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AN INTEGRATED RFBSE MODEL FOR MANAGING AND REUSING ENGINEERING DESIGN KNOWLEDGE

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Abstract

Design efficiency has significant influence on a company's sustainable competitiveness. Reusing part of the previous product design can undoubtedly improve design efficiency, and thus the need of design knowledge management and reuse is raised. In order to reuse the previous design effectively and efficiently, informal design knowledge, e.g. design experience and design rationale, is required to understand the previous designs completely before reusing them. However, most of the knowledge management activities undertaken in the companies are focused on formal design data and information. Therefore, this research aims to fill in this gap by proposing an integrated knowledge model to guide engineers in capturing useful design knowledge within the design process. The knowledge model integrates four key design elements, namely requirement, function, behaviour, structure, and considers the evolution of the design, to capture informal design knowledge with specific design context. This model has been used in the design and development of a Web-based knowledge management system and preliminary evaluation shows it can achieve effective knowledge capture and reuse.

Keywords: Integrated knowledge model, Knowledge management, Information management, Model-based knowledge representation

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1 INTRODUCTION

Design efficiency largely determines a product's lead time and thus holds the key to a company's sustainable competiveness. As a range of products in the industry are not created from none but built on the previous designs, reusing the previous designs has become essential in shortening the design time of a product (Hicks et al., 2002). As pointed out in Oldham et al. (1998), the design lead time can be reduced significantly by reusing past design. In order to reuse previous design effectively and efficiently, design knowledge management is required (McMahon et al., 2004). In this case, how to undertake knowledge management in engineering design and what kinds of methods and tools can be used to support this process has become a focus of design research. During the engineering design process, a huge amount of data and information is generated. To reuse design data and information effectively, informal design knowledge such as experience and design rationale should also be captured to provide useful design context (Bracewell et al., 2009). This kind of knowledge has significant influence in reusing previous design. In order to capture design knowledge, a knowledge representation model which can provide a clear structure and method for capturing and reusing multi-faceted design knowledge is required (Brandt et al., 2008). Although there are several models proposed to deal with engineering design and knowledge management, there is little research on an integrated model that focuses on not only formal design objects but also informal design knowledge captured as design context within an engineering design process. Moreover, the evolution process of design solutions where both formal and informal knowledge are largely required is not well addressed in the models currently available.

This paper aims to fill in these gaps by proposing an integrated knowledge representation model for knowledge management and reuse in engineering design which addresses the Requirement, Function, Behaviour, Structure and Evolution of design, and thus is called the RFBSE model. This model tries to provide guidance to designers in capturing, organising, storing and reusing design knowledge as the design process proceeds. Preliminary evaluation has been undertaken in an automotive engineering design project. Compared to several existing models, the RFBSE model can be regarded as an integrated model which not only incorporates the basic design elements of function, behaviour and structure in the FBS ontology (Gero et al., 1990), but also concentrates on capturing design knowledge with rich design context, e.g. design rationale, from consideration of requirements and the evolution of design. Also, a model-based and diagrammatic representation of design knowledge has been developed for this model, which depicts an integrated knowledge space involving know-what, know-how and know-why knowledge, to provide an easy and straightforward way for engineers to undertake design knowledge management and reuse.

The rest sections of the paper will be structured as follow. Next section reviews the existing models and methods that may help for knowledge management in engineering design. Section 3 describes the core ideas of the RFBSE model with a brief comparison to previous models. Section 4 demonstrates how the model is applied to guide engineers in undertaking design knowledge management and reuse using an automotive engineering design project as example. A discussion is made in Section 5 on effectiveness of the model and a preliminary evaluation of a prototypal Web-based knowledge management system which is developed based on the RFBSE Model, followed by a conclusion of the paper and future work for improvement in Section 6.

