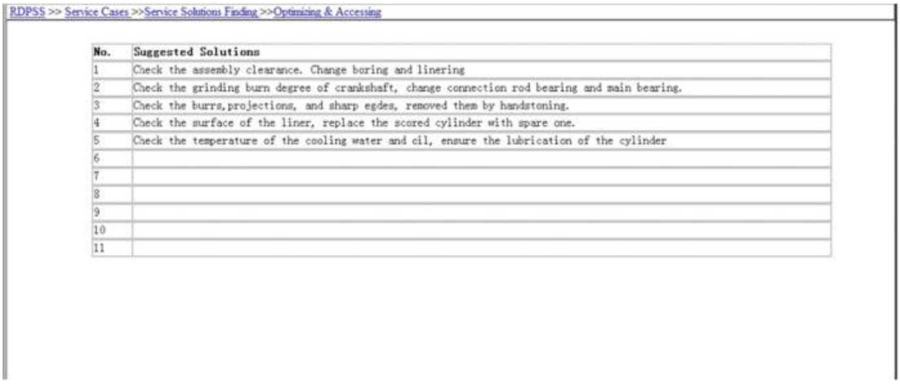
Non-technical Criteria

Developing Time	0.34
Developing Cost	0.52
Developing Quality	0.14

Technical Criteria

Pressure of the 5th Bleed Air	0.11
Pressure of the 9th Bleed Air	0.06
Opening Angle of the Precooler Ctrl Valve Sensor	0.23
Temperature of the bleed aor	0.12
Opening Angle of the PRSOV	0.09
Opening Angle of the 450° F Thermostat	0.32
Pressure of PRSOV	0.07

Figure 11.
The interface of the evaluation criteria



No.	Suggested Solutions
1	Check the assembly clearance. Change boring and linering
2	Check the grinding burn degree of crankshaft, change connection rod bearing and main bearing.
3	Check the burrs,projections, and sharp egdes, removed them by handstoning.
4	Check the surface of the liner, replace the scored cylinder with spare one.
5	Check the temperature of the cooling water and oil, ensure the lubrication of the cylinder
6	
7	
8	
9	
10	
11	

Figure 12.
The result of the example processed in the knowledge-based PSS

9. Conclusions and further work

The main contribution of this project is developing a RdPSS. The difficulties in identifying CRs and in satisfying ECs in the early stage of PSS planning are considered. Ontologies have been developed to represent, accumulate and collect knowledge and experience existed in the existing cases and generated during the daily product and service design activities. A knowledge-based reasoning method has been proposed to generate the semantically similar PSS ideas by referring to predefined ontologies.

The next stage of this research is to integrate the developed PSS with other enterprise systems to acquire contributions regarding knowledge that previous cases made with respect to relevant requirements. With the help of knowledge acquired, the resulting solutions will be made more accurately.

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