A collaborative system for capturing and reusing in-context design knowledge with an integrated representation model

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ARTICLE INFO

ABSTRACT

Current research on design knowledge capture and reuse has predominantly focused on either the codification view of knowledge or the personalisation view of knowledge, resulting in a failure to address designers' knowledge needs caused by a lack of context of information and insufficient computational support. Precisely motivated by this gap, this work aims to address the integration of these two views into a complete, contextual and trustworthy knowledge management scheme enabled by the emerging collaborative technologies. Specifically, a knowledge model is developed to represent an integrated knowledge space, which can combine geometric model, knowledge-based analysis codes and problem-solving strategies and processes. On this basis, a smart collaborative system is also designed and developed to streamline the design process as well as to facilitate knowledge capture, retrieval and reuse as users with different roles are working on various tasks within this process. An engineering case study is undertaken to demonstrate the idea of collaborative knowledge creation and sharing and evaluate the effectiveness of the knowledge representation model and the collaborative technologies employed. As evidenced in the development and evaluation, the methods proposed are effective for capturing an integrated knowledge space and the collaborative knowledge management system not only facilitates problem-solving using knowledge-based analysis but also supplies in-context tacit knowledge captured from the communications between users throughout the design process.

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1. Introduction

Engineering design is a knowledge-intensive process and designers need a lot of informational support throughout this process. A recent study has shown that engineers spend nearly 60% of their working time engaged in all types of information-related activities [1]. These activities include using software packages to process information and facilitate knowledge-based engineering analysis as well as sharing knowledge with colleagues to improve decision making. In this sense, design knowledge takes the form of both tangible objects that can be edited, copied, transferred and programmed and precious experience that can only be learnt through a community of expertise, i.e. the codification view and the personalisation view of design knowledge [2]. Knowledge Management (KM), as a key enabling technology for distributed enterprises in the 21st century, has attracted considerable attention in recent engineering design research [2]. Previous research on KM for engineering design tends to be very diverse, ranging from understanding engineering designers in design activities in terms of their information needs, information organisation and usage, and information-seeking behaviours [3–10], to the development of structured models to represent design knowledge [11–16] as well as the development of methods and tools for knowledge capture, retrieval and reuse [14,17–21].

However, there still exist a few barriers to effectively applying KM tools to design projects. First, a recent study has revealed an apparent failure to satisfy designers' knowledge needs due to the variety of the needs and current knowledge models' particular emphasis on formal design knowledge [7]. Second, knowledge capture tools are quite intrusive in the sense that they are not used as an integral part of the design process, resulting in a lack of design context [21]. In addition, knowledge retrieval research is far from being enough, making the tools hard to use especially when a large amount of knowledge records have accumulated [22]. Third,

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current research has a particular focus on either designers or knowledge objects while an integrated approach to addressing both the knowledge objects and the processes whereby these objects are created and designers' communications largely take place [21].

These barriers are to some extent ascribed to a separation of the personalisation and codification views in the current research on KM for engineering design [2,22]. The emerging collaborative technologies have great potential for addressing these barriers by providing a smart collaborative computing environment and facilitating designers' knowledge acquisition and sharing activities. This research precisely aims to address this gap by developing a novel knowledge representation model that emphasises placing designers in the very centre of the knowledge creation and sharing process. The capture of informal knowledge created and shared during design communication can provide important design context for formal knowledge objects. Additionally, it is also focused on exploring the potential of the collaborative computing technologies towards the development of next-generation collaborative knowledge management systems.

The rest of this paper is organised as follows. Section 2 reviews related work on knowledge management, knowledge representation and designers' collaboration and communication during the design process. In Section 3, a knowledge model for representing an integrated knowledge space is described with a particular focus on the integration of different kinds of knowledge with different forms and granularities of information. Section 4 details a method for knowledge-based engineering analysis which, based on knowledge of domain experts, can transform customers' needs and expectations into detailed functional requirements. In Section 5, the design, development, and evaluation of a smart collaborative system for design knowledge management is explained. Finally the discussions and conclusions are given in Section 6.

2. Literature review

2.1. Data, information and knowledge

Knowledge engineering is critical to research and development of enterprises [23]. In the context of engineering design, knowledge management specifically aims to reuse useful knowledge in new design tasks and this reuse is realized through transferring knowledge in the form of information. As such, the terms 'knowledge' and 'information' are often used interchangeably while 'knowledge' is particularly used to emphasise reusing knowledge [1,3,4,7,12,16,20,24–27]. A differentiation of the terminologies can help researchers identify the particular focus of research to achieve an appropriate scope of definition [2,7]. Specifically, data refer to raw data in the form of numbers, words, symbols, etc. to describe basic facts, which can be created, copied, edited and deleted. Information usually takes the form of structured data, which is more tangible than knowledge. The terms 'information' and 'information management' are often used in the context of knowledge and knowledge management as information is a necessary medium or material for eliciting and constructing knowledge [2]. Information in itself does not necessarily embody knowledge which is more about beliefs and commitment and is usually associated with actions and particular business processes [2].

Knowledge is difficult to assimilate and has a personal aspect which demonstrates the key difference between knowledge (as a 'competence notion') and information (as tangible objects that can be managed) [2]. In this sense, the terms 'tacit knowledge' and 'explicit knowledge' have proposed as a way of differentiating between personal knowledge and that which has been codified as a company information resource. Tacit knowledge resides in a com-

munity's know-how which can be market-based (in products), infrastructure-based (in systems), personal (concerning staff and competence of suppliers) or administrative (concerning workflow and processes) [2]. The term 'knowledge model' has been used to refer to an information representation scheme for facilitating codification [12,16,28–30]. In this paper, unless otherwise stated, formal knowledge is used to describe engineering know-what and know-how embodied in codified information sources such as a 3D geometric model, a simulation model, a data-accessing source (e.g. material and manufacture data) or a computer routine (e.g. parameters optimization); and tacit knowledge refers to engineering know-how and know-why in relation to personal knowledge and experience (within a community) of understanding an issue, developing a problem-solving strategy, considering necessary constraints and options, and reasoning on possible decisions. These are within the scopes of term definitions identified in literature. A knowledge model is used as a scheme of representing an integrated knowledge space covering both the formal and tacit aspects.

2.2. Knowledge management for engineering design

Engineering design is heavily informational [9] and designers require a variety of information and knowledge from various sources to support their decision-making [2,7]. Therefore, understanding the knowledge needs and information usage behaviours of engineering designers has long been a focus of KM research for engineering design [3–6]. It is a common practice for designers to use formal knowledge in various forms such as sketches, CAD models, calculation sheets and simulation results [10,24]. In addition, a good design largely depends on the experience relating to design strategies generally possessed by experienced designers. This kind of experience is often termed 'internal knowledge' or 'informal knowledge', which provides the basis for developing a 'corporate memory' bank [31]. Research on KM for engineering design generally falls into two categories in terms of the two focuses on different knowledge types, namely personalisation and codification [2]. The former is more focused on informal knowledge, emphasising a range of organisational issues such as the communication between designers in a distributed design team, while the latter involves technological issues such as the application of Information and Communication Technologies (ICTs) to the codification of formal knowledge. Work on understanding through-life knowledge and information represents one of the trends for recent research in this area [27,32]. In addition, despite it is difficult to codify informal knowledge, its importance has been highlighted by many researchers [14,22,33]. It has been indicated that, in terms of reuse, KM needs to focus on the experiences pertaining to the decision processes associated with the various design phases, e.g. the utilisation of new technologies and the specification of engineering components [25]. However, the valuable knowledge of experienced departing staff is not readily captured [22]. This is in part ascribed to the particular focus of existing KM research for engineering design on either the personalisation view or the codification view, e.g. ICTs are typically only used for codification [2,33]. Therefore, an integrated approach to KM can facilitate capturing and reusing informal knowledge and thus can achieve improved design quality and efficiency.

2.3. Knowledge representation, retrieval and reuse

Research in this area aims to develop enabling technologies for KM tools. For instance, the organisation and storage of design information has been explored [10,25,34], and its computer support has also been developed [26,35,36]. Various models have been developed to represent formal knowledge such as the knowledge model for an artefact repository [37], the

function-behaviour-structure model [11,13] and the knowledge model describing design processes [12]. In addition, the models for representing informal knowledge have also been developed such as design rationale [14,30]. Ontology-based approaches have been developed for specific applications of knowledge engineering such as those related to innovation, intellectual property and patent analysis [23]. However, a major problem of the models is the ineffectiveness to address the multi-faceted feature of design knowledge as design involves different issues requiring knowledge at different levels and from different sources [2]. This results in either the tools based on formal models failing to capture useful context or the tools using informal models being not an integral part of design [14,21]. To enable effective reuse, integrated models are required for next-generation KM tools to capture knowledge that is related to the evolution of design models and has rich context for retrieval and reuse [21,28,29]. Knowledge retrieval is also of significant importance to KM tools. Ontology-based methods and intelligent systems have been introduced to enable effective classification and search of design knowledge [38]. However, previous research has shown that, despite the ever-increasing investment in ICT within enterprises, the most effective and efficient way of finding and re-using design information is still by consulting experienced colleagues [3,6,21,31], which is in part due to information overload and ineffectiveness of retrieval [22]. Work in this area is much less compared to knowledge capture [17]. Moreover, most knowledge retrieval methods developed in previous research are based on formal knowledge models and cannot effectively find contextual design information [17,39,40]. Consequently, more research is required to develop intelligent retrieval methods in conjunction with the development of effective knowledge models.