2 LITERATURE REVIEW

Knowledge management in engineering design has been an important research topic for decades, considering how to capture, organise and reuse knowledge during the design process. In this case, questions such as what kinds of knowledge should be captured and how to capture it become the key issues to address. There are several ways of supporting knowledge management in engineering design including developing knowledge model, language, and computer support tools. From (McMahon et al., 2004), there are two strategies for knowledge management, codification which codifies and stores knowledge in database for reuse, and personalization that share knowledge through interpersonal communication, namely explicit and tacit knowledge, which require various methods for implementation. However, both of them should clarify what kinds of knowledge are useful to be captured for reuse first. Ahmed et al. (2003) found that there is a significant difference between novice and experienced designers in their ways of understanding design knowledge. Compared to experienced designers, novice designers need guidance on what kinds of information and knowledge are useful for reuse and how to conduct reuse. This raises the needs of providing methodological tool to guide designers in knowledge management, i.e. a knowledge model and its application process.

Several kinds of knowledge models have been proposed in engineering design, and some of them can be used to support capturing and reusing design knowledge. The existing models help for capturing and reusing design knowledge includes design ontology, design process model, and knowledge representation model. Design ontology like FBS (Gero et al., 1990; Gero and Kannengiesser, 2004) and SBF (Bhatta and Goel, 1994) is more focused on classifying the inner relationships between the key design elements such as function, behaviour and structure, to give a clear view on how and where design knowledge is embedded. Also, they remind engineers the key issues to be considered during the design process, as well as what kinds of design knowledge are important to be captured for reuse. Alongside design ontology, knowledge representation model is also helpful in exploring how to structure and represent the design knowledge in a more understandable way, e.g. Functional Representation (Chandrasekaran, 1994, 2005), the TSBF model (Tian et al., 2006), RFBS model (Christophe et al., 2010) and the FCBS model (Gu et al., 2012). In addition to these, the design process model (Pahl et al., 2007) contributes to depiction of the engineering design process and demonstrates which tasks include important design information and knowledge during the process.

The three kinds of knowledge models mentioned above have specific advantages in supporting knowledge management in engineering design. However, they mainly focus on their own aspects while not being able to combine the advantage of each other. For example, design ontology does not consider how to capture design knowledge; design process model mainly explains the engineering design process; and knowledge representation model may not address the design process. Therefore, an integrated knowledge model is required to combine all the advantages of these three kinds of model in order to classify what kinds of design knowledge are useful to capture for reuse and how to implement effective capture and reuse as the design process proceeds.

3 THE REQUIREMENT-FUNCTION-BEHAVIOUR-STRUCTURE-EVOLUTION MODEL

In order to capture and reuse design knowledge, a knowledge representation model is required. For design engineers, the guidance from the model can be understood better if it is based on the design process. Thus, the Requirement-Function-Behaviour-Structure-Evolution (RFBSE) model is proposed to achieve this goal. As its name suggests, the RFBSE Model considers 5 aspects in supporting design knowledge management and reuse throughout the design process. Among them, the Function, Behaviour and Structure are considered in the way similarly to the ones in the FBS ontology (Gero, 1990), which describes the key design elements in engineering design as well as their relationships. Function is the objective to be achieved through the design process, which determines the expected behaviour to be generated and has influence on the structure decomposition of a design solution. Structure includes the form of the product, e.g. geometry and materials, classifying its physical construction. There are two aspects of behaviour, one is the expected behaviour derived from function and another is the actual behaviour generated by a structure. As not all the requirements are known at the beginning of the design task, conceptual design involves finding what is needed and modifying it again during the process (Gero and Kannengiesser, 2004). In this case, the relationship between requirement and function should be captured, as well as the evolution of the requirement and reason behind it. Moreover, development time, product quality and customer value can be improved by effective requirements management (Baxter et al., 2007). Thus, the requirement element is also regarded as an important aspect in the model. The fifth element of the model is evolution, which focuses on capturing the considerations and reasons behind the changes and developments across the design process by the integration of know-what, know-how, and know-why knowledge. For these three kind of design knowledge, know-what describes what change has been done and what the issue is, know-how considers how the change has been done and how to solve the problem, and know-why explains the reasons behind the changes. In this way, the evolution element enables the integration of the other aspects by considering a range of change during the design process, including functional decomposition based on requirements, design iteration when comparing the expected behaviour and actual behaviour, etc. Thus, by exploiting the evolution process, informal knowledge generated and used during design iteration can be effectively captured in addition to formal design knowledge.

