Web Services-based Knowledge Sharing, Reuse and Integration in the Design Evaluation of Mechanical Systems

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Abstract: The process of design evaluation is a complicated task for designers due to the need to employ sufficient multi-disciplinary design knowledge. To aid this task, the sharing, reuse and integration of multi-disciplinary knowledge between workers, who play different roles and perform different operations in the design evaluation process, is of great importance. Web services provide an appropriate means to transfer design knowledge between individuals and teams in different disciplines, offering reductions in operation costs and enhanced efficiency, with a better, more streamlined service. This paper identifies and clarifies the knowledge needs required in the design evaluation process, models the knowledge flow among various organizations and the knowledge shared between them, and proposes a web services-based knowledge flow framework to enhance collaboration among various disciplinary experts. An illustrative case is presented to demonstrate how the proposed model may be used to represent design knowledge and integrate it into the design evaluation process. Results from this study contribute significantly to efforts in fulfilling the diverse knowledge needs of workers in the evaluation process. It also helps integrated designers to obtain a clear view of knowledge flow during design evaluation and facilitates knowledge sharing, exchange and reuse among various organizations via a web service-based method.

Keywords: Web Services; Design Evaluation; Design Knowledge Reuse; Knowledge Sharing; Knowledge Integration; Collaborative Design.

1. Introduction

Design evaluation, as a necessary part of the design process, is pivotal in the development and refinement of products, as it provides alternative design solutions that can be compared and evaluated according to functional requirements and constraints to deliver an optimum solution for a given problem. The evaluation process requires a significant amount of knowledge from different disciplines, which makes the process a complex task and sets a high requirement standard for system evaluation engineers. The knowledge acquired during the evaluation process not only determines whether the design solution meets functional requirements and constraints, but can also be fed back to previous design for knowledge reuse and guidance for the modification of unreasonable design solutions [1]. To satisfy the knowledge requirements of system evaluation engineers in each phase of the evaluation process, answers must be obtained in relation to “what kinds of knowledge is needed in the design evaluation process” and “How is the knowledge shared, acquired and integrated in the evaluation process” [2]. By mapping the knowledge flows in design evaluation, system evaluation engineers can be provided with task-relevant knowledge, which helps them fulfill their knowledge needs quickly and effectively [3]. Studies on knowledge flow have attracted much attention since the value of knowledge keeps increasing [4-7].

In today’s highly-competitive business environment, one way to create, build and maintain competitive advantage is through the utilization of knowledge and collaboration among various disciplinary experts [8]. By integrating the knowledge and experiences of various multi-disciplinary experts, manufacturing companies can broaden their scope for solving interdisciplinary problems and improve the quality of evaluation results, thus providing competitive design solutions [3]. Developments in a distributed resource environment increase the demand for methods of sharing, exchanging and re-using design knowledge [9]. As dispersed design teams become ever more common, with disciplinary experts now distributed around the world [10], web services have subsequently become a suitable means to transfer design knowledge during the evaluation process between individuals and teams from different disciplines, which is beneficial in terms of reducing operating costs, gaining greater efficiency and offering better service. Many computer-aided tools have been developed to assist the design process, including CAD, CAE and CAM, which are mainly used for analysis and evaluation of a specific disciplinary problem.

However, few studies have considered how to share and integrate knowledge in the evaluation process of the collaborative design of multi-disciplinary systems. This lack of consideration makes it difficult not only to share and integrate valuable design knowledge effectively, but also to satisfy the knowledge needs of related workers during the evaluation process. This study has three key objectives: (1) to identify and clarify the knowledge need requirements in the design evaluation process, (2) to model the knowledge flow between different organizations and different kinds of knowledge, and (3) to propose a web services-based knowledge flow framework for use in the design evaluation process to enhance collaboration among various disciplinary experts.

The rest of this paper is organized as follows: Section 2 provides a summary of related work. Section 3 clarifies the knowledge required in the evaluation process and presents its representations. Section 4 builds a design knowledge flow model for use during the evaluation process. Section 5 applies the proposed design knowledge flow model to a case study based on the friction evaluation process of a piston ring liner system in an internal combustion engine. In Section 6, a web services-based knowledge flow framework is proposed to analyze knowledge activities. Finally, Section 7 provides conclusions and suggestions for future research.

2. Related Work

The evaluation of design artifacts is a key activity required during the design process, as it provides feedback for further development and assures the sustainability of the design solution [11]. Design solution selection, which aims to evaluate and choose the best or most desirable design scheme among several candidates for the subsequent detailed design stage, often requires a set of methods to conduct the process of design evaluation. For example, Huang et al. [12] proposed several design evaluation methods to deliver conceptual design selection under different scenarios using computational intelligence techniques. Chami and Bruel [13] suggested an integrated conceptual design evaluation approach for mechatronic systems based on SysML, which is called SysDICE. The model generation phase showed how SysML diagrams were used to model the requirements, functions and conceptual solution entities. Gupta et al. [14] used a quality index approach to evaluate and compare alternative designs and choose the best design from the perspective of quality. They identified that a high value on a quality index indicates that the product structure is closer to the ideal state. Cebi [15] proposed a novel approach named ‘The Quality Evaluation Model’, which includes fuzzy set theory, the decision-making trial and evaluation laboratory method, and generalized Choquet integral techniques. Unfortunately, those mentioned have a limited scope of application, as their evaluation methods are too technical and difficult to implement. Venable et al. [11] suggested that the process of design evaluation comprises 4 steps: (1)

explicate the goals of the evaluation, (2) choose the evaluation strategy or strategies, (3) determine the properties to evaluate, and (4) design the individual evaluation episode. However, to date, little attention has been given to the design knowledge needs and collaborative work for evaluating designs [16].

Design knowledge is a collection of different cognitive artifacts with different purposes, which contain visions that stimulate and steer strategic discussion, proposals to integrate into the development of specific products, tools to implement design ideas and reflections about what the company is doing or could do in future. Types of design knowledge include tacit and formal knowledge, product and process knowledge, and compiled and dynamic knowledge [17]. Design knowledge must be explicit, able to be discussed and transferable. Thus, it should have the ability to be clearly expressed by whoever produces it, discussed by anyone who is interested in it, and applied by other designers in different regions [18]. Davis et al. [19] categorized the notion of knowledge representation into five roles: (1) a substitute for the thing itself, (2) a set of ontological commitments of thinking about an entity, (3) a fragmentary theory of intelligent reasoning, (4) the computational environment in which thinking is accomplished, and (5) a language to describe an entity. Sowa [20] understood knowledge representation as the application of logic and ontologies to the task of constructing computable models for contextual domains. Knowledge representations can be classified by five categories: pictorial, symbolic, linguistic, virtual and algorithmic [21]. Paulo et al. [22] represented design knowledge to be used during surgeries in a machine readable format. They defined a conceptual model of the ontology for robotic orthopedic surgery, which consisted of a biomedical/human anatomical ontology, a robot ontology, and how to represent and manage clinical data, e.g. image, case, patient data. Since knowledge can be viewed as information about content and context, the representation of design knowledge, in an evaluation process, is dependent on both the content and the context of the evaluation process [17].