2.4. Collaboration and communication in knowledge sharing

Effective communication between engineers can support the creation of a shared understanding of the problem and facilitate knowledge dissemination, which is a critical part of a successful project particularly for the newly-formed teams [41]. Additionally, communication has an important role to play in KM for engineering design as it involves rich contextual information that can facilitate knowledge reuse [21] while not compromising innovation [42]. Additionally, advanced KM methods are also very important for design collaboration and thus raise the need of researching smart KM methods supporting a collaborative design process [38]. The multi-disciplinary, highly-collaborative and highly-contextual nature of engineering design has raised the requirement of supporting integrated and collaborative product development for next-generation design systems [37]. In the meantime, engineering companies need to make best use of various electronic information and knowledge repositories as well as the person-to-person sources [25]. As their working practices have become more mobile and distributed [37], distributed KM has been identified as one of the key enabling technologies for collaborative product development [43]. In addition, collaboration in KM is needed to utilise not only internal knowledge but also external out-of-sector knowledge sources [44]. This necessitates the development of computer-mediated methods in support of communication and collaboration in KM. Although e-mail is currently the most common means of communication and plays an important role in project management [45], it does not possess the capability to effectively support design communication [37]. While the importance of developing advanced ICT tools and systems to support collaboration and communication has been highlighted in recent research, little work has yet been done in this area [21,44]. The reasons for this are twofold: (1) it is a very new area and (2) it largely relies on the development of effective knowledge models and retrieval methods that can effectively address collaboration and communication. However, this opens up the opportunity for timely and novel research on developing ICT methods and tools to support collaborative KM.

In summary, the multi-disciplinary, highly-collaborative and highly-contextual nature of engineering design has raised the need of managing designers' communication and collaboration in capturing and sharing knowledge, i.e. supporting collaborative KM. This paradigm emphasises the capture of contextual informal knowledge to facilitate effective knowledge creation, sharing and reuse in a distributed and collaborative environment. It can greatly improve KM effectiveness, and thus help improve design quality, facilitate innovation generation and reduce design cost [21]. Meanwhile, it emphasises an open virtual working environment and has the potential of offering KM functionalities as software services, making KM more accessible to Small and Medium sized Enterprises (SMEs).

3. Representation of an integrated knowledge space for collaborative engineering design

3.1. Problem statement and research methods

Existing solutions for capturing and reusing design knowledge have mainly focused on either codifying knowledge for specific design problems to enable computer-assisted generation of design objects and analysis routines, e.g. Knowledge-Based Engineering (KBE), or capturing designers' knowledge and experience of analysing design issues and making decisions, e.g. capturing design rationale. Previous research has identified a number of shortcomings of current KBE research: (1) case-based, ad hoc development of KBE applications with a lack of generic solutions suitable for a wider range of engineering problems; (2) a tendency towards development of 'black-box' application - apparently there is a lack of explication of formulas and the actual meaning and context of the captured knowledge; and (3) a lack of knowledge reuse - higher-level knowledge such as project constraint reasoning, problem resolution methods, solution generation strategies, design intent and supply chain knowledge is often not captured [46]. As an effective and contextual means of describing how design tasks are approached and how design issues are addressed, design rationale has a limitation in its focus on high-level knowledge at early design stages [14]. Moreover, the accumulation of design rationale records will increase the difficulty of knowledge retrieval as well as the difficulty of linking descriptive knowledge records and detailed information such as design variables and mechanisms for the optimization of these variables [29].

The limitations of these solutions will inevitably lead to some intrusive tools which involve knowledge capture in a retrospective manner without useful design context and cause obstructive interactions that limit knowledge sharing. Additionally, little work has been in current research to provide computational support for knowledge retrieval and reuse [29]. As such, this research seeks to develop a new solution to capture knowledge exchanged by design engineers in a collaborative working environment as design issues are resolved and design objects are created. Unlike existing work, such a solution also explores collaborative technologies and emphasises developing computational methods for effective retrieval and reuse of knowledge particularly for embodiment design when design parameters are specified through design iteration. Although it is hardly possible to use one solution to address tacit knowledge codification for all design tasks, the proposed solution moves a step forward through supporting capture of tacit knowledge from a collaborative working process and linking it to low-level details (e.g. design variables) for effective reuse.

This solution can lead to development of new knowledge management systems that can support designers by supplying

in-context design knowledge for reuse in generation of design concepts and embodiments and is particularly useful for iterative design tasks such as those in the aerospace and automotive industries. As such, the research methods employed are predominantly computational. First, a framework for such a collaborative knowledge management solution is proposed as a reference structure for developing this kind of knowledge management systems. Second, a knowledge model is developed to provide a graphic representation of an integrated knowledge space about both how design objects are created and how design issues are addressed. Third, an intelligent knowledge retrieval method is developed to efficiently match designers' knowledge needs and contexts of working to actions and solutions previously considered and taken in other projects. Fourth, a prototype system is developed to demonstrate the proposed methods and evaluate the effectiveness of the model. Fifth, further extension to the system is made to conduct more case studies in different projects from different sectors and on this basis systematic evaluation can be done by comparing data obtained from these studies. This paper describes results from this early stage of the project and has a focus on describing the overall solution, reporting the proposed solution along with some enabling technologies, i.e. the first three methods. Preliminary results obtained from the fourth method are also included to demonstrate the prototype system as an example of the solution as well as to evaluate the model and retrieval method. Results from the fifth method together with detailed improvements (e.g. integration with existing CAX systems) to the methods are outside the scope this paper and will be reported in future publications.

3.2. A framework for integrated and collaborative knowledge management

The solution proposed in this work consists of a number of methods each of which aims to address a specific issue such as representing an integrated knowledge space or supporting automatic suggestion of potential solutions and actions. To give an overview of this Integrated and Collaborative Knowledge Management (ICKM) scheme as well as descriptions to its key components, a system framework is developed and shown in Fig. 1. In the centre of the figure are the lifecycle stages of knowledge management all of which are linked to specific design activities (e.g. selecting the

diameter of a turbo charger). For each of these activities, formal knowledge and tacit knowledge is linked through an integrated knowledge model. Different users with different roles can work in this virtual collaborative environment as a design project proceeds to create knowledge records and receive suggested knowledge records. Four main underpinning technologies are listed in the bottom of the figure, which need to be developed to implement an ICKM system.

An advanced distributed computing environment is exploited in this framework to facilitate collaborative work and system integration, providing a virtual working space for different users to undertake design tasks as well as knowledge management tasks. This means a range of computational methods need to be developed to integrate design objects and associated problem-solving and decision-making knowledge as well as to enable supplying design knowledge according to specific context of working. Another feature of the framework is that design activities are placed in the very centre, meaning this ICKM scheme aims to make knowledge capture and reuse an integral part of the design process. In other words, design knowledge will be captured as a design project proceeds (i.e. as design issues are being addressed) whilst previous knowledge will also be supplied to designers to drive the design process. The whole knowledge lifecycle is also an important part of the framework, which applies to any knowledge records to be created within ICKM. A knowledge record can be created in response to a request for any level of information granularity, i.e. knowledge capture can be done for both large scale projects and small scale issues. In ICKM, both formal knowledge (e.g. use of a set of formulas, structured material data and geometric models) and informal knowledge (e.g. experience of considering issues, strategies of problem-solving, and justification and evaluation of solutions) are supported across the lifecycle.

Supporting collaborative design is another important feature of the framework and this collaboration can take place between participants with different roles across the whole product lifecycle such as design engineers, project managers, system analysts, service engineers and manufacturing engineers. This not only extends applications of knowledge-based engineering to the whole product lifecycle but also enables capture of complete, contextual and trustworthy knowledge through combining the considerations and options of different participants of the same project. A
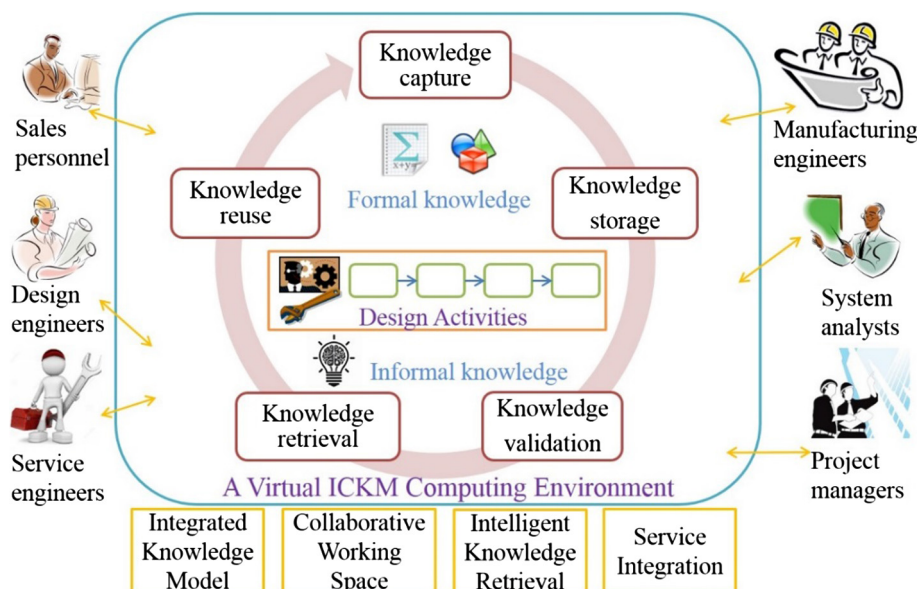

Fig. 1. A framework for integrated knowledge management for collaborative engineering design.

considerable amount of work is required towards a full implementation of the framework for the development of next-generation ICKM systems. First, a knowledge model is required to integrate formal knowledge and tacit knowledge into an integrated knowledge space. Second, a lot of computational methods are needed to enable representation and exploitation of design context. Third, a distributed computing environment needs to be developed to support acquisition and dissemination of design information as well as to facilitate completion of design tasks. Last but not least, advanced knowledge retrieval methods need to be developed particularly for high-level and in-context tacit knowledge. This paper focuses on the development of an integrated knowledge representation model as well as a few enabling methods for a prototype collaborative system.