To be more specifically, requirement, function, behaviour and structure are the four design elements considered according to different design tasks (indicated as 1 through 4 in Figure 1) during the design process.

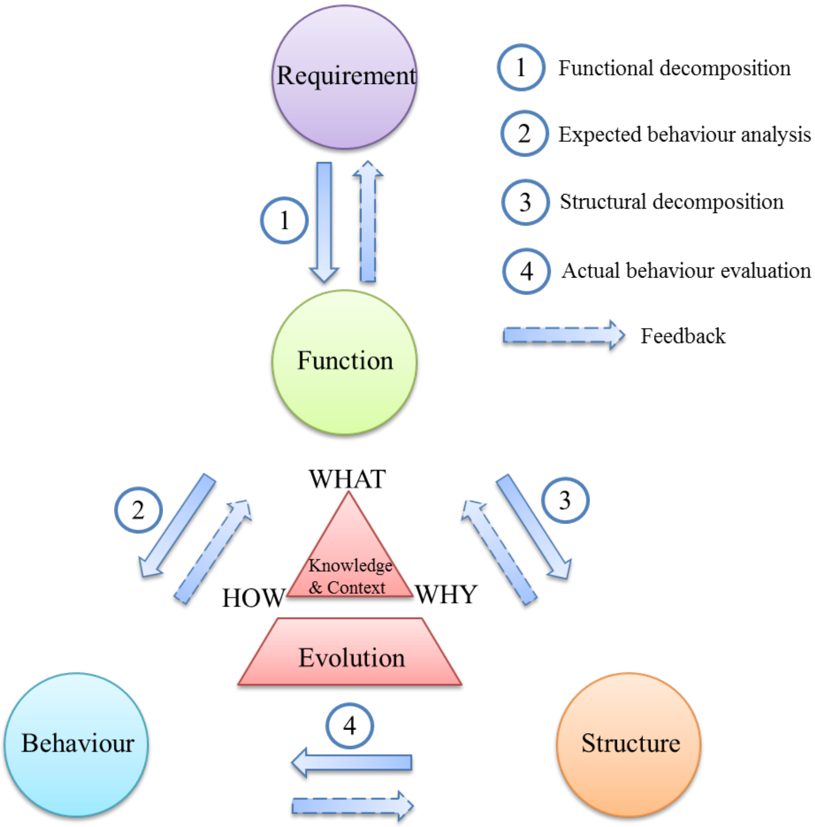

Figure 1. Structure of the Requirement-Function-Behaviour-Structure-Evolution model

At the beginning of design process, a range of requirements and constrains are analysed to determine functions which are the objectives to be achieved during the process. Based on the needs identified a functional decomposition will be undertaken to obtain a range of sub-functions. During this process, the knowledge on how a function can meet a specific requirement is valuable for reuse, especially when the requirement has been changed. In order to achieve the functions, several activities are undertaken, such as idea generation and evaluation, which obtain the expected behaviours of product at the conceptual design stage. Within this stage, a large amount of knowledge will be generated and shared during design divergence and convergence, problem-solving, and decision-making processes. These kinds of knowledge indicate the key issues for the design, especially the design rationale, thus should be captured for reuse. At the same time, a structural decomposition can be derived from the result of functional decomposition, which has the benefit of structuring and organising the design knowledge about sub-components. When structure is generated, the actual behaviour derived from it can be compared with the expected behaviour obtained from functions for evaluation. Within the evaluation process, several changes might be undertaken in order to obtain an optimal design to meet the requirement, and the design knowledge generated during this process is useful to indicate what kinds of change have been made (know-what), how the changes have been made (know-how) and the reason behind them (know-why). Besides, there are feedbacks for all these four stages as part of the design iteration, which involve design knowledge explaining how the design can be further improved. Thus, the RFBSE model aims to capture the design knowledge generated during these four design stages and the feedback-providing procedures by classifying the knowledge into know-what, know-how, and know-why. Considering the efficiency of reuse, the knowledge context is also significant and should be captured together with specific design knowledge. Overall, the RFBSE model can be used during the design process to capture design knowledge from the evolving processes for future reuse.
Based on the above discussion, the RFBSE Model has incorporated the three main elements in the FBS ontology, which thus allows the model to process the advantages of FBS in clarifying the relation