Design knowledge flow represents the flow of an individual's or group member's design knowledge needs and the referencing sequence of documents for performing the design process [3]. Zhuge and Zhang [23, 24] proposed that design knowledge flow involves three main elements: (1) knowledge carrier, (2) intellectual content, and (3) knowledge flow direction. Wang et al. [25] established a knowledge–flow–oriented Petri net model, from which a knowledge activity unit was constructed, involving knowledge sender places, transitions, knowledge receiver places and directed arcs connecting them. Chen et al. [26] proposed a knowledge flow framework for the creative conceptual design of multi-disciplinary systems by reusing and synthesizing known principle solutions in various disciplines together. Gregor et al. [27] presented a knowledge contribution framework that aims to assist researchers understand knowledge roles in design science research and then identify appropriate ways of consuming and producing knowledge when they are preparing journal articles or other scholarly works. Zhang et al. [28] proposed an ontological framework, purpose-function-working space-structure-behavior, for knowledge representation and knowledge flow, based on design process modeling. Erden et al. [29] examined the relationship between knowledge flow and firm performance using longitudinal data on a pure sample of public biopharmaceutical firms; results indicated that if firms focus on securing knowledge flows from very few partners, or follow an explicit strategy of pursuing many alliances, managers should be aware that alliances may grant the firm better financial performance. However, modeling design knowledge flow often depends on the stages of a product's life cycle. Previous research has predominantly focused on the concept design stage. None of the above studies analyzed the knowledge flow during the design evaluation process, which is in the detailed design stage and of significant importance for ensuring product quality.

Design knowledge flow during the evaluation process requires collaboration between customers, suppliers and designers, to form knowledge sharing communities within and across organizational boundaries which can work together to achieve a shared business objective, resulting in benefits to all community members [8]. Web services provide a method for connection from person to person and for the efficient sharing of knowledge. Web services are defined by IBM as a "new breed of Web application; they are self-contained, self-describing, modular applications that can be published, located and invoked across the Web" [30]. Some researchers have focused on the application of web services for knowledge service. For instance, Tao et al. [31] investigated the application of Internet of Things (IoT) and cloud computing in manufacturing and proposed a framework of the service system, consisting of four layers: Internet of Things layer, service layers, application layer and bottom supporting layer. Ryu et al. [32] developed a prototype service for a smart office using an integrated semantic service platform, which can provide a preset, personalized office environment by interpreting user text input via a smartphone. Chen et al. [33] suggested an optimization approach for the matching of knowledge demanders and suppliers in knowledge services, in which they proposed novel measurements of satisfaction degree for matching, based on fuzzy axiomatic design; this is especially beneficial to the activity of knowledge acquisition. Cai et al. [34] introduced a platform for knowledge service, based on big data processing techniques, which has guided the implementation of the integration of industrialization and IT applications. Beetz et al. [35] further explored how they may use the cloud-based knowledge service OPENEASE to realize open robotics research. From this research, it is obvious that web services could enhance the flow of design knowledge during the evaluation process by making it easier for customers, suppliers and designers to participate in design knowledge creation, sharing and integration [36]. These researches focus on the technical level of web services in different domains. This paper, on the other hand, attempts to build a web service-based design knowledge flow framework to transfer design knowledge in the collaborative evaluation process.

3. Design Knowledge in the Evaluation Process

3.1 Design Evaluation Process

If the product design process is classified into functions, behaviors and structures, as suggested by Gero's FBS model [37], the process of evaluation begins from structure. When product structure is certain, product behavior can be obtained through concrete analysis, using simulations and/or experiments. Generally, simulations are the first step in this process, due to their low costs and high efficiency. Therefore, some commercial tools, such as CAD, CAE and CAM, have been developed to analyze product structure and obtain product behavior. Experiments also need to be conducted to assure accuracy of simulation results. After the actual behavior is ascertained, whether it meets the product function can be evaluated by comparing actual behavior with expected behavior, and it can be decided whether to start batch production. To this end, the evaluation process is finished. However, if the product behavior does not meet the product function, according to evaluation results, the product structure should be changed through synthesis and another evaluation process begins. The cycle from structure to function is illustrated in Fig.1. As the figure shows, the circles represent the main stations, while the arrows represent the transition from a station to the next station.

Triangles inside the cycle represent the assignments needed by designers to cycle between the various phases. The analysis assignment achieves the transformation from structure knowledge to behavior knowledge. Structure knowledge explains what a mechanical system is and behavior knowledge explains what a mechanical system does. Designers can acquire behavior knowledge by analyzing structure knowledge. The evaluation assignment means the comparison between behavior knowledge and function knowledge. Function knowledge explains what a mechanical system is for. By comparing behavior knowledge and function knowledge, designers get to know whether a mechanical system works. The synthesis assignment occurs when the behavior of a mechanical system fails to meet its function; this means finding the failure reasons and adjusting the structure of the mechanical system. Therefore, there will be new structure knowledge and evaluation process. All the design knowledge in an evaluation process can be categorized into knowledge segments and the relationships among them can also be defined [38]. From Fig.1, it can be assumed that during the evaluation process, design knowledge can be classified into structure knowledge, behavior knowledge and function knowledge. Behavior knowledge is core knowledge that is derived from structure knowledge and used for evaluating whether the proposed design solution meets the function.