3.3. Interaction and integration of formal and tacit design knowledge

Integration of formal and tacit design knowledge is highly important for the ICKM framework. Understanding the differences between formal and tacit design knowledge needs to be done in the first instance. A lot of research has been done to provide a clear understanding of the concepts of data, information and knowledge in the context of design [2]. Fig. 2 gives some examples to explain the main differences between formal and tacit knowledge and interested readers can refer to the references for more detailed discussions of these concepts. In this figure, formal knowledge practically refers to a range of know-what and know-how embodied in codified information resources in computers with various granularities of information from a CAD model or simulation model to the use of a computer procedure to conduct a calculation using structured data, and even to particular sections of a design report. In this sense, formal knowledge means tangible objects that can be arranged, programmed, copied, transferred and measured. On the other hand, tacit knowledge largely exists in designers' brains and can drive a process of using intelligence and knowledge to complete a problem solving process. Fig. 2 gives some example of tacit knowledge and it can be seen that tacit knowledge is hard to articulate and requires elaboration of a knowledge model.

Formal knowledge often relies on important contextual information and an explanation of associated procedures and considerations to make it easy to reuse. Tacit knowledge, although very contextual and logical, requires an effective method of articulation and representation. As such, a generic structure is needed to consolidate the advantages of formal and tacit knowledge in the integration of the two.

To develop such a structure, a form needs to be given to tacit knowledge and the interactions between this form and formal knowledge items need to be identified. As supporting design activities sits in the centre of the ICKM framework, an issue-based process model is developed in this research to describe tacit knowledge as design issues are addressed. The interactions between formal knowledge items and this process-based knowledge description are analysed based on how the knowledge needs of designers identified in [5] are fulfilled, as summarised in Table 1. It can be seen that an integration of formal and tacit knowledge can fulfil all the knowledge needs through various ways. In some cases, the issue-based integrated model can directly provide information to fulfil designers' needs such as (4), (5), (6), (7), (8) and (10). There are some cases where knowledge needs can be met by either referring to previous processes or by linking to external formal knowledge records such as (2), (3) and (9). In the other cases, the interactions between formal knowledge items and an issue-based process model are needed such as (1) and (11). Thus, a knowledge model for representing an integrated knowledge space needs to address these interactions and support various ways of accessing external resources and displaying information.

3.4. Representation of an integrated knowledge space

The interactions between formal knowledge items and a process-based model can be categorised as follows: (1) referring to information in documents such as a design manual; (2) linking to formal knowledge records to obtain generic data such as material data, typical values and calculation results; (3) linking to formal knowledge records to obtain product data such as 3D model and drawings; (4) linking to formal knowledge records to run a
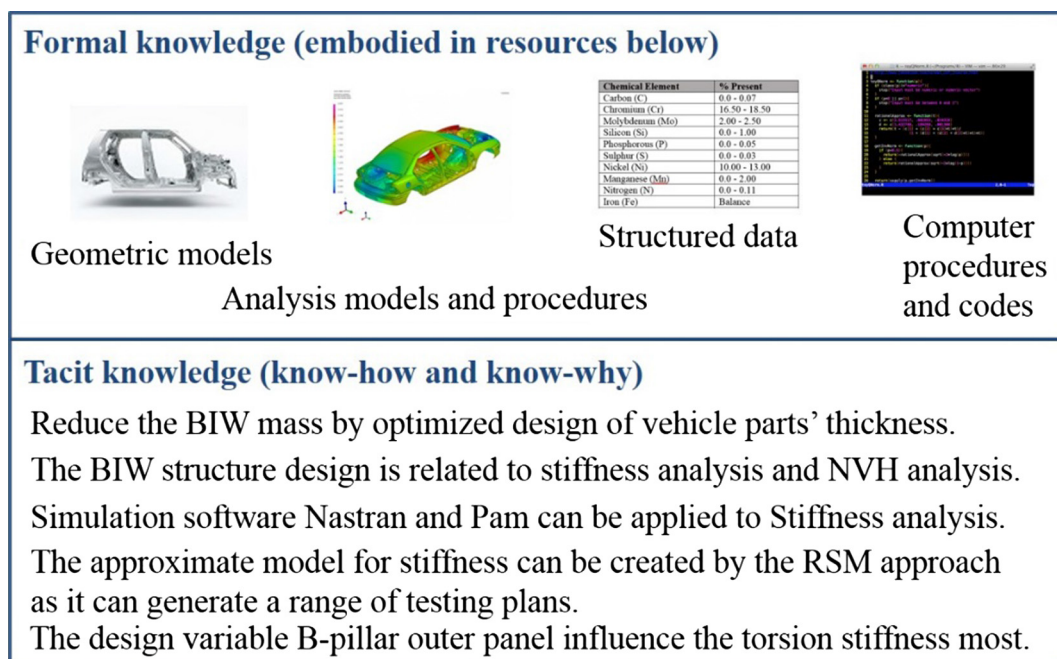

Fig. 2. Formal and tacit design knowledge.

Table 1
Interactions between formal and informal knowledge to fulfil knowledge needs.

Knowledge needs	Explanations of the needs	Fulfilment of needs by capturing an integrated knowledge space
Obtaining information (1)	Requesting where specific information in the form of documents, numerical data, etc., could be obtained	Retrieving process-based knowledge and obtaining links to formal knowledge records
Typical value (2)	Requesting typical values, as well as maximum and minimum values	Either locating particular relevant tasks in a process or linking to formal design manuals
Terminology (3)	What the meaning of a particular term is	Possible ways include: (1) referring to a previous task with a similar context; and (2) linking to formal design manuals
Trade-offs (4)	Effects of one issue on another	Finding considerations from previous processes with a similar context
How does it work (5)	How a particular part of the product functioned	Finding explanations from previous processes with a similar context
Why (6)	Why a design is carried out in a particular way	Finding explanations and justifications from previous processes with a similar context
What issues to consider (7)	Issues that should be considered during particular stages of the design process and also the importance of issues	Finding problem-solving strategies and processes from previous projects with a similar context
When to consider issues (8)	When issues should be considered	Finding problem-solving strategies and processes from previous projects with a similar context
How to calculate (9)	The methods used by a designer to achieve a task	Reusing a computer procedure or finding explanations from previous processes
Design process (10)	Aspects of the design process including: the information provided during the design process; what is expected to be produced, etc.	Retrieving previous processes with a similar context
Company process (11)	The distribution of design work between departments; the relevant company procedures; information on relevant people; other aspects of company procedure fell into this category	Retrieving previous processes with a similar context and finding links to formal documents

procedure of calculation or analysis such as simulation; and (5) linking to knowledge-based engineering procedures to facilitate idea generation, evaluation and optimisation. As such, a number of requirements are raised for the integrated knowledge model. First, it needs to support problem-solving strategies and procedures so as to support the design process. Second, it needs to provide a flexible interface between formal knowledge and informal knowledge to enable the various linking operations mentioned above. Third, it needs to achieve simplicity and clarify so that it can be used for implementation of non-intrusive ICKM tools. Fourth, it needs to capture rich collaborative design context and thus facilitate effective knowledge reuse. Last but not least, it needs to adopt a relatively formal structure to support effective and efficient knowledge retrieval. A knowledge representation model is proposed in this study to address these considerations, based on a novel integration of components from the Issue Based Information System (IBIS) and the Bayesian approach.

The main components of the model are shown in Fig. 3 together with descriptions to their ideas and usage within the integrated representation model. These components not only address the formal elements central to a design process, e.g. design variables and parameters, but also involve less formal contextual information about issues to consider as well as solutions to develop and evaluate. They are used to describe a design process using a connected graph model. An illustrative scheme is placed in the right of Fig. 3. Specifically, the 'Object' component means a design object such as a turbocharger, and such an object can be obtained by dividing a big design topic into a product tree structure. The content within this component can be a description of the object. For each object, a graph-based model of process knowledge can be established by first creating a 'State' component to indicate the main design variables alongside the main targets (specified immediately after the 'State' component to set up the target values/states for the variables). These targets are specified in another

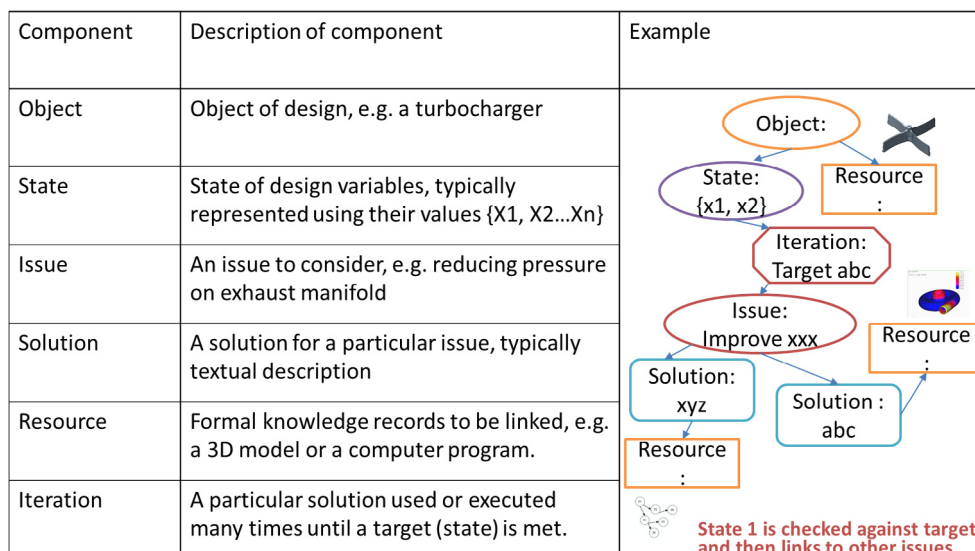| Component	Description of component	Example
Object	Object of design, e.g. a turbocharger	
State	State of design variables, typically represented using their values {X1, X2...Xn}	
Issue	An issue to consider, e.g. reducing pressure on exhaust manifold	
Solution	A solution for a particular issue, typically textual description	
Resource	Formal knowledge records to be linked, e.g. a 3D model or a computer program.	
Iteration	A particular solution used or executed many times until a target (state) is met.	