between key design elements. However, the FBS ontology, although being able to record design iteration, cannot address the evolution of design for the reasons stated above while the RFBSE model considers the dynamic changes during the design process. More importantly, the RFBSE model not only identifies the relationship between the design elements, but also concentrates on capturing the design knowledge through the design evolution process. Comparing to the existing RFBS model (Christophe et al., 2010) which is based on FBS ontology and considers the synthesis of structural concepts, the RFBSE model focuses on the design knowledge management and reuse throughout the design process by classifying design knowledge into know-what, know-how and know-why with specific design context. Therefore, the RFBSE model is an integrated model which incorporates the key elements of some previous design ontology, design process model and knowledge representation model, and more importantly concentrates on how to capture and reuse design knowledge generated during design evolution.

4 APPLICATION OF THE MODEL

An example in automotive engineering design has been chosen to demonstrate how to apply the RFBSE model in capturing design knowledge during an engineering design process. The example is an intake system design from a Formula Student racing car design project. Formula Student (FS) is Europe's most established educational motorsport competition, run by the Institution of Mechanical Engineers (IMechE). The main requirements of this design come from the official regulations of the competition organiser. By understanding and analysing the requirements, the functions and sub-functions are derived with a functional decomposition process, as shown in Figure 2. This is the initial step of general design process as well as the first procedure demonstrated in the RFBSE model to capture design knowledge. During the functional decomposition process, the relationship between a particular requirement and the specific function to be generated to meet the requirement can be captured, as well as the knowledge about this relationship. For example, the requirement 'the inner diameter of the intake main body neck should not beyond 20mm, in order to control the maximum power of the engine' is relative to the sub-function 'Control air supply' in Figure 2, this relationship is recorded as a piece of know-what knowledge which allows the quick adjustment of function if the requirement needs to be changed in the future. Besides, it also gives a clue on what kinds of function can be used to meet a certain requirement. Thus, capturing the relationship between a requirement and a function helps future update and reuse.