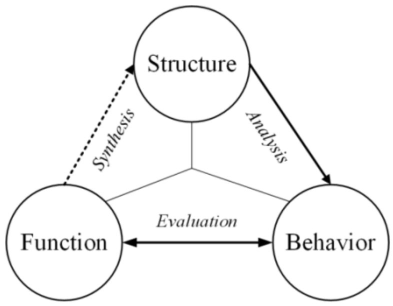

Fig.1 Knowledge Recycling in the Evaluation Process

3.2 Structure Knowledge

Structure is defined as all elements and their relationships [37]. The Structure Knowledge (SK) of a mechanical product includes not only all its elements, but also the geometrical and physical properties of all elements. In addition, the relationships between these elements are also part of SK; hence, the representation of structure knowledge is shown in formula (1) [39, 40].

$$SK=(E, P, R) \tag{1}$$

where

(1) E=$\{e_1, \cdots, e_i, \cdots, e_m\}$ is a finite set of elements,

(2) P=$\{p_1, \cdots, p_i, \cdots, p_m\}$ is a finite set of element properties,

(3) R=$(a_{ij})_{m\times m}$ is an incidence matrix.

3.2.1 Representation of Element

An element comprises three parts: (1) name of element, (2) input-output name pair, and (3) the attribute constraints on the input-output [26]. Fig.2 shows a general schema for representing an element. The name of element represents the element type. According to element type, the input and output can be known. The input-output name pair is employed to represent the transformation from input to output achieved by the element. It should be noted that an element can have multi-inputs and multi-outputs since it typically achieves many kinds of transformations. The attribute constraints are used to represent the attributes of input or output. It is represented as: (attr_name, "attr_description"). Attr_description can be the value range of the attribute or semantic description of the attribute.

```
ELEMENT
{ Name:
  Input_name:
    [(attr_name,  "attr_discription" )]
    ...
  Output_name:
    [(attr_name,  "attr_discription" )]
    ...
}
```

Fig.2 A Schema for Representing an Element

3.2.2 Representation of Property

The property of an element comprises five parts: (1) name, (2) geometrical information, (3) physical information, (4) attributes that are used to represent the geometrical information and physical information, and (5) figures that can be employed to assist the representation of geometrical information. Fig.3 presents a general schema for representing properties of an element. Name of property is employed to represent property type. Geometrical information is employed to represent the geometrical property of an element, which is described by attributes and figures. Attribute is represented as: (attr_name, "attr_description"). Figure is employed to show the geometry of an element. Geometrical information includes length, width, height etc. Physical information is employed to represent the physical property of an element that is described by attribute. Similarly, attribute is represented as: (attr_name, "attr_description"). Physical information includes mass, temperature, material, processing method etc.

```
PROPERTY
{ Name:
  Geometrical information:
    [(attr_name,  "attr_discription" )]
    ...
  Physical information:
    [(attr_name,  "attr_discription" )]
    ...
}
```

Figure:

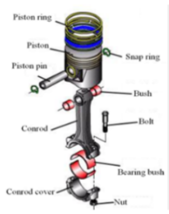

Fig.3 A Schema for Representing Properties of an Element

3.2.3 Representation of Relation

Relation (R) is an incidence matrix used to represent system element interactions. R=$(a_{ij})_{m\times m}$. Here, a_{ij}=0 implies that there is no direct relation between element e_i and e_j. a_{ij}=1 implies that there is a direct relation between element e_i and e_j. Fig.4 presents a schema for representing a relation. There are 5 elements in the system. e_1 is connected directly to e_2 and e_5. e_2 is connected directly to e_1 and e_3. Besides, there are direct relations between e_3 and e_5, e_4 and

e_5. The relationships between these elements can be established from Fig.4. It may be seen that the incidence matrix is a symmetric matrix. It is similar in intention to the Design Structure Matrix (DSM) that concerns the interactions between system elements [41].

	e_1	e_2	e_3	e_4	e_5
e_1		1	0	0	1
e_2	1		1	0	0
e_3	0	1		0	1
e_4	0	0	0		1
e_5	1	0	1	1	

Fig.4 A Schema for Representing Elements Relations

3.3 Behavior Knowledge

Behavior knowledge is core to the knowledge required during the evaluation process, since it is the foundation upon which to decide whether the design solution meets the function. To acquire behavior knowledge, structure knowledge must first be collected. Product structure then needs to be analyzed to acquire behavior knowledge. In the process, software such as CAD, CAE and CAM might be used. Behavior knowledge includes Behavioral Variable (BV) and Behavioral Principle (BP), as shown in formula (2).

$$BK=(BV,\ BP) \tag{2}$$

3.3.1 Behavior Variable (BV)

The behavior of a mechanical system can be described as its ability to perform functions [42]. Hence, it can be presented by measurable behavior variables. These behavior variables can be divided into two catalogs: Positive Behavior Variables (PBVs) and Negative Behavior Variables (NBVs). PBVs refer to variables where, when the value is higher, the performance of the mechanical system is better, such as engine efficiency; this always relates to Functional Requirement. NBVs are the opposite. The lower the value is, the better the performance obtained, like engine friction loss; this usually corresponds to Constraints.

3.3.2 Behavior Principle (BP)

To obtain the Behavior Variable values, the Behavior Principle must first be known. This knowledge is stored in either explicit or tacit form, such as in the minds of employees or in recorded outputs, such as videos, reports or books etc. BP knowledge is complicated, involving the integration of a large amount of knowledge and crossing multiple disciplines. It can, for example, be provided by physicists, chemists, computer specialists, mathematicians etc. Once the BP is established, the knowledge must then be utilized to calculate the value of BV and make the results visible and understandable.

3.4 Function Knowledge

Function knowledge contains Functional Requirement (FR) and Constraint (C). FR is derived from the Customer Need (CN) [43]. The difference between FR and CN is the varying methods of thought used by designers and customers. C is mainly influenced by social and working environments, like energy-saving and emission reduction policy constraints, weight constraints, volume constraints etc. When FR and C are considered in the context of the product design process, they can be transformed into measurable Behavior Variables. Therefore, by comparing function with actual product behaviors, quantification evaluation of product behaviors can be realized. The representation of function knowledge is shown in formula (3).

$$FK=（FR，C）\tag{3}$$

3.4.1 Functional Requirement (FR)

Functional requirement is defined as the minimum set of independent requirements that entirely characterizes the functional needs of the product [44]. It is usually presented in a form of "verb + noun". For example, "Convert X axis rotation into Z axis translation" is a FR.

3.4.2 Constraint (C)

Constraints are the specifications that designers must take into consideration during their design decision making process [28]. Cost, time, reliability, maintainability etc. are general constraints that should be considered in the evaluation process. Of course, there are more detailed constraints for special systems, which are directly related to mechanical system behaviors. Only when the behaviors have been obtained, can the evaluation results be realized. For example, the constraints could be "friction must be below a certain value", "components' life must be longer than a certain value" and "exhaust gas emission should meet pollution standards".

