Building an Ontological Knowledgebase for Bridge maintenance

Guoqian Ren [a] , Rui Ding [a], Haijiang Li [a]

[a] Cardiff School of Engineering, Cardiff University, Queen's Buildings, Cardiff, CF24 3AA, Wales UK

Highlights

- Demonstrate that the process of traditional bridge maintenance lacks effective computer-aided tools.
- State how ontology provides potentials for integrating multiple domain knowledge into a knowledge model.
- Propose a semantic approach to help build a knowledge base for bridge maintenance that offers better deliverables.
- The selection of material suppliers and the arrangement of events are holistically considered through reasoning-based knowledge processing.

Abstract:

The operation stage has the biggest potential value in the bridge life cycle management, and it often critically influences the overall cost of the bridge. As such, changes in the efficiency of the project's operation stage could be of significant benefit to the overall project. However, current approaches in the operation stage often lack the effective support of computer-aided tools. This research presents a holistic method based on an ontology to achieve automatic rule checking and improve the management and communication of knowledge related to bridge maintenance. The developed ontology can also facilitate a smarter decision-making process for bridge management by informing engineers of choices with different considerations. Three approaches; semantic validation, syntactical validation, and case study validation, have been adopted to evaluate this ontology and demonstrate how the developed ontology can be used by engineers when dealing with different issues. The results showed that this approach can create a holistic knowledge base that can integrate various domain knowledge to enable bridge engineers to make more comprehensive decisions rather than a single objective-targeted delivery.

Keywords: Bridge maintenance, Semantic Web, Ontology, Multi-criteria decision support, Suppliers selection, Event management

1. Introduction

The development of information and communication technology (ICT) in recent years has facilitated the evolution of information and knowledge management in architecture, engineering, and construction (AEC) domains. One area in which the influence of technology has been particularly evident is in that of Semantic Web technology. Technical developments in this area have helped knowledge management methods to progress from interpretation systems based on human actions to semantic-based approaches (Rezgui et al., 2010). ICT has had major implications for the architecture industry. The introduction of Semantic Web technology has led to significant changes that have reduced the time and cost associated with architectural projects. However, despite the impact that Semantic Web technology has had on architectural projects, research on the implementation of Semantic Web technology is severely lacking. The ICT holds significant potential, especially in terms of the development of bridges. As such, there is a need for researchers to develop a better comprehension of the application of ICTs in this area.

The bridge is a vital infrastructure facility for the continuing development of the social and economic activities of a country, city, or area. It can provide commodities and services essential to enable, sustain, or enhance societal living conditions. The bridge project lifecycle typically consists of four stages: planning, design, construction, and operation. Of these, the operation stage is the most time and cost intensive, generally consuming around 55% to 75% of the full project lifecycle resources (Zhao & Yue, 2011). As such, changes in the efficiency of the operation stage of the project could be of significant benefit to the overall project.

In recent years, ICTs have found increasing application in activities that are designed to enhance the efficiency of the construction phase of engineering projects (Chan et al., 2016). However, there is a lack of research that has formally evaluated the use of ICTs during the operation phase. In addition, at present, there is no solid workflow in existence that defines how ICTs can be applied within the bridge maintenance process to enhance the efficiency of the key processes. Furthermore, knowledge and information about the whole bridge maintenance process are typically dispersed across various teams and individuals. People of different skill sets and professional backgrounds perform individual tasks, and various engineers tend to focus on their deliverables and operate in silos. As such, information and knowledge are not readily shared among different departments and individuals, and this detracts from the efficiency and accuracy of the decision-making process and increases costs. Additionally, it is hard for engineers to access and combine the fragmented knowledge and information required to make bridge maintenance decisions in the absence of effective computer-aided tools. Therefore, it is difficult for decision-makers to access holistic information and make an efficient decision. In this case, ICT has the potential to facilitate information-sharing between different engineers and thereby enhance collaboration and cut costs.

The Semantic Web acts as an extension of the World Wide Web that aims to achieve the vision of the World Wide Web Consortium (W3C) of structuring the data on websites in such a way that it can be read by machines. The Semantic Web has a variety of different applications (Hou et al., 2015) and it can be beneficial to research processes in many ways; for example, it can optimize information retrieval, data annotation, and natural language processing (Rajput & Haider, 2011); facilitate decision making, and enhance data interoperability. As one of the emerging Semantic Web technologies, ontology is widely used for knowledge sharing and reuse across different domains; it has great potential to address the problems related to holistic structural design. Ontology has many attractive features, which include the following: (1) it provides a vocabulary and a framework through which to structurally model knowledge of a given domain in a format that can be processed by both machine and human; (2) it not only defines the terms in a specific domain but also describes the relationships between these terms in various domains; and (3) it provides a hierarchy of concepts in a particular domain. Given these advantages, it is expected that ontology could be used as a tool to improve bridge maintenance. However, in the field of bridge maintenance, more advanced deductive reasoning capabilities are required due to the existence of a large number of calculations and many types of knowledge related to bridge maintenance. In order to extend the flexibility of ontology to meet the requirements of bridge maintenance, an effective and robust tool in addition to ontology is needed for more specific calculation purposes. As such, semantic web rule language (SWRL) is employed in this research.