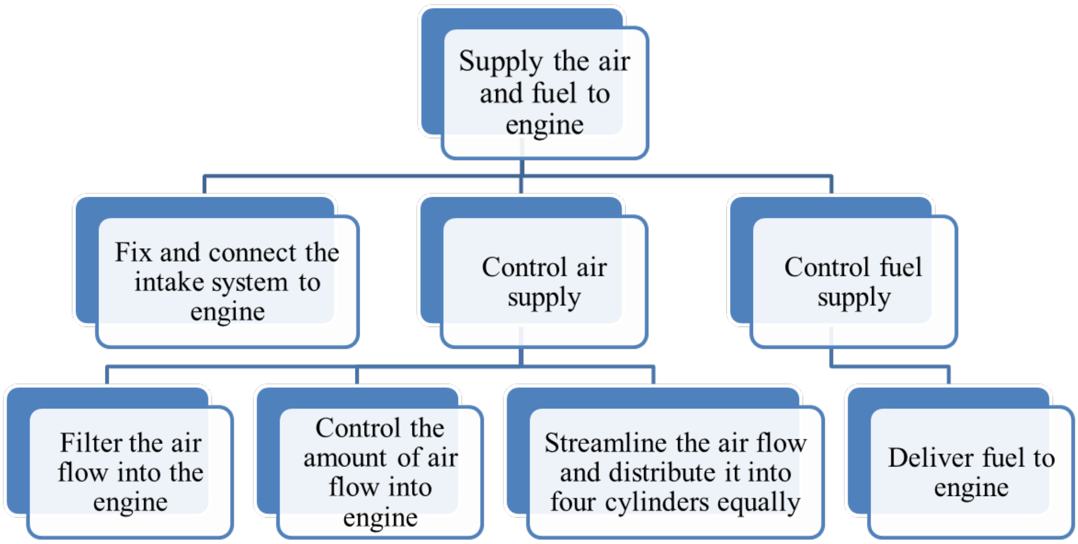

Figure 2. The functional decomposition process

Then, the expected behaviour analysis process will be undertaken based on the decomposed functions. For the functions and sub-functions, a range of expected behaviours are considered to achieve them and followed by analyses undertaken, as shown in Figure 3. This is the second procedure specified in the RFBSE model, which takes place during the conceptual design process. During this process, there are a range of iterative activities to be undertaken, e.g. idea generation and evaluation, problem solving, and decision making processes. Through these activities, knowledge created can be categorised into three types, namely know-what, know-how, and know-why. Which means each piece of complete knowledge can be described and demonstrated using these three types of knowledge, e.g. 'what materials will be used to product this intake plenum', 'how to manufacture this intake plenum', and 'why the intake plenum is designed using this structure'. These kinds of knowledge can be linked together to the component intake plenum to form a complete piece of design knowledge. Also, in this way, the context of the knowledge can be captured. Besides, this way of structuring design knowledge can be used to explain design rationale, and links to specific design process in order to clarify the context of knowledge.

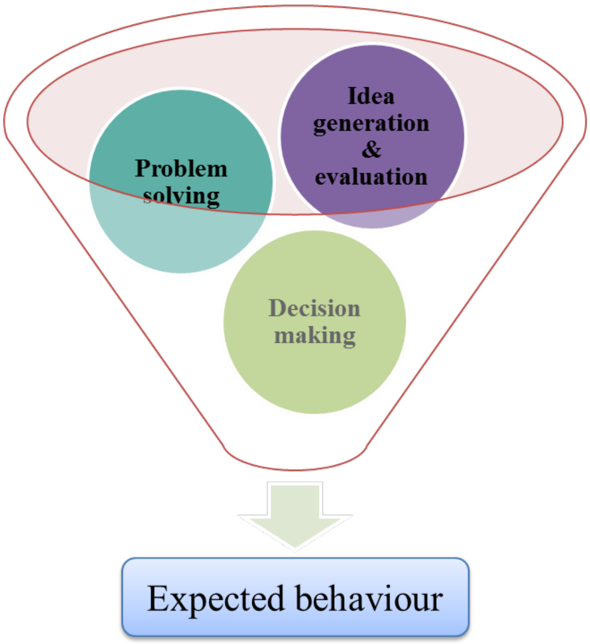

Figure 3. The expected behaviour analysis process

At the same time, structure of product is obtained through the synthesis based on expected behaviours. As the design knowledge generated during the expected behaviour analysis process relates to specific component of the product, it will be much easier to understand and reuse if it is organised base on product structure. In this case, structural decomposition is required to provide a clear framework to organise the design knowledge, which can be undertaken according to the functional decomposition. The RFBSE model proposes a method to derive structural deposition according to functional decomposition, which is to divide a system into several components based on the main functions they are going to achieve. This method can not only provide a clear way to structure design knowledge relevant to different components, but also build a relationship between function and structure. According to the functional decomposition, in this example, the intake system has been divided into 5 main components, namely air filter, throttle, intake plenum, connector, and fuel injector relating the main functions they aim to achieve, as shown in Figure 4. This composition is derived based on the functional decomposition of the intake system, which not only helps to establish a connection between sub-functions and components of the product under specific context, but also provides convenient ways to capture and organise the design knowledge of each component. Thus, it has the benefit of reusing design knowledge based on the classified relationship and knowledge context.