4. Design Knowledge Flow Modeling

Design knowledge flow in the evaluation process refers to the passage of knowledge between different organizations and the transformation of different kinds of knowledge. Fig.5 depicts the design knowledge flow among different organizations and different kinds of knowledge. Design knowledge flow can be identified as a particular type of directed graph, populated by three knowledge layers and four types of objects. The knowledge layers are: Structure Layer (SL), Behavior Layer (BL) and Function Layer (FL). The objects are: organization, knowledge, knowledge flow in the same layer, and knowledge flow across different layers.

In the structure layer, structure knowledge consists of Element (E), Property (P) and Relation (R). Component suppliers offer element knowledge (E) and property knowledge (P). The assembly engineer integrates this element's property knowledge and offers Relation (R) through assembly of these components. Thus far, the system structure knowledge is clear. For example, an internal combustion engine is made up of many kinds of elements, such as piston, piston ring and liner etc. These elements are produced in different factories that are often geographically dispersed. These factories are component suppliers. They know their element and the property of their element best. When designing an internal combustion engine, the assembly engineer firstly obtains element knowledge and property knowledge from component suppliers, then assembles these elements and provides relation knowledge of the elements in the internal combustion engine. It should be noted that E, P and R are offered by different organizations. Therefore, acquiring complete structure knowledge requires collaboration among different organizations. Neumann et al. [45] designed a systemic platform for assembly line planning, which was based on a collaborative problem solving concept.

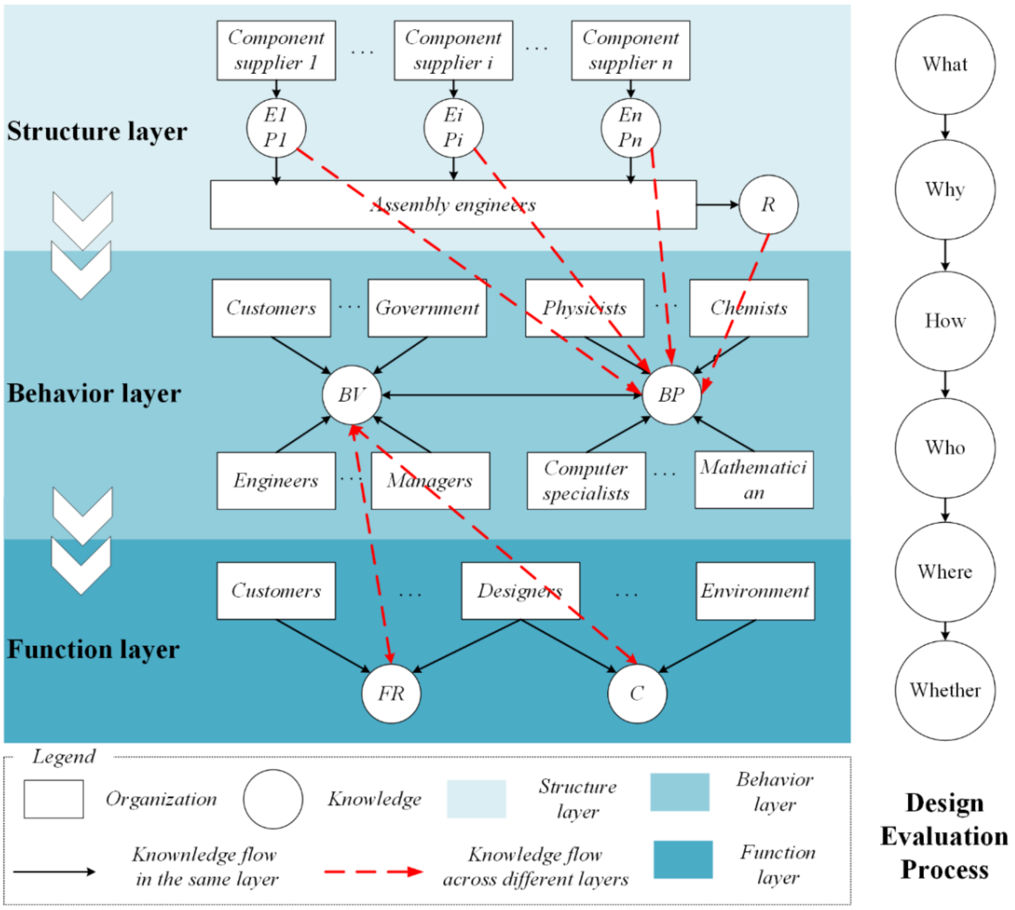

Fig.5 Design Knowledge Flow Model in the Evaluation Process

In the behavior layer, behavior knowledge can be depicted and interpreted by Behavior Variables (BV) and Behavior Principles (BP). BV refers to the variable related to functional requirements and constraints, which show the performance of a mechanical system. BVs can be provided by customers, government, engineers and/or managers. Customers propose Functional Requirements that influence the selection of BV. Governments make policies that could be a constraint of the mechanical system. Engineers and managers always find more constraints during the product development process and will create measurable design evaluation criteria. BP is a specialized type of knowledge, which is provided by expertise from multiple disciplines. For example, friction, in an internal combustion engine is a BV. Knowledge about how to get the value of the friction is a BP. According to BV, what kind of BP is required will be known. According to BP, the value of BV can be obtained. Therefore, there is a strong link between BV and BP.

In the function layer, function knowledge comprises Functional Requirement (FR) and Constraints (C). Customers and designers offer FR knowledge by their anticipation for the product, which describes what behaviors the product should have. In the meantime, the designers and the environment provide C knowledge, caused by policies, working conditions and worker conditions etc. The C knowledge describes what behaviors the product should not have. By synthetically analyzing FR and C, Behavior Variables can be chosen for design evaluation.

In addition, knowledge flows across different layers exist, which are represented by the dotted arrow line in Fig.5. To understand the BP in the behavior layer, E, P, R knowledge in the structure layer is needed. For example, if a designer wants to know how to get friction in an internal combustion engine, he needs to identify the structure knowledge of the internal combustion engine first. When choosing the BV, FR and C, knowledge in the function layer must be understood because, in functional modeling, FR and C should be translated into desired product behavior [46]. For instance, the reason why the friction is chosen as a BV is that there is a constraint: "the friction of the internal combustion engine must be less than a certain value". As the ultimate goal of the knowledge flow is to provide evaluation results, when knowing the value of BV, designers can determine whether the mechanical system meets the specified FR and C and are able to reach a conclusion on whether to start batch production or change the product structure.