This study involved an in-depth review of the current literature that describes the methodologies, techniques, and tools that are employed within Semantic Web technology to assist in bridge maintenance activities. The main tasks of this study focus on establishing a novel ontology that is based on a full and comprehensive decision-making approach that bridge engineers can employ to obtain knowledge from various fields to make more effective decisions. The study proposes to create a unique formal OWL ontology that represents knowledge in bridge maintenance by managing the interconnected relationships that exist between multiple domains, such as potential reasons for damage, automatic damage evaluation, maintenance regulations, workflows of construction procedure, cost, and material supplier selection. Furthermore, this ontology uses SWRL rules to define the criteria that should be applied within bridge maintenance activities and employs reasoning functions to calculate bridge evaluation, represent maintenance regulations and adopts Semantic Web queries to make a multi-criteria decision in bridge maintenance.

2. Literature review

2.1 Review of bridge maintenance

The bridge project lifecycle typically consists of four stages (Group, 2010): planning, design, construction, and operation, as shown in Figure 1. Of these, the operation stage is the most time and cost intensive and generally consumes around 55% to 75% of the full project lifecycle resources (Zhao & Yue, 2011). As such, the operation stage has the biggest potential value in asset management and changes in the efficiency of the project's operation stage that could be of significant benefit to the overall project.

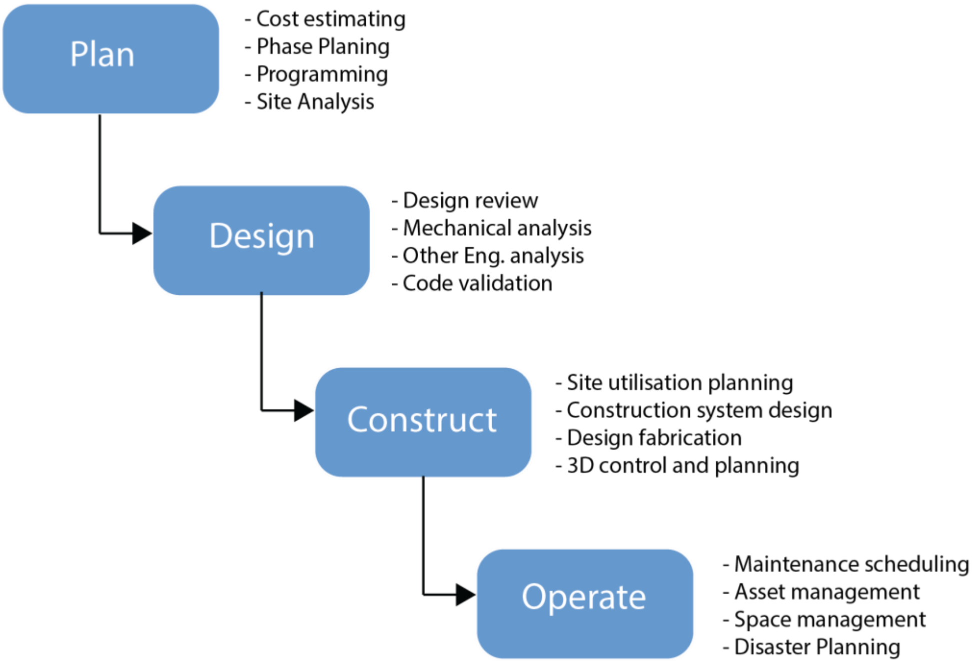


Figure.1 The bridge lifecycle management

The process by which bridges are traditionally maintained involves five main phases: (1) Inspection and monitoring: In the case of small or medium-sized bridges, the majority of the data is collected using a human, paper-based approach (Chan et al., 2016). The approaches that are commonly used by inspectors include a combination of equipment monitoring and visual inspection. During the first stage of the process, inspectors take photographs of any damage and use the data that is available from sensors to facilitate their analysis. (2) Evaluating the technical condition of the bridge: the information about the damage that was collected during the inspection phase is verified against the Standards for Technical Condition Evaluation of Highway Bridges (Li, 2011). The inspectors assess the condition of every element and produce a detailed inspection report in which they detail the severity and quantity of any faults, the technical state of the bridge components and parts, and present recommendations as to the maintenance activities that are required. (3) Decision making: The inspection report is employed to make decisions regarding what steps must be taken to maintain the bridge. (4) Repair and reconstruction: Construction teams perform the required maintenance in accordance with the Technical Code of Maintenance for Highway Bridges. (5) Data recording: After the bridge is repaired or reconstructed, maintenance records are updated so that key information is available to the bridge inspectors that conduct the next maintenance process. A high-level overview of these phases is presented in Figure 2.