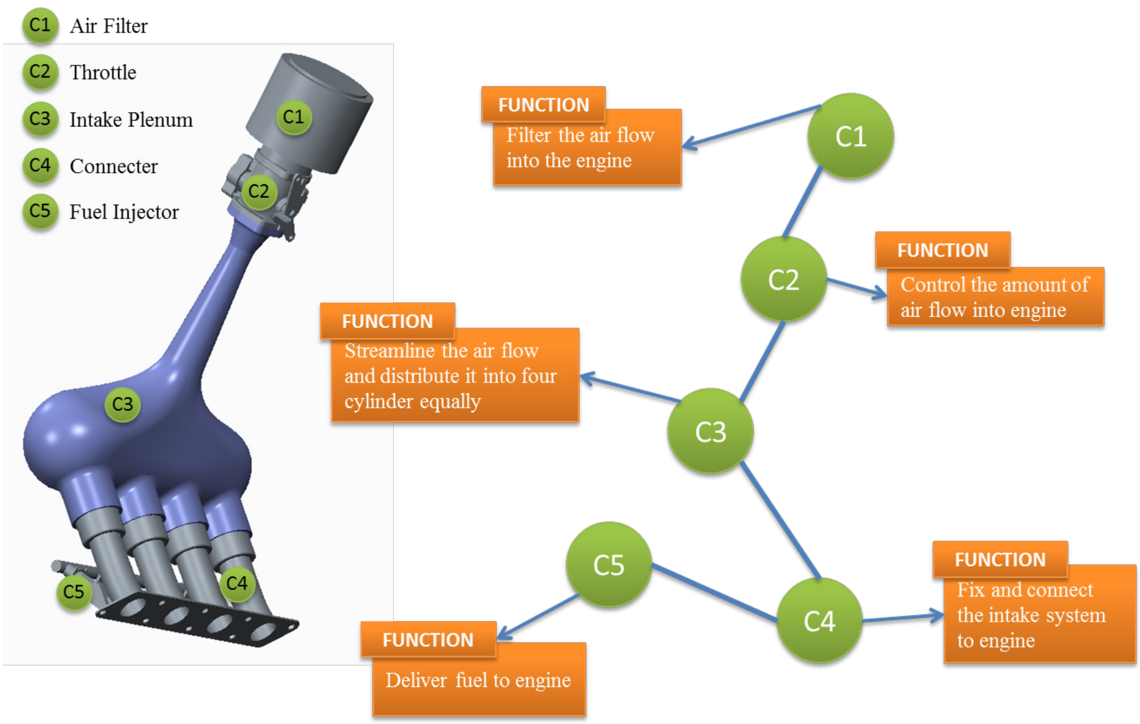

Figure 4. The structural decomposition process

When the structure of the system and its components are generated, their actual behaviours can also be determined. Then, the next design task is to evaluate the actual behaviour of the system or components by comparing them with their expected behaviours so as to identify areas for improvement. This is actually an evolution process which contains a range of iterations and changes in evaluating whether the structure meet the requirements, an example is shown in Table 1. In this case, the design knowledge generated throughout the process, especially design rationale, is significant as it describes what the aspects to be improved are (know-what), how to improve these components (know-how), and why the improvements have been undertaken in this way (know-why). This evolution process happens not only during the conceptual design process, but also in the embodiment and detailed design processes. As the design knowledge driving decisions made in the evolutional process relates to how to improve the product, it is significant for future reuse.

Table 1. The actual behaviour evaluation process

	Expect Behaviour(Be)	**Actual Behaviour (Ba1)**	**Actual Behaviour (Ba2)**	**…**
Air flow rate	Limit the amount of air flow into intake plenum	The maximum air flow rate into intake plenum by simulation	The maximum air flow rate after modifying the structure	
Parameter 2	Expected physical parameter/state	Result of simulation/calculation	…(comparing to Be & Ba 1 after modification)	
Parameter 3	Expected physical parameter/state	Result of simulation/calculation	…(comparing to Be & Ba 1 after modification)	
. . .				

According to the demonstration above, the RFBSE model guides engineers to capture useful design knowledge through four design processes, functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour evaluation. It reminds which kinds of knowledge is significant to capture for reuse and on this basis provides a way for implementation.