In Fig.5, it is shown that the design evaluation process can be proceeded by answering 6W questions: What, Why, How, Who, Where and Whether; the meanings of the 6W questions and related knowledge requirements are described in Table 1, which has been adapted from [41].

Table 1: 6W Questions in the Design Evaluation Process

Question	Description	Knowledge
What	What are the BVs of concern?	BV
Why	Why are these BVs worthy of attention?	BV, FR, C
How	How to acquire these BVs?	BV, BP, E, P, R
Who	Who can obtain these BVs?	BV, BP
Where	Where are the BVs represented?	BV
Whether	Whether the BVs meet FR and C?	BV, FR, C

In the design evaluation process of a mechanical system, behavior knowledge is core knowledge that is derived from structure knowledge and used for evaluating whether the proposed design solution meets the function. Behavior knowledge includes BV and BP. BP assists in calculating the value of BV. Therefore, the 6W questions all relate to BV. To answer each question relating to BV requires relevant structure knowledge, behavior knowledge and function knowledge. The evaluation process of a mechanical system can be finished gradually in the answer process. Specifically, which Behavior Variable is of concern and should be understood initially. To avoid wasting time and effort acquiring unnecessary behavior, research purposes must be clearly understood, i.e. analyzing why the BV is worthy of attention. This requires FR and C knowledge. After that, search for suitable research methods to obtain the BV, i.e. know how to obtain the BV. It requires BP, E, P, R knowledge. If designers are not equipped with related BP knowledge or they do not have the required related simulation tools and experimental equipment, they could find related research teams who can obtain the BV via the Internet. Then, the related research teams will provide them with research results. It might be represented in a document, drawing or other file type; this depends on a visualized post-processing process. By analyzing these research results, designers can identify whether the BV meets FR and C and draw evaluation conclusions.

5. Case Study: Friction Evaluation of the Piston Ring Liner System

In this paper, the authors take the friction evaluation of the Piston Ring Liner System (PRLS) in the internal combustion engine as an illustrative case study to verify the proposed design knowledge flow model. It has been estimated that 20 to 30 percent of an engine's mechanical power loss is caused by the friction loss in the PRLS system [47]. A low friction in the ring/liner system is vital for improving engine performance. The value of friction in the PRLS can be gained by simulation and experiment. Normally, to reduce the experiment cost, simulation is the first step used in friction evaluation. The friction calculation in the PRLS is related to multiple behavior variables, such as piston speed, gas pressure, and oil film carrying capacity. Fig.6 shows the structure of the PRLS in the internal combustion engine. The partial enlarged drawing presents the force analysis of the piston ring. Here, P_1 is the gas pressure acting on the upper side of the ring, P_2 is the gas pressure acting on the lower side of the ring, F_g is gas force on the inner side of the ring, F_e is the ring elastic force, F_{oil} is the oil film load-carrying capacity, W_a is the asperity contact force, h_m is the minimum oil film thickness, V_p is the piston reciprocating velocity. These behavior variables are necessary to calculate the friction in the PRLS. The relationships between these behavior variables, which are types of behavior principles, are related to multiple disciplinary knowledge, like mechanical dynamics knowledge, aerodynamics knowledge etc. During the friction evaluation process, the structure knowledge should be known firstly. Then the behavior knowledge can be gained though simulation analysis. Finally, the evaluation results will be understood through comparing the actual friction and the friction constraint. In the next part, the friction evaluation process of PRLS will be conducted in line with the 6W questions, proposed above. Each question will be answered using relevant structure knowledge, behavior knowledge and function knowledge. By analyzing the friction evaluation process of the PRLS, the feasibility and efficiency of the proposed knowledge classification and knowledge flow model can be proved to some extent.

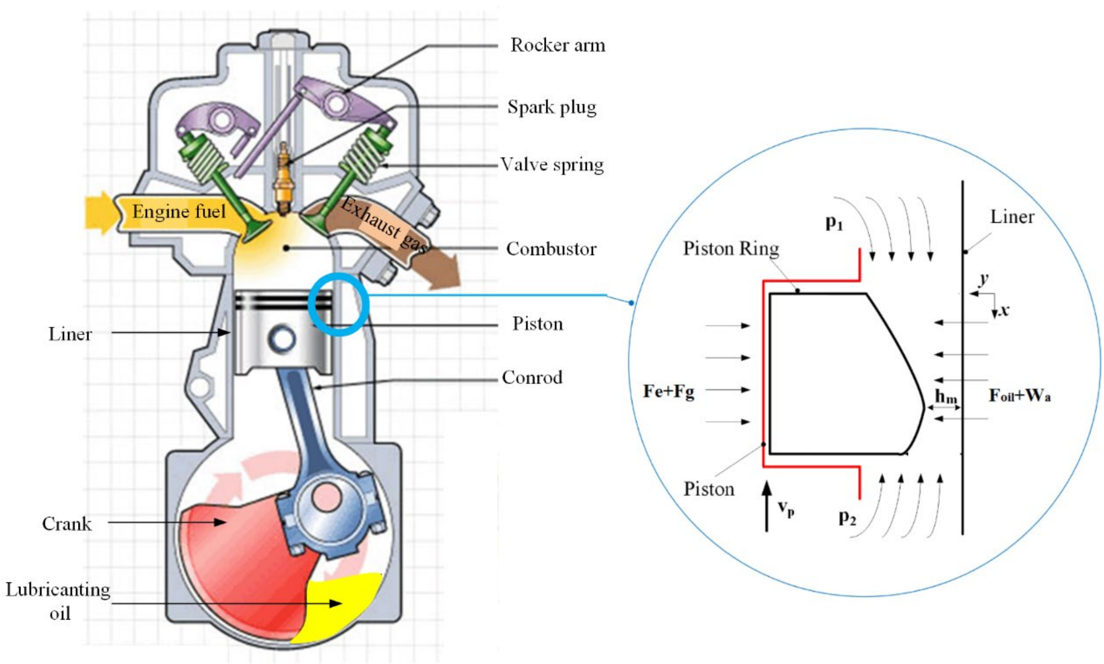

Fig.6 The Piston Ring Liner System in The Internal Combustion Engine

- **What**: What are the Behavior Variables of concern?