Fig. 3. The integrated knowledge representation model.

component 'Iteration' which is used to achieve the targets through conducting some iterative steps of improving the proposed solutions or developing new solutions. Then, some 'Issue' components (due to the limited space in the figure, only 1 component is shown in the scheme) will be created to improve the current state towards the target, i.e. driving the design process to proceed to detailed tasks about generation and evaluation of solutions. The 'Solution' component is used to describe a possible solution (many solutions can be created for a particular 'Issue' and only 2 are shown in the figure) and this description includes both formal operations on the variables and informal information about advantages and disadvantages. The 'Issue' and 'Solution' components are created through collaborative work by different people and involve a lot of tacit knowledge captured as descriptive contents of the nodes in the graph. For each solution, 'Resource' components (in this work these components are predominantly simulation analysis linked through Web services and they can also be geometric model extracted from a CAD package or other useful external information resources) can be created to obtain data, conduct analysis and run simulation. It is noteworthy that when some solutions are created and the targets are checked, more issues (and their solutions) can be created and linked to the new state (i.e. State 1 in the figure). This allows a large graphic model to be created to capture the reasoning process. Due to the limited space, Fig. 3 only gives a simple illustrative example.

Referring to the few key requirements mentioned above, the integrated knowledge model provides a simple and clear solution whilst facilitating capture of design context as well as easiness of reuse. The interfaces between formal elements and informal ones are actually quite straightforward and flexible – access to formal knowledge records is generic and independent of the forms of these records. Moreover, it attempts to model a design process with the key design considerations in its central place, addressing the support of a design process. Last but not least, it provides a structured way of presenting information which fits with the structure of Bayesian reasoning, and as such enables effective and efficient knowledge retrieval. The proposed model is novel in the sense that it provides effective way of combining formal knowledge elements into a process-based description and thus enables capture of missing context and access to formal elements for better reuse.

4. A service oriented ICKM system

4.1. Framework of a service oriented ICKM system

An ICKM system aims to facilitate engineering activities by supplying contextual and trustworthy knowledge to designers to improve decision making, which not only supports collaborative work between designers also addresses knowledge capture and reuse throughout this collaborative process. This is enabled by developing an integrated knowledge model to describe knowledge objects with rich design context captured from designers' collaboration and communication throughout a design process. On the basis of such a model, an ICKM system is designed and developed with a focus on evaluating the methods proposed in this work and explore possible technological supports towards the full implementation of next-generation ICKM systems. In this sense, this paper, for the sake of brevity, will only focus on the system framework of such a system together with some enabling methods developed. The key requirements for such a system are threefold. First, it needs to effectively support designers' collaborative work during a design process and allow them to complete the main design tasks. Second, it needs to facilitate capture of tacit knowledge when it emerges from the collaborative working process.

Third, it needs to facilitate knowledge reuse by effectively integrating tacit and formal knowledge and implement effective and efficient knowledge retrieval.

The system framework for the ICKM system is shown in Fig. 4, which consists of four main parts. On the right of the figure is the Graphical User Interface (GUI) layer that underpins effective interactions between multi-users within such a distributed and integrated working environment. These users will have a personal working space within the virtual ICKM environment where they can do specific tasks associated with their roles within a project. In addition, the main components of this framework include three layers, namely models, methodology and resources. Specifically, the resources layer refer to various formal knowledge records including design reports and manuals, 3D models and drawing, simulation models, computer programmes, etc. The models layer consist of the models developed to support the implementation of the system, including the product structure tree model for system decomposition according to the spatial and logical relationships between components, the integrated knowledge model for design knowledge representation and the retrieval and matching model for knowledge retrieval. As discussed in Section 3.3, the integration of tacit and formal knowledge requires a generic and flexible way of resources integration as the working mechanisms of these resources can be diverse. Hence, a flexible service-oriented computing architecture is proposed for the proposed ICKM system. In this architecture, all the resources are encapsulated as Web services that can be accessed and integrated within an Internet distributed environment. The interfaces of these services will be registered in a service centre as shown in Fig. 4. In this way, the system can support creation of design knowledge records based on the integrated model without requiring details about the integration with external formal knowledge records, thus allowing designers to focus on high-level knowledge. The knowledge capture part (i.e. modelling functionality) can also be implemented as a service as well as the knowledge retrieval part (i.e. retrieval algorithms developed and deployed in specific servers). This arrangement enables a very open and flexible computing architecture that is easily maintainable and scalable. As such, a range of enabling technologies are needed to support the implementation of such a system such as the development of knowledge modelling toolkit on the Web that supports synchronous operation and task allocation. In addition, effective retrieval algorithms also need to be developed to enable process knowledge retrieval. The registration, operation and integration of services also need to be supported.

4.2. Knowledge retrieval and reasoning methods

Fig. 5 shows the process of knowledge retrieval and reuse. First, a design task is specified as well as its current stage in the whole design process and then it is represented using the semantic language described in Section 4.2.1. Then, the bank of knowledge records is searched to find the most relevant records based on a case matching algorithm to be described in Section 4.2.2. Design context can be obtained from the models found, which is then applied to a trained Bayesian network to find resources that can best solve a problem in the current context. A piece of process knowledge for solving previous tasks is then obtained from which the problem-solving procedure and relevant resources can be identified. These resources will be integrated in a similar process to evaluate the solution obtained. The design targets will be checked in an iterative manner until a satisfactory solution is obtained. This solution is then stored in the knowledge records bank and is used as an input to the Bayesian network through a learning mechanism [47].
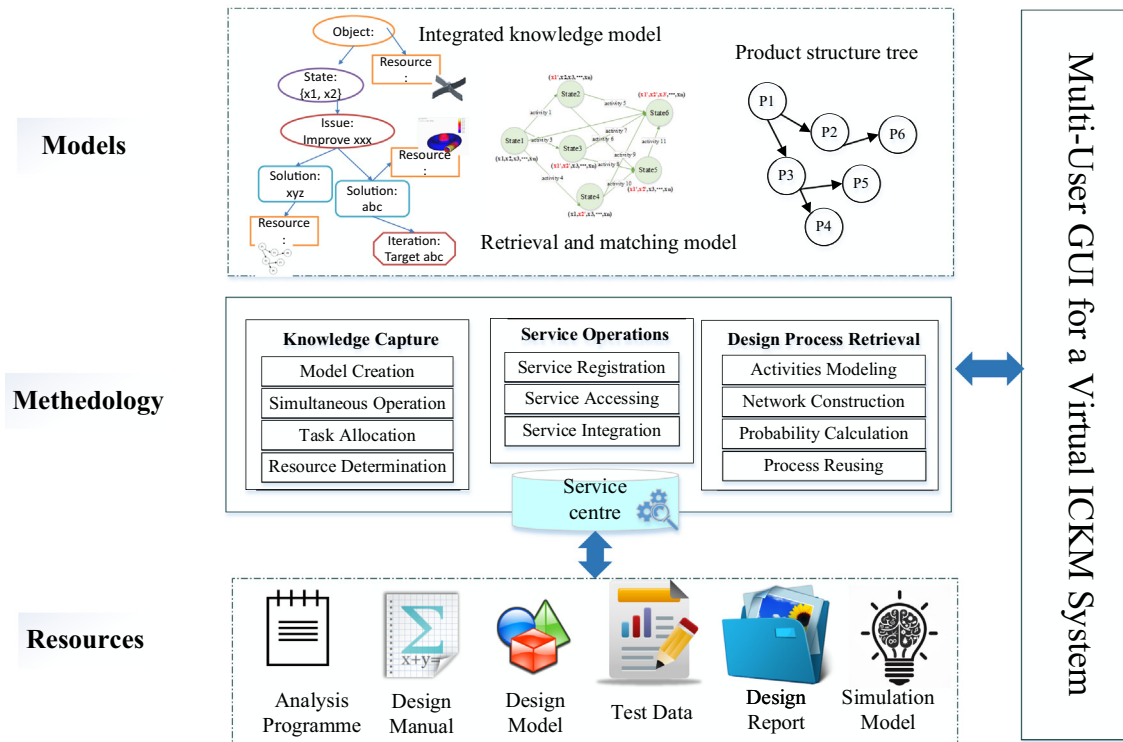
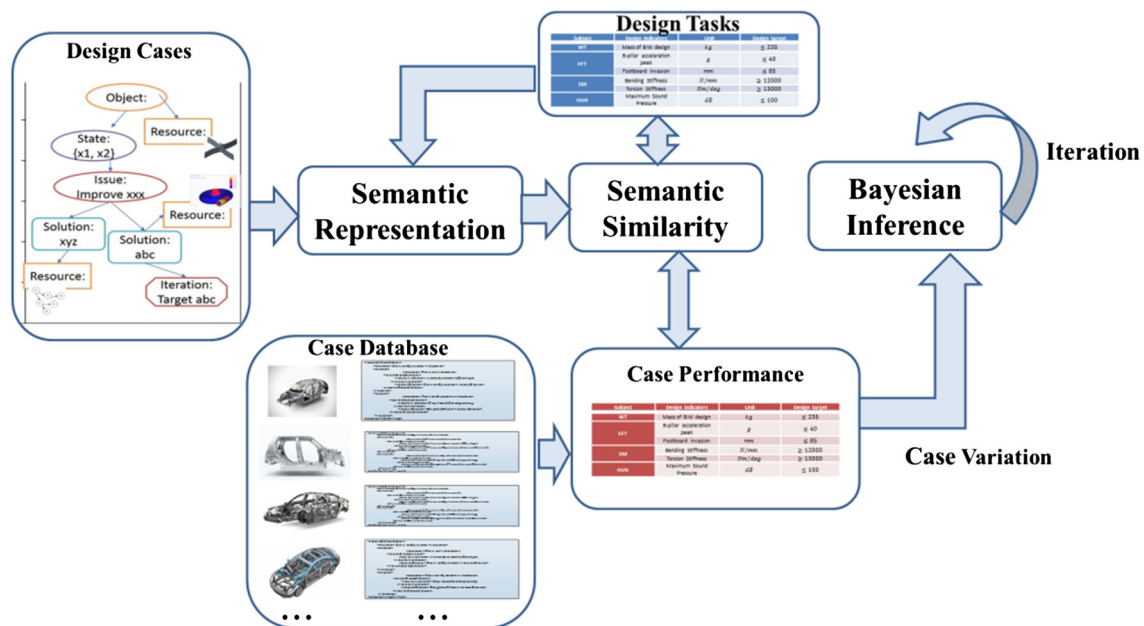**Fig. 4.** System framework for a service oriented ICKM system.