5 PRELIMINARY EVALUATION AND DISCUSSION

Compared to the existing models, the RFBSE model can be regarded as an integrated model. It incorporates the advantages of the FBS ontology in clarifying the relationship of three basic design elements, and aims to capture informal knowledge such as design rationale within the evolving design process. Based on the four key design elements, namely requirement, function, behaviour and structure, the model involves three knowledge types, know-what, know-how, and know-why to describe different pieces of knowledge containing specific contexts in different design tasks. Apart from capturing design knowledge through four main processes, namely functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour evaluation, the evolution of design solutions is also considered and included in the model as another core element. The co-evolution processes relating to product function, behaviour and structure involve a large amount of knowledge in particular design rationale, and thus holds the key to effective understanding and reuse of design knowledge. Moreover, the RFBSE model emphasises the importance of capturing design knowledge as the design process proceeds, which results in two main advantages. Firstly, the knowledge model can not only help the engineers to capture and reuse design knowledge, but also can provide guidance on specific design tasks within the design process. Secondly, as the design knowledge capturing is undertaken as part of the design process, it decreases engineers' burden to complete knowledge management tasks, e.g. writing a design report. Besides, the RFBSE model considers the time factor during the design process through exploiting the evolution of design solutions, and it allows considering dynamic issues throughout the design process. Frequently, it is necessary for the current designer to understand that why the previous design has been changed in certain ways in order to continue to improve the current design. Then, tracking the evaluation of the design becomes significant. Furthermore, the RFBSE model has raised the importance of categorised knowledge type and considering knowledge context. The model classifies design knowledge into know-what, know-how and know-why knowledge, and proposes to capture them based on their specific context during the design tasks, which can support subsequent design knowledge retrieval and reuse.

For further evaluation and application, a prototypical Web-based knowledge management system has been developed to implement the RFBSE model in the design knowledge management and reuse tasks, and a part of its Graphical User Interface (GUI) is shown in Figure 5