For the PRLS described above, piston speed, gas pressure in the combustor and inter ring, oil film carrying capacity, asperities contact force between piston ring and liner and friction that contains fluid-solid friction and solid-solid friction are the behavior variables that designers care about.

- **Why**: Why are these BVs worthy of attention?

In the PRLS scenario, piston speed is important as it influences the main axle speed output.

Gas pressure in the combustor and inter ring is important as it drives the motion of piston. Oil film carrying capacity and asperities contact force are important because they are related to friction and the wear of the piston ring and liner. The friction in PRLS is important as it influences engine life, fuel consumption and emissions. The main axle speed output, the motion of piston, the friction and wear of the piston ring and liner, the engine life, the fuel consumption and the emissions all belong to Functional Requirements and Constraints of the PRLS.

- **How**: How to acquire these BVs?

To acquire the BVs, the structure knowledge needs to be understood first. Fig.7 shows the representation of structure knowledge of the crank-slider system in the PRLS, which includes Element, Property and Relation knowledge.

ELEMENT:
{ Name: *"the crank-slider system"*
Input_name: *"angular velocity"*
[(*direction*, *"clockwise"*)
(*value*, *"2000rpm"*)]
Output_name: *"linear velocity"*
[(*direction*, *"X"*)
(*Value*, *"variable"*)]
}

RELATION:

	Crank	*Conrod*	*Piston*	*Piston ring*	*Liner*
Crank		1	0	0	0
Conrod	1		1	0	0
Piston	0	1		1	1
Piston ring	0	0	1		1
Liner	0	0	1	1	

PROPERTY:
{ Name: *"the property of the crank-slider system"*
Geometrical information:
[(*Bore-B*, *"0.073m"*)
(*Crank radius-R*, *"0.039m"*)
(*Conrod length-L*, *"0.129m"*)
(*Cylinder angle-d*, *"0rad"*)
(*Cylinder axis offset-e2*, *"0m"*)
(*Piston pin offset-e1*, *"1.3mm"*)
(*Piston pin to top-h*, *"0.05m"*)
…]
Physical information:
[(*Conrod mass*, *"3.826Kg"*)
(*Conrod moment of inertia*, *"0.0474Kg.m^2"*)
…]
}

Figure:

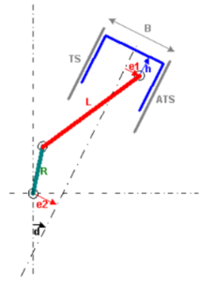

Fig.7 The Structure Knowledge in The Crank-Slider System in PRLS

For Element knowledge, the input name of the crank-slider system is angular velocity, while the output name is linear velocity. The crank-slider system can finish the transformation from input to output, while the attributes of angular velocity include direction and value, which are corresponding to attr_description "clockwise" and "2000rpm". Similarly, the attributes on linear velocity include direction and value, which are corresponding to attr_description "X" and "variable".

For Property knowledge, the geometry information of the crank-slider system includes attr_name: bore, crank radius, conrod length, cylinder angle, cylinder axis offset, piston pin offset and piston pin to top, that are corresponding to attr_description: "0.073m", "0.129m", "0rad", "0m", "1.3mm", "0.05m". The figure is used to show the geometry of the crank-slider system and assist the representation of geometry information. The physical information of the crank-slider system includes attr_name: conrod mass, conrod moment of inertia, that are corresponding to attr_description: "3.826Kg", 0.0474Kg.m^2".

In terms of Relation Knowledge, the crank-slider system contains 5 elements: crank, conrod, piston, piston ring and liner. The relationships among these elements can be established from Fig.6. Then, the incidence matrix can be written, as shown in Fig.7. For example, the piston ring is assembled in ring grooves of piston, with direct contact between them. Therefore, the relation between piston ring and piston equals 1. Similarly, there is no direct contact between piston ring and crank, the relation between piston ring and crank equals 0.

As shown in Fig.8, after acquiring structure knowledge in PRLS, the piston speed can be established though calculation, using mechanical dynamic knowledge. Gas pressure in the combustor and inter ring are gained by measurement and calculation using aerodynamics knowledge. The carrying capacity of the oil film can be gained by calculation using hydromechanics knowledge, the Reynolds equation [47, 48]. Asperities contact forces can be gained by calculation using solid mechanical knowledge, the G-T model [49]. Finally, friction in PRLS can be determined by calculation using tribological knowledge. As identified, multi-disciplinary knowledge is needed to acquire friction in PRLS. This knowledge belongs to Behavior Principles. It is hard for one designer to be equipped with all related knowledge. Therefore, it requires positive collaboration between experts from various disciplines. A web service is a suitable platform that transfers related knowledge among these experts and promotes the development of integrated design.

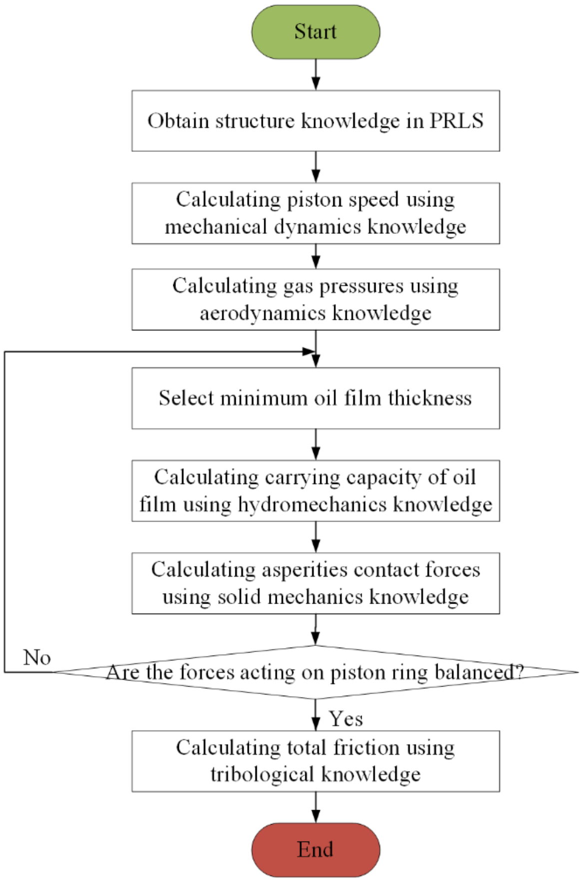

Fig.8 Flow Chart to obtain Friction in PRLS by Simulation

- **Who**: Who can obtain these BVs?