Fig. 5. The process of semantic knowledge retrieval and reuse.

4.2.1. Semantic information representation for design knowledge

The integrated knowledge model developed in this work holds the key to implement the ICKM system and this implementation highly relies on a formal scheme for model description on computers. Such a formal and comprehensive description of design knowledge plays a key role in facilitating the automatic and efficient matching of required resources, and lots of work has been done on resource modelling technologies. Existing Web service standards such as the eXtensible Markup Language (XML), the Web Service Description Language (WSDL), and the Resource Description Framework Schema (RDFS) have been widely used in various resource modelling applications. This to some extent resolves the problem of information interaction and sharing for a networked collaborative environment necessary for modern distributed enterprises. The emerging Semantic Web technology has made significant progress in addressing the service retrieving and matchmaking difficulties [48]. Although, semantic models can achieve improved interoperability between computer systems,

there still exist some shortcomings in current research, and as such, it is not possible to employ a generic model to address various needs. Thus, a semantic information representation scheme is proposed in this work together with its construction methods, based on existing semantic modelling techniques and specifications. A Semantic model allows engineers to represent design knowledge in a flexible, extensible and reusable manner along with a formal and machine understandable standard, which facilitates the collaboration of multi-domain design group.

Such a customised semantic model needs to address a couple of needs. First, it needs to represent the important concepts and deep semantics inherent in design cases. Second, this model also needs to support the implicit relationships in design semantics. Third, it needs to support the rules for reasoning and inference. Fourth, it needs to be able to describe context in design so as to support integration of tacit and formal design knowledge. The proposed information representation scheme is based on the popular Web Ontology Language (OWL) model due to its advantages including: (1) highly extensible and enabling customers to define structured documents; (2) separate contents and formats, enabling richer information presentation on Web browsers; (3) support of data with different formats and easiness of data exchange, sharing and integration; (4) ability to update data with a fine granularity; and (5) support of smart search and reasoning due to easy computer-understandable information. A fragment of the scheme used in this work is shown in Fig. 6 as an example.

4.2.2. A case matching algorithm based on semantic similarity

As mentioned above, designers' needs of knowledge services are described as semantic-based hierarchical models. The semantic search algorithm consists of three phases: (1) a customer need is parsed into a collection of elements refined by attributes and values; (2) a hierarchy product ontology with multiple nodes and branches is constructed based on a collection of elements and relationships between these elements; and (3) similarity is then calculated between the customer need ontology and knowledge ontology database and a set of records from the database is retrieved for reuse. By semantic measure the designers are able to explicitly locate the issue to detailed artefact elements, such as the specific sub-assembly, parts, features or dimensions.

The match between knowledge units based semantic similarity takes both elements match and structure match into consideration.

In this paper, two types of similarity are considered, namely semantic similarity and structure similarity [49,50]. Mark $T_q = \{N_1, \ldots, N_m, R_{12}, \ldots, R_{ij}\}$ as the requirement tree and $T_d = \{N'_1, \ldots, N'_n, R'_{12}, \ldots, R'_{ij}\}$ as the description tree in a knowledge database.

(1) Semantic similarity (sim_{Se})

sim_{Se} measures the functional similarity between a requirement node and a database node. Let $g = \{g_1, g_2, \cdots g_m\}$ represent the feature set of design requirement k, and m is the node number or the knowledge number of the set. $f = \{f_1, f_2, \cdots f_n\}$ represents the feature set of the retrieved knowledge k', and n is the node number. The semantic similarity $Sim_{Se}(k, k')$ is then calculated using Eq. (1).

$$sim_{Se} = \sum_{i=1}^{m} w_i(g_i) \times s_i(g_i, f_i) \tag{1}$$

$w_i(g_i)$ is the weight value of the ith feature after normalization processing. $s_i(g_i, f_i)$ represents the similarity of the two values g_i and f_i, which can be represented as $s_i(g_i, f_i) = 1 - \frac{|g_i - f_i|}{\max(g_i, f_i) - \min(g_i, f_i)}$.

(2) Structure similarity (sim_{St})

Structure similarity sim_{St} is defined based on the hierarchical structure and relationships between multiple nodes. sim_{St} is estimated as the taxonomical distance of two nodes defined in the semantic tree, which is based on the analysis of the lengths of paths for linking the pieces of knowledge concerned. Let s_1, s_2 represent the requirement node and knowledge node, respectively. Then sim_{St} can be calculated as follows based on the method given in WordNet [51]:

$$sim_{St} = \begin{cases} \frac{2 \times logp(s)}{logp(s_1) + logp(s_2)} \\ 0 \quad \text{if no common parent exits between } s_1 \text{ and } s_2 \end{cases} \tag{2}$$

In Eq. (2), s means the common parent node of s_1 and s_2 and $p(s) = count(s)/total$ is the proportion of the sub node counts of node s in the total word counts. Based on the definitions given above, the matching algorithm based on two similarity measures can be described in Algorithm 1.
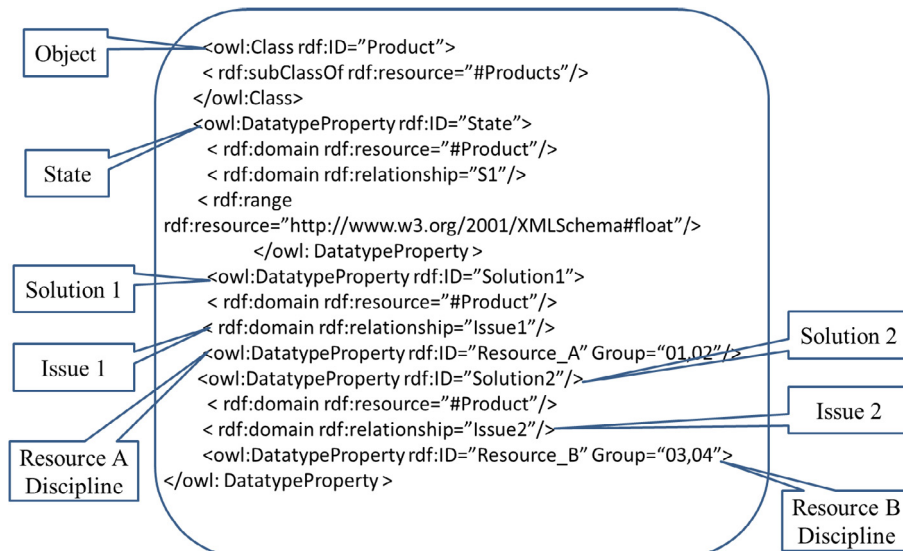

Fig. 6. An example of semantic information representation.

Algorithm 1. Main body of the ontology-based retrieval algorithm

Input: The requirement semantic tree and the knowledge database

Output: A set of usable semantic tree from the knowledge database

1.   Begin
2.   **For** each semantic node N_i in requirement tree **do**
3. $f_i = \{\} \Leftarrow f_i$ is the set of attributes in node N_i
4.   **For** semantic node N_i' in database tree **do**
5. $sim_{Se}(N_i, N_i') \Leftarrow$ calculate the semantic similarity according to (1)
6.   **if** $(sim_{Se} > limit)$
7.   Add N_i' to set $g_i = \{\}$
8.   **End if**
9.   **End for**
10.   **for** each node s_m in g_i **do**
11. $p_m \Leftarrow$ find the parent node set of s_m
12. $q_m \Leftarrow$ find the parent node set of N_i
13.   **if** $(p_m \cap_m^q \neq \varnothing)$
14.   count$((p_m \cap_m^q)$
15. $sim_{St}(N_i, s_m) \Leftarrow$ calculate the structure similarity according to (2)
16.   **else**
17.   move s_m from g_i
18.   **end if**
19.   **end for**
20. $Rank = \{\} \Leftarrow$ Rank the nodes in g_i based on similarity
21.   **end for**
22.   **Return** g_i
23.   **End**