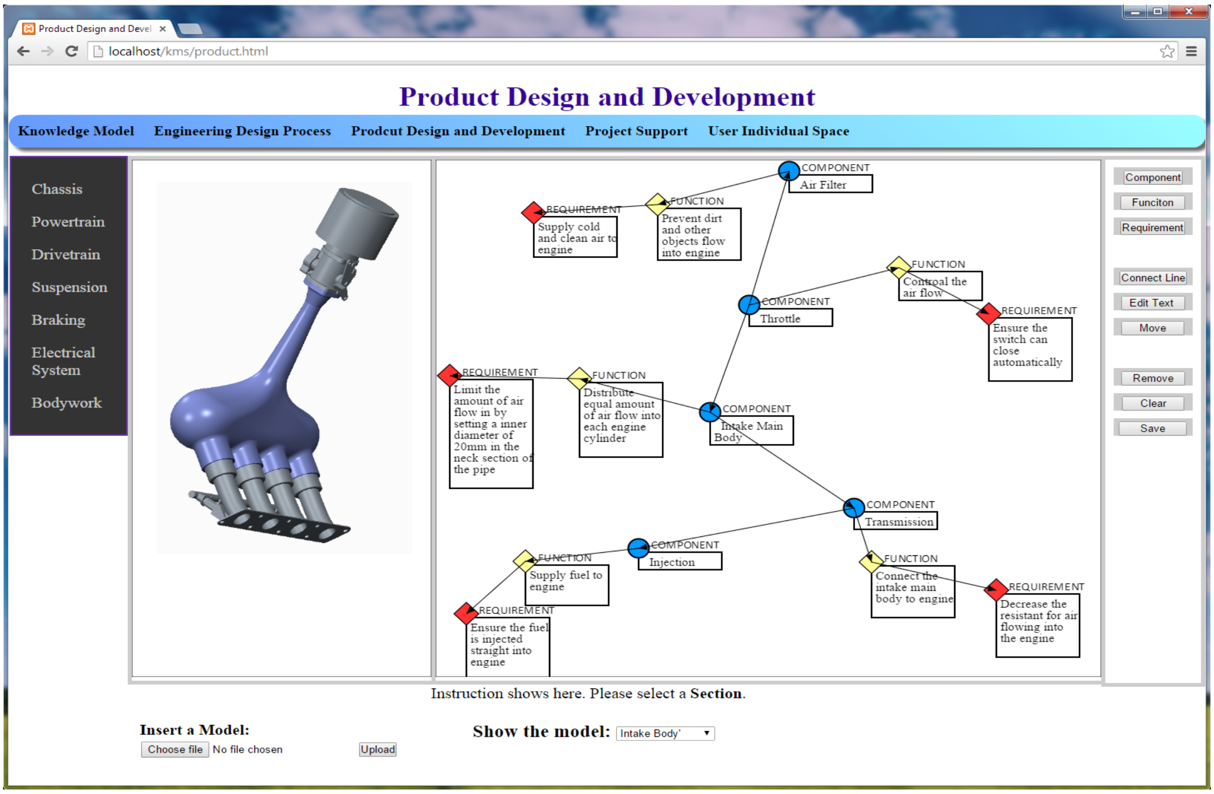

Figure 5. The Prototypical Web-based knowledge management system

As shown in Figure 5, the interface of the system is Web-based, which has the benefit of supporting a distributed and collaborative working environment. The core of the system is built based on the RFBSE model, aiming to implement the methodology proposed based on the model to capture and reuse design knowledge. Thus, within the system, a model-based and diagrammatic representation is used, which has the benefit of giving the engineers a clear and visualised structure of design knowledge to be captured and reused. As the functions of the system will be implemented based on the RFBSE model, the knowledge model can be used to guide the process of capturing design knowledge through the system. In the preliminary evaluation of the system, design engineers are asked to capture the design knowledge with and without the model to test whether the model can improve the effectiveness and efficiency in design knowledge management process. According to the feedback of a group of automotive engineers who have used the prototype system without knowing the RFBSE model for evaluation found that it is good to have a system to capture design knowledge, however they have little idea in what should be recorded down and how to structure it. By comparison, another group of engineers have been taught about the RFBSE model and the way to use it to support capturing design knowledge. The feedback of this group is positive and showed the model gives them the ideas on how to capture the knowledge during the design process and how to organise it. Besides, both the groups have highly recommended on using diagrammatic representation as it gives a clear view on both the capture and reuse of design knowledge. Moreover, using 3D representation (attach design knowledge on the various section of its specific 3D model) is also welcomed by the engineers according to their feedback. Thus, the preliminary evaluation results indicate that capturing design knowledge using a Web-based knowledge management system supported by the RFBSE model is useful and viable, as it can guide engineers on what kinds of design knowledge are useful for reuse and how to structure it, which can offer further help to them to decrease the time of gathering information and knowledge.

6 CONCLUSION

A RFBSE model is proposed to improve knowledge management and reuse for engineering design. Integrating four key design elements (requirement, function, behaviour and structure) and a core element (evolution), the model aims to capture design knowledge for reuse during four main design tasks, namely functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour evaluation. This model incorporates the advantages of the FBS ontology in clarifying the relationship of key design elements, and captures informal knowledge such as design rationale in considering the co-evolution of product function, behaviour and structure as well as the reasons and considerations behind changes and developments. This knowledge representation model is designed to be an integrated part of the design process, through which the design knowledge can be captured as a design proceeds rather than retrospectively, thus it can provide support to the design process at the same time. Moreover, the model has classified design knowledge into know-what, know-how and know-why, and emphasised the importance to capture the knowledge context together with the design knowledge in order to achieve better retrieval and reuse.

Based on the RFBSE model, a prototypical Web-based design knowledge management system has been designed and developed for implementation and evaluation. Future research work will be focused on evaluating the prototype system in terms of how to combine the knowledge representation model and system for effectively undertaking design knowledge management and reuse, as well as on optimising the functionality of the system.

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