After identifying how to acquire these BVs, designers could search for who has related knowledge (i.e. behavior principle knowledge to obtain these BVs) via web services. They can then ask for help to complete integrated design. For example, if designers want to identify piston speed, they could search for experts with mechanical dynamics knowledge, which is a kind of BP; then ask the experts for help via the web services. After giving them relation structure information, the experts will be able to calculate piston speed and transfer it to designers through the Internet.

- **Where**: Where are the BVs represented: in a document, drawing or other file type?

After behaviors are established, they are always in the form of data and ultimately hard to interpret. This requires visualized post-processing, whereby data is transformed into drawings. As shown in Fig.9, when friction in PRLS is established, it can be found that it is a variable in a whole cycle. Therefore, there is much data to describe the friction. If designers do not turn the data into drawings, they cannot find changing rules of friction and ultimately obtain evaluation results. Hence, designers should find suitable forms to represent these BVs. Fig.9 presents the simulation results of piston velocity, gas pressure, oil film carrying capacity and friction in the form of drawings [47].

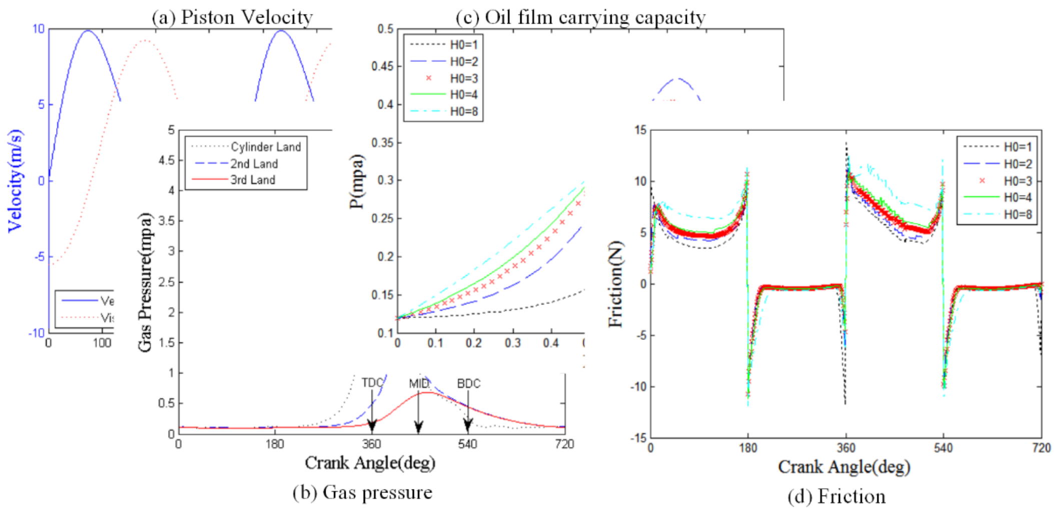

Fig.9 The Simulation Results of Piston Velocity, Gas Pressure, Oil Film Carrying Capacity and Friction

- **Whether**: Whether the BVs meet FR and C?

At the end of the behavior acquisition process, designers must analyze the behavior variables and utilize them to evaluate whether the product structure meets the function. For example, designers find that friction in PRLS is a variable during the engine cycle and, at the top dead center, its value achieves the maximum result. If the maximum value of friction is within an acceptable range and will not cause serious friction and wear of the piston ring and liner, they can draw a conclusion that the structure satisfies friction constraints.

6. Proposed Web Service-based Design Knowledge Flow Framework

After establishing design knowledge classifications and the flow among different organizations, the Internet can be used as an effective tool to enhance design knowledge flow in the evaluation process. Only by constructing a system with appropriate knowledge and knowledge flow can one simplify online knowledge transfer to meet design evaluation demand [50]. Therefore, a web services-based design knowledge flow framework is proposed to support knowledge sharing and integration during the process of design evaluation, see Fig.10.

Fig.10 describes four types of design knowledge and the flow among these during the design evaluation process. Design knowledge includes: (1) structure knowledge E and P, (2) structure knowledge R, (3) behavior knowledge BV, BP, and (4) function knowledge FR, C., which are sufficiently described in Section 3. The flow among the different knowledge and organizations is described in Section 4. In a web services environment, this design knowledge can be regarded as web resources. This means that the design knowledge can be obtained via the Internet. Therefore, the participants in the design evaluation can be divided into two types: knowledge supplier and integrated designer. Knowledge suppliers share their knowledge on the Internet. Integrated designers search, acquire and integrate related knowledge via web services to achieve their own task. Knowledge suppliers and integrated designers are often geographically distributed. Web services can transfer the design knowledge between them. Furthermore, a platform using the 6W questions to guide the design evaluation process efficiently can be developed.

Based on these ideas, web service-based knowledge activities in the evaluation process should include six portions: (1) Web Service Registration, (2) Knowledge Sharing, (3) Knowledge Service, (4) Knowledge Searching, (5) Knowledge Acquisition, and (6) Knowledge Integration [51]. The detailed description of these knowledge activities is presented in Table 2.

During the knowledge sharing activity, the design knowledge classification and representations proposed in this study can be used to represent supplier knowledge. In addition, knowledge suppliers should post the inputs that they need and the outputs that they could offer, which would effectively improve participant communication and information transparency.

During the knowledge service activity, the proposed knowledge flow model can be used as a guide to explain knowledge transformation. For example, assembly engineers transform structure knowledge E, P into structure knowledge R. This is a typical knowledge service. They use their own knowledge and experiences to provide assembly drawings and data by uploading it to the Internet.

During the knowledge searching activity, the proposed knowledge classification, knowledge representation, and the 6W questions can help integrated designers identify their needs efficiently. Knowledge searching requires support search algorithms, which need developing, based on the proposed knowledge classification and knowledge flow model.

During the knowledge acquisition activity, when the knowledge needs are well presented, the formats in which knowledge can be transmitted to integrated designers, through the Internet or by downloading e.g. compressed zip files, need to be discussed in the web service process; this relates to the "Where" question in the 6W questions.

During the knowledge integration activity, integrated designers could integrate related design knowledge to conduct the process of evaluation, according to the knowledge flow model. When answering the 6W questions, the design knowledge will be integrated. The knowledge flow model shows how the design knowledge is integrated.

The knowledge activities should be taken into consideration during the development of the web services platform for design evaluation.