4.2.3. Bayesian approach based design knowledge reasoning

Due to the rich context and semantic information in a solution-searching process, a knowledge retrieval method is necessary to find knowledge records in a precise and efficiency manner to supply useful suggestions for designers. The integrated knowledge model proposed in this work emphases formal elements (e.g.
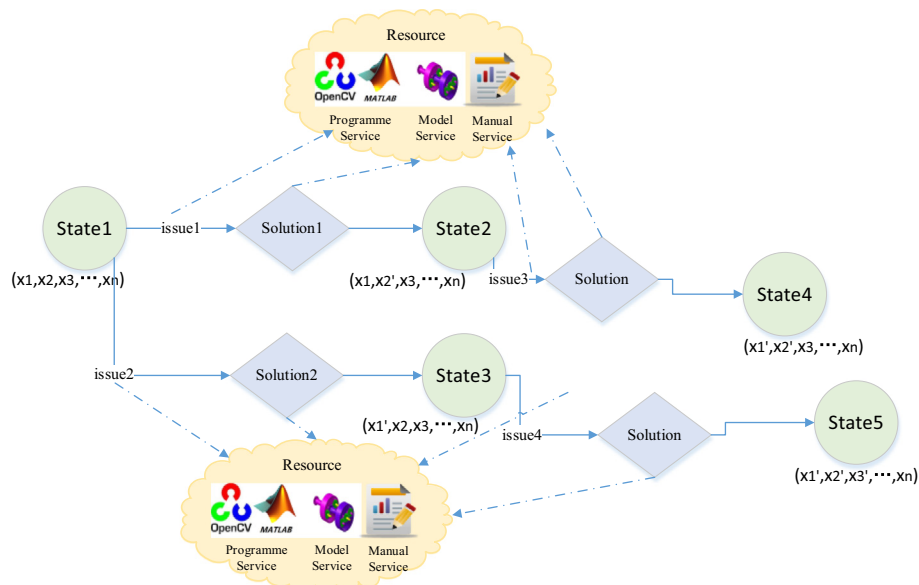
'state') as they not only determine how well the key design requirements have been met but also drive the deliberation and argumentation process. In this process, a lot of experience is involved, which is hard to describe using very simple semantic representation. In this work, the Bayesian approach is employed to transform the integrated knowledge model into a network graph for describing state changes. As shown in Fig. 7, 'State' refers to design states at different stages and can be represented using variable values $(x_1, x_2, x_3, \ldots, x_n)$; 'Issue' refers to issues considered and the decision process in which tacit knowledge can be captured, which can be retrieved from a design case bank; 'Solution' means the solutions for the issues, which are typically linked to external services such as numerical calculation, finite element analysis, material design and design report. Through calling these services, a solution can be improved in an iterative process until specified targets are met.

The mechanism of Bayesian inference is explained as follows. First of all, let $\Omega = \{State_1, State_2, State_3, \ldots, State_k\}$ represent the state set of product in the design process, and $A = \{activity_1, activity_2, activity_3, \ldots, activity_m\}$ represent the set of activities determined by designers. Each state contains n elements $(x_1, x_2, x_3, \ldots, x_n)$, which are related to the features of the design node.

Bayesian inference calculates the posterior probability based on a prior probability and a likelihood function derived from a statistical model for the observed data, which is expressed as Eq. (3) where P(H) stands for the prior probability, P(E|H) stands for the posterior probability (i.e. the probability of H given E).

$$P(H|E) = \frac{P(E|H) \cdot P(H)}{P(E)} \tag{3}$$

In the design process, it is often difficult for designers to decide which activity should be taken to adjust the parameters under a certain state. By applying the Bayesian approach, the dynamic process is captured with a Bayesian network.

$$P(activity1|x_1 \rightarrow x_1') = \frac{P(x_1 \rightarrow x_1'|activity1) \times P(activity1)}{P(x_1 \rightarrow x_1')} \tag{4}$$

In Eq. (4), $P(x_1 \rightarrow x_1')$ represents the probability that x_1 changes in the design process and $P(x_1 \rightarrow x_1'|activity1)$ is the probability of change for x_1 given activity1.

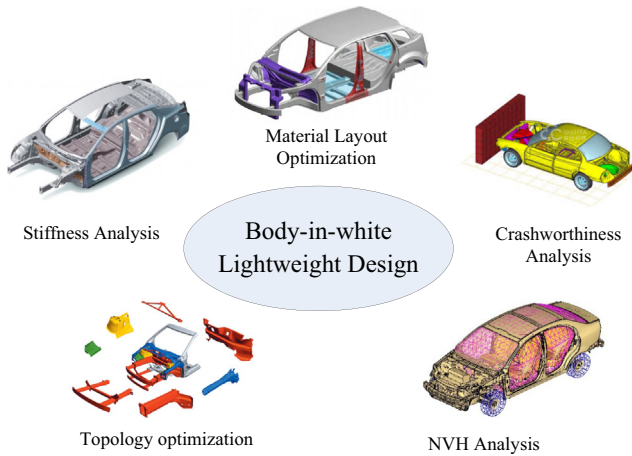**Fig. 7.** Semantic knowledge retrieval based on Bayesian inference.

Fig. 8. The BIW lightweight design.

Table 2
Part of the variables with their upper and lower limits.

Design variables	Part name	Min	Max
DV1	Seat beams	1.25	2.0
DV2	B-pillar reinforcement board	1.25	2.0
DV3	Threshold reinforcement board	1.2	1.75
DV4	Front seat rail bracket	0.6	0.75
DV5	Inner plate front	0.8	1.1
DV6	Wheel arch	0.6	0.75
DV7	C-pillar inner panel	1.2	1.75
DV8	C-pillar connector	1	1.25
DV9	A-pillar reinforcement board	1.5	2.5
DV10	B-pillar outer panel	1.25	2.0
DV11	B-pillar inner panel	1	1.25

5. System development and evaluation

5.1. A case study

In a vehicle design process, the Body In White (BIW) lightweight design is typically knowledge-intensive and time-consuming, which needs the collaboration of multi-disciplinary engineers. As shown in Fig. 8, the lightweight design process is completed in a few stages by considering the topology of structure, parameters of thickness, mechanical performance of material which has influence on BIW stiffness, mode and crashworthiness. Inefficient processes and the inability to easily capture and access product information or other types of intellectual properties often force engineers to restart designs from scratch or carry-over data for each new car design.

Twenty-one parts' thickness and eleven kinds of material from the BIW design example are selected as design variables. Table 2 lists part of the variables with their upper and lower limits. The design tasks considered in this case study determine these design variables step by step to minimize the weight while satisfying multidisciplinary constraints such as static stiffness, vibration characteristics, low/high speed crash, and Noise Vibration Harshness (NVH) analysis. Each combination of the design variables represents one state of the knowledge model. And variations between states are realized by identifying occurrence of different issues, which are solved with different design resources from multi-domains.

These design constraints are defined in different domains and some of them are partially or totally contradictory with each other, e.g. increased thickness of parts can enhance static stiffness and crashworthiness of a car but bring worse NVH performance and a larger weight. Thus, the knowledge about correlations between certain design requirements and functions needs to be captured and reused, which is helpful to solving similar problems in the future. This kind of tacit knowledge is involved within design activities of engineers from different domains. This paper studies the engineering application of lightweight design for a new energy vehicle based on the proposed collaborative knowledge management system so as to engineering designers capture and reuse their knowledge and experience alongside the design process. With this solution, design engineers will be able to capture and reuse much of the design knowledge from one successful project to another, fully capitalizing and leveraging corporate knowledge. Equipped with design templates, the integrated knowledge model, relational design methods and morphing techniques, engineers can save considerable amount of time developing a new BIW design.
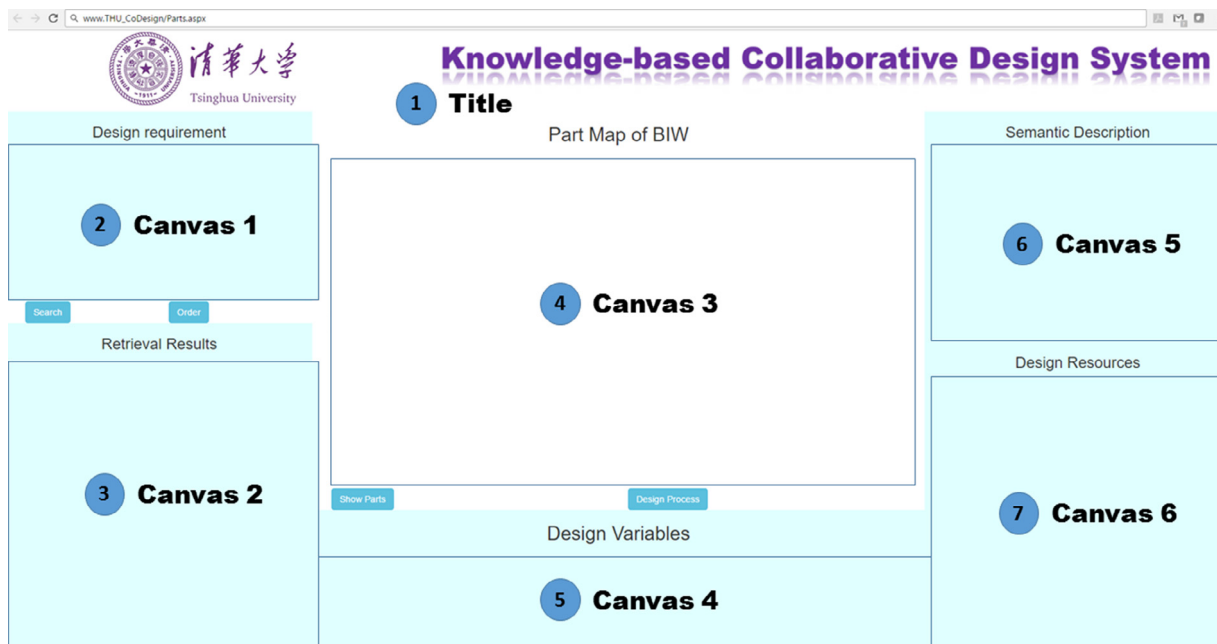

Fig. 9. Main GUI of the ICKM system.

Table 3
Structural performance indicators and design targets.

Disciplines	Design indicators	Unit	Design target
WT	Mass of BIW design	kg	$\leqslant 235$
FFT	B-pillar acceleration peak	g	$\leqslant 40$
	Footboard invasion	mm	$\leqslant 85$
SM	Bending Stiffness	N/mm	$\geqslant 12,000$
	Torsion Stiffness	Nm/deg	$\geqslant 13,000$
NVH	Maximum Sound Pressure	dB	$\leqslant 100$

Table 4
Performance indicators of Case X.

Disciplines	Performance indicators	Objective
WT	Mass of BIW design	350
SM	Bending stiffness	14,000
	Torsion stiffness	12,000

5.2. Prototype implementation

To evaluate the proposed frameworks and methods, a Web-based ICKM prototype system has been developed using the ASP. NET technology. This is the very first step towards a large-scale ICKM system with a focus to evaluate the effectiveness of the models as well as to demonstrate the ideas of using a smart collaborative system to support design management. The software and hardware environments for system implementation are summarised as follows: (1) Application server: A DELL desktop with Intel Core i7 CPU (3.40 GHz) and 8 GB memory, 256 GB SCSI HD and a Windows 7 operating system. (2) Programming platform: Microsoft Visual Studio Premium 2012, .Net framework 4.0 and C#. (3) Database: My SQL 6.0. (4) Network configuration: 100 M Ethernet network connection between testing clients and applica-

tion server. The Web services for accessing formal knowledge records are deployed in the application server in the current work. The Graphical User Interface (GUI) of the system is shown in Fig. 9.

On the left of the GUI is the product design requirement and candidate cases, while on the left shows the model and resources for collaboration. In the middle are the reasoning process and the design variables of the current state. Specifically, all the design requirements are shown in the design task table on Canvas 1. Based on the similarity calculation methods introduced in Section 4.2, some knowledge records from previous design cases are retrieved and listed with their 2D drawings and similarity values on Canvas 2. Canvas 3 displays the design process in which useful design knowledge is organised and recorded, as well as the part map of the BIW which gives engineers a straightforward way of understanding the design object. The updates of all the design variables within each step are detailed on Canvas 4. Canvas 5 shows the OWL description of the design task which can be further processed by computers to facilitate streamlined knowledge reuse and design support. Canvas 6 shows the design resources in the current collaborative design task as well as the list of supplementary documents, e.g. simulation results and manual documentations.

5.3. Evaluation of the model

A new energy vehicle BIW design example is used as a case study to demonstrate the application of the prototype system as well as the support for conducting design tasks. Table 3 presents the main design performance indicators and their target values in different domains including the weight (WT), crashworthiness (FFT), stiffness and modal (SM), and noise, vibration, harshness (NVH). As this design project proceeds, designers need to generate some concepts to meet the requirements. This can be done by first searching for matching cases from the knowledge records. Table 4 lists the performance indicators of Case X.
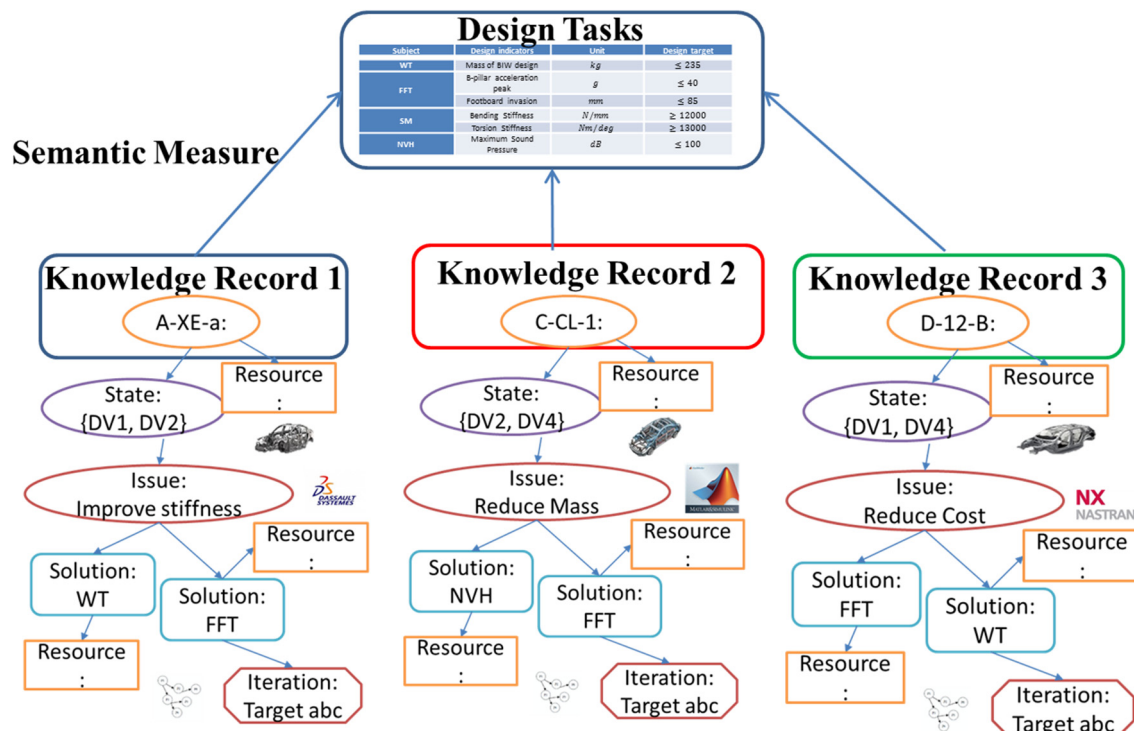
Fig. 10. Illustration of the semantic measure based matching.

As shown in Fig. 10, the design task is described in performance indicators, which corresponds to the object element in the integrated knowledge model.

The semantic similarity can be calculated as follows based on the similarity measure method described in Section 4.2.2.

$$sim_{Se} = 0.3 \times \left(1 - \frac{350 - 235}{235}\right) + 0.2 \times \left(1 - \frac{12000 - 14000}{12000}\right)$$
$$+ 0.2 \times \left(1 - \frac{13000 - 12000}{13000}\right) = 0.571$$

From the knowledge record bank constructed from previous design records, top four cases returned are shown in Table 5. By adjusting variables using these pieces of information, engineers in different domains can carry on with new tasks. Fig. 11 shows the semantic retrieval GUI of the ICKM system.

The designers have some ideas and some requirements are given by sales people who have limited knowledge about how to evaluate the design solutions. The selection of values for the design variables of the BIW example highly relies on previous experience as they are not only determined by material but also concern the strain-stress interfaces. As such, it is useful to find previous problem-solving strategies and tacit design knowledge to improve decision making. On the ICKM system, users can search previous knowledge records based on a Bayesian reasoning process knowledge retrieval method.

As the design variables include 17 thickness variables at 4 levels and 21 material variables at 7 levels, it is very difficult to determine the variables selection. The prior knowledge of this Bayesian process model includes the design indicators of task, the performance indicators of retrieved cases, and the transition probability of design variables. As shown in Table 6, the performance indicators of the retrieved case with the highest similarity score have to be adjusted by evaluating the performance against the specific requirements of the current design task. According to the table, it can be seen that the mass and bending stiffness are too big and as such the variables need to be modified. These pieces of in-context knowledge can provide important support for designers as they focus on particular design task in a collaborative design process.

After a case is retrieved, the Design of Experiments (DoE) matrix is created. Samples of stiffness, modal and side impact of body-in-white are taken by simulation. The contribution ratio and main effects of design variables to stiffness, modal and side impact of body-in-white is analysed in order to provide technical information for later design variables reasoning. From Fig. 12 (added to the revised paper), it can be seen that DV2, DV3, DV7, DV1 are the most influential design variables on bending stiffness, with the contribution ratio values of 0.32, 0.28, 0.13, respectively.

The reasoning process knowledge record retrieved shows that previous projects have found that most in-service faults were ascribed to failures to meet requirements at the cross sections where stiffness was a concern. A FEA resource service was also used in that projects to conduct stiffness analysis. The results of this analysis is obtained as part of the knowledge record, as shown in Fig. 13. According to design knowledge record, in order to decrease the bending stiffness, the most relevant solution is to reduce the thickness of variable DV2, then to reduce the thickness

Table 5
Retrieved cases based on the semantic measure.

Class	Model	Similarity
A-XE-alum		0.8698
B-N-One		0.7354
C-CLA		0.6623
D-12-b		0.5654

Table 6
Performance indicators of the retrieved case with the highest similarity score.

Subject	Performance indicators	Objective
WT	Mass of BIW design	↓
FFT	B-pillar acceleration peak	↑
SM	Bending stiffness	↓
	Torsion stiffness	↑

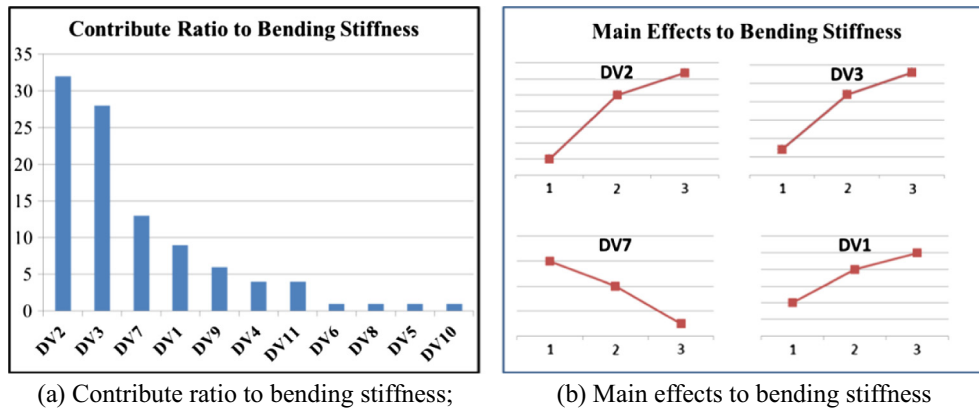Fig. 11. The semantic retrieval GUI of the ICKM system.