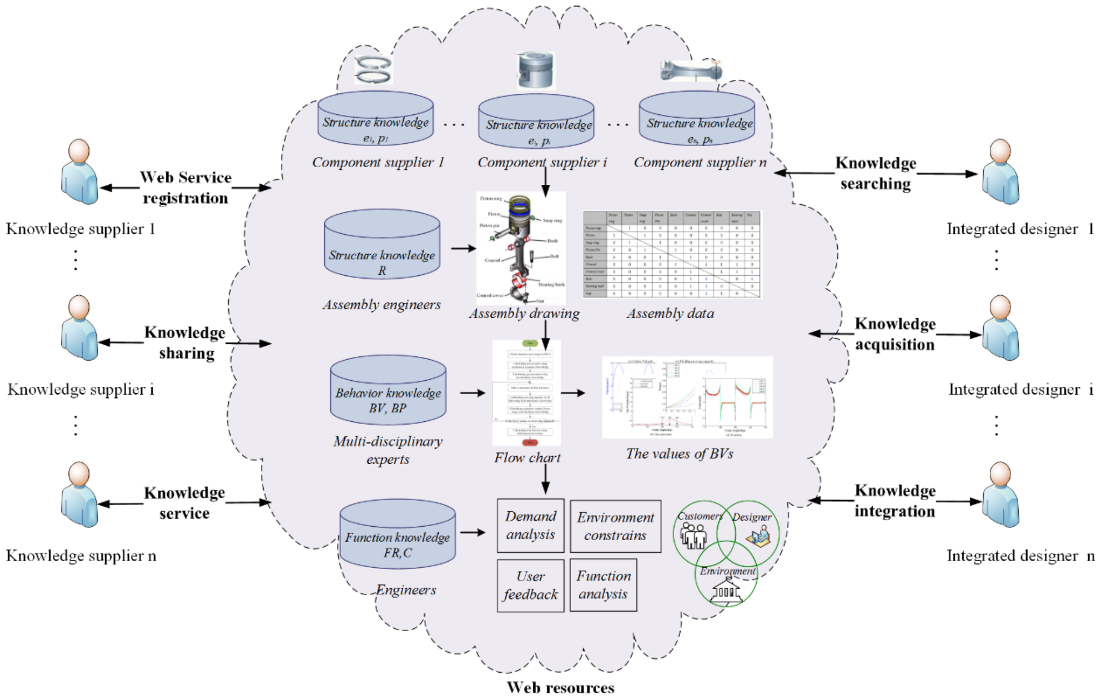

Fig.10 Web Service-based Design Knowledge Flow Framework

Table 2 Web Service-based Knowledge Activities

Activity type	Participant	Description
Web Service Registration	Knowledge supplier Integrated designer	*All design evaluation participants are offered a registration channel for knowledge sharing or knowledge acquisition via a web service method [2].*
Knowledge Sharing	Knowledge supplier	*Relevant design evaluation participants share their knowledge on the Internet.*
Knowledge Service	Knowledge supplier	*Knowledge service means that participants not only transfer knowledge, but also transform knowledge.*
Knowledge Searching	Integrated designer	*Integrated designers search for related knowledge according to the knowledge classification, the knowledge representation, and the 6W questions.*
Knowledge Acquisition	Integrated designer	*This relates to the identification and capturing of knowledge used in the design evaluation process for solution, documentation and storing [41].*
Knowledge Integration	Integrated designer	*Knowledge from different organizations is integrated into the design evaluation process using the 6W questions.*

7 Conclusion and Future Work

This study clarifies design knowledge required in the evaluation process, which includes structure knowledge, behavior knowledge and function knowledge, and builds a design knowledge flow model among different knowledge and organizations for design evaluation. A case study of the friction evaluation of the piston ring liner system in the internal combustion engine is presented to showcase how to use the model and to validate the model's practical effectiveness. Furthermore, a web services-based design knowledge flow framework is proposed to support the design evaluation process. The main contributions of this study are summarized as follows:

- The structure knowledge of a mechanical system comprises of Element (E), Property (P) and Relation (R). The representation of this knowledge is presented in this study, which helps knowledge suppliers share their structure knowledge of mechanical systems online.
- Behavior knowledge can be depicted and interpreted by Behavior Variable (BV) and Behavior Principle (BP). BV is the core knowledge during the design evaluation process. Its selection is derived from function knowledge. Its value depends on behavior principle, which closely relates to structure knowledge.
- Function knowledge includes Functional Requirement (FR) and Constraint (C). Customers and designers offer FR knowledge by their anticipation for the product, which describes what behaviors the product should have. In the meantime, the designers and the environment provide C knowledge, caused by policies, working conditions, worker conditions etc. The C knowledge describes what behaviors the product should not have.
- This study builds a design knowledge flow model for use in the process of evaluation with three structural layers, which shows the links between various knowledge and organizations involved. The design evaluation process can be conducted by answering the 6W questions: What are the BVs of concern? Why are these BVs worthy of attention? How to acquire these BVs? Who can obtain these BVs? Where are the BVs represented? Whether the BVs meet FR and C? Each question requires the related structure, behavior or function knowledge mentioned before. How the knowledge is integrated is shown in the case study of the friction evaluation of the piston ring liner system for the internal combustion engine.
- This study also proposes a web services-based design knowledge flow system framework for design evaluation. Web services-based knowledge activities include six portions: Web Service Registration, Knowledge Sharing, Knowledge Service, Knowledge Searching, Knowledge Acquisition and Knowledge Integration. The proposed knowledge classification and knowledge flow model can be applied to these activities to enhance knowledge sharing, reuse and integration in the design evaluation of mechanical systems.

Although the results of this study aid integrated designers in understanding knowledge flows in design evaluation, they have limitations. Firstly, the study does not define the representations of behavior knowledge and function knowledge. Some of this knowledge is tacit and stored in human brains. How to share this knowledge needs further research. Secondly, the application of the proposed model can be extended to other domains, such as electronics, chemicals, materials and so on. Due to different disciplinary backgrounds, the model should be separately validated and adjusted. Thirdly, a web services-based platform, in which the proposed design knowledge flow model is embedded, is yet to be developed; this is planned as future research.

Future work will include exploration of the representations of behavior knowledge and function knowledge, and the validation of the design knowledge flow model for knowledge management and reuse in order to expand to more applications for multi-disciplinary system design evaluation. The authors will also develop a web services-based knowledge sharing, exchange and integration platform, based on the implementation of the design knowledge flow framework presented in this paper.

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