(a) Contribute ratio to bending stiffness;   (b) Main effects to bending stiffness
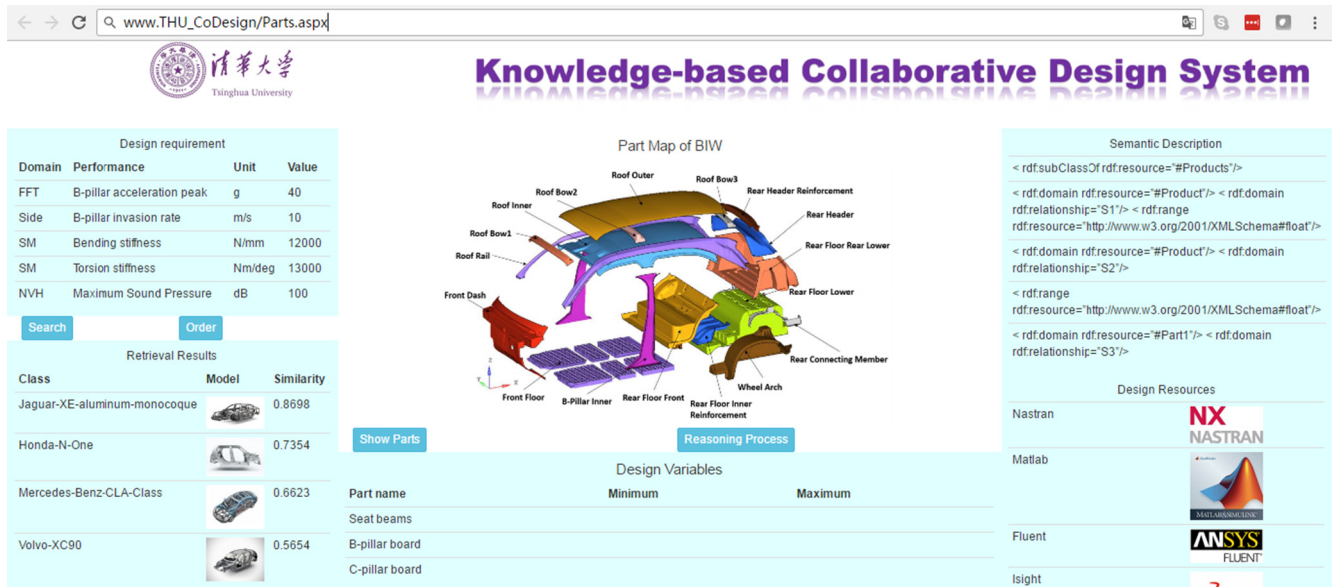
Fig. 12. Contribute ratio and main effects of design variables to stiffness.

(a) Variables related to bending stiffness;   (b) Variables related to torsion stiffness
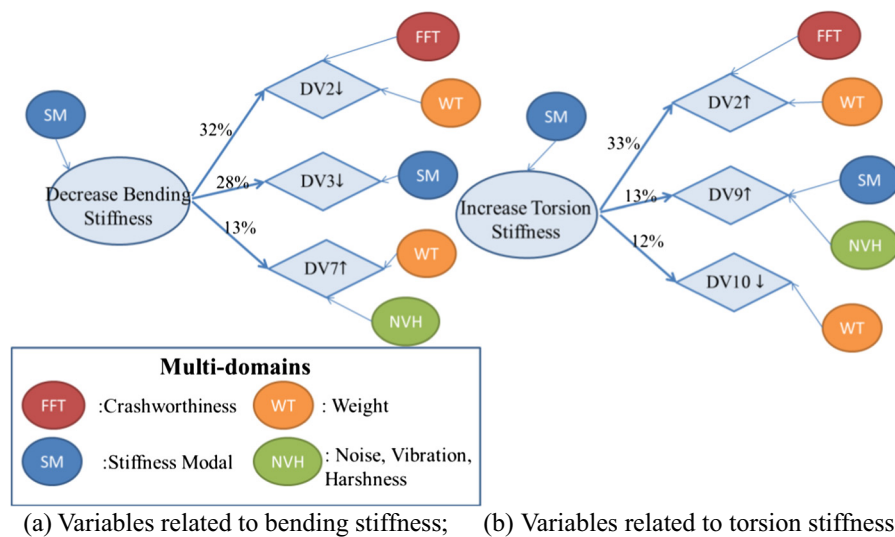
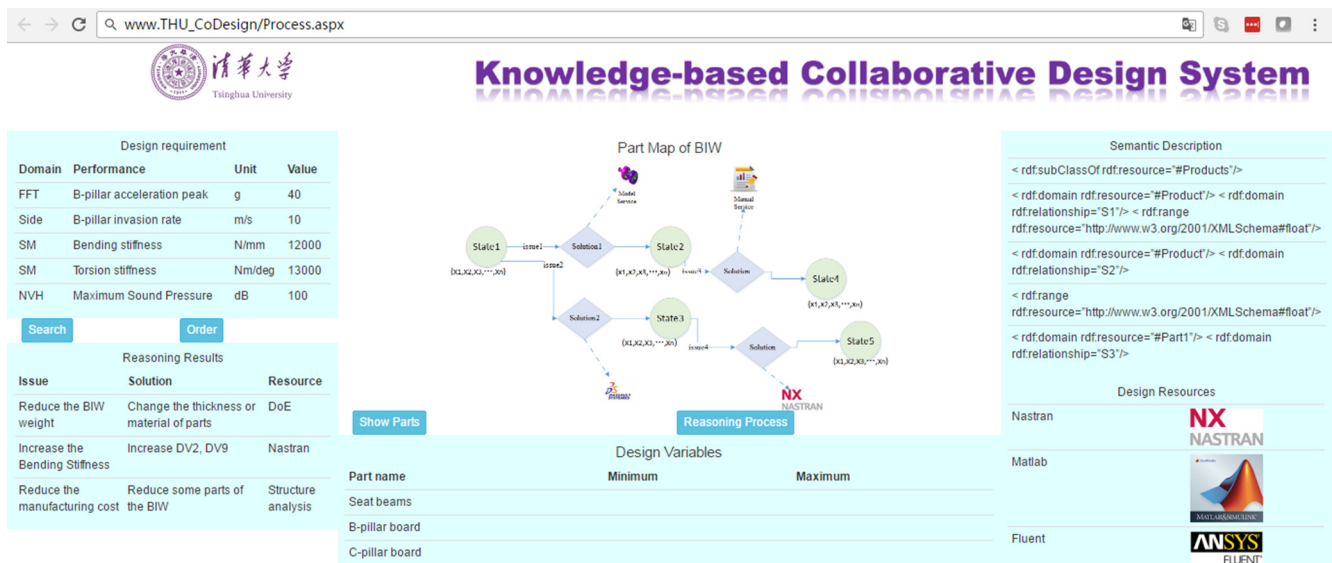**Fig. 13.** Reasoning process knowledge suggestion based on Bayesian approach.

Fig. 14. The reasoning process reuse GUI of the ICKM system.

of variable DV3 or increase the thickness of variable DV7. These activities are accomplished by the collaboration of users with different roles. This is a simple example for explaining the proposed issue-based process knowledge representation which can be used for much more complex designs in terms of variables numbers and variation possibilities in industrial vehicle design processes. As shown in Fig. 14, the design requirements of performance are shown in the design task table on left-top, which is then described in the Semantic language.

It can be seen that the main functionality of the proposed ICKM system has been implemented although it is still an early stage towards large-scale next-generation ICKM systems. First, users with different roles can work in this virtual space to create elements for the knowledge process. Second, design tasks are supported through effective knowledge retrieval and knowledge capture and reuse takes place as a design project proceeds. Third, these users can contribute to different parts of the knowledge model throughout a design process, allowing tacit knowledge to be created by users in some elements while formal knowledge to be created by other users with the support of IT experts. Last but not least, the knowledge retrieval method effectively exploits design context and can find useful results based on semantic similarity and structure similarity. These confirm that the proposed system framework is viable and the main features identified are feasible.

6. Conclusions

In an attempt to address the separation of the personalisation and codification views of design knowledge, a knowledge model for representing an integrated knowledge space is developed in this research. On this basis, the design and development of a smart collaborative system is described to provide useful knowledge for users with various roles within a collaborative design process. As demonstrated in the system evaluation section, the prototype system can support different users throughout a design and development process by identifying formal knowledge elements and integrating them into a process-based knowledge model. The retrieval methods is effective and can help designers to find relevant knowledge records according to their contexts of working, paving the way for more intelligent information recommendation as a design task is addressed.

The integrated knowledge includes both formal elements and components (e.g. issue and solution) related to problem-solving strategies and processes. The knowledge representation enables an effective integration of knowledge elements into a graph representation, enabling both capture of context and retrieval of process knowledge. The simple structure of the knowledge reduces the complexity of knowledge capture and reuse. More importantly, the knowledge model also emphasises a flexible integration of formal elements and tacit knowledge that can be represented as issues, options and argumentations. This flexibility can be further facilitated by employing a service oriented computing environment for resource access and integration. This work is still at an early stage and in our future work we will focus on further evaluation of the model as well as more applications of an updated version of the system to large-scale design projects.

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