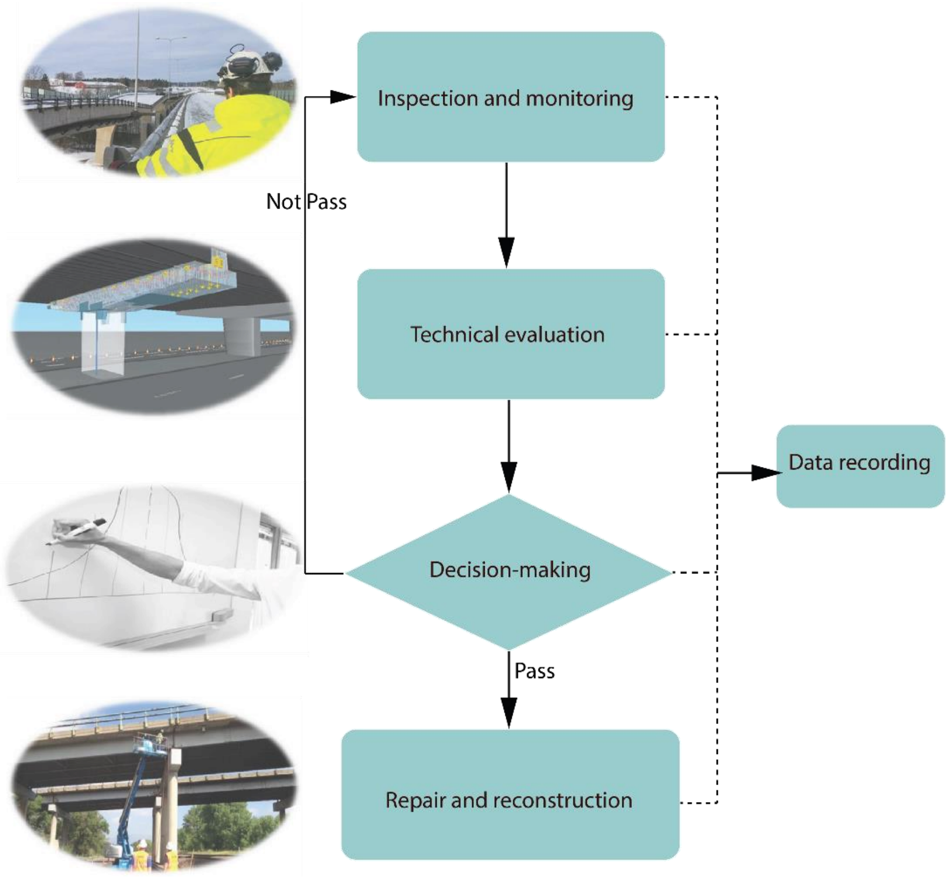


Figure.2 A high-level overview of the five phases of bridge maintenance

Based on the understanding of traditional bridge maintenance, it is easy to conclude that manual evaluation plays a vital role in the whole maintenance process. However, the current method still has some drawbacks: (1) The outcome of an inspection can vary from inspector to inspector and relies on the inspector's individual experience and subjective judgment. In practice, bridge inspectors generally lack the professional knowledge and practical experience required to perform an accurate assessment. (2) Information and knowledge are dispersed across different individuals and groups across the whole lifecycle of the project. Different tasks are assigned to different engineers who are from different professional backgrounds; as such, it is difficult for engineers to manage knowledge and make effective decisions.

To overcome these shortcomings and improve the efficiency of the project, some researchers have integrated bridge maintenance problems into Building Information Modelling (BIM) or extracted BIM information for bridge maintenance procedures. According to Zou et al. (2016), the BIM technique represents a systematic management approach that guides the maintenance process, generates crucial data, and acts as a solid platform upon which other BIM techniques can be interactively employed. Furthermore, Chiu et al. (2011) found that BIM technology was beneficial for automatically detecting physical spatial clashes, while Eastman et al. (2009) described how specific regulations and building codes had been translated into computer-read rules and checks in Industry Foundation Class (IFC) information models that have been completely automated. However, to date, the majority of current research has focused on the technical aspect of the testing phase and has not successfully integrated the human element (Forsythe, 2014). As such, there remains much work to be done before BIM approaches can be implemented in the AEC domains.

2.2 Review of ICTs in bridge maintenance field

In recent years, ICTs, such as BIM, Geographic Information System (GIS), and Virtual reality (VR), have found increasing application within bridge maintenance operations. There are two main reasons for this: (1) BIM and BIM-related digital technologies have been proven to be beneficial to project managers and can enormously improve the project efficiency. (2) The people who have the responsibility for creating policies and regulations are increasingly recognizing the importance of introducing advanced IT approaches into bridge maintenance activities and guidelines have been developed to help project managers realize these benefits.

In addition to providing advanced tools that designers and project managers can employ to address the limitations associated with traditional approaches, the application of these technologies also enhance communication across organisations and practitioners (Dossick & Neff, 2011). For example, database technology holds significant potential in the bridge maintenance field. The use of a database allows valuable information to be captured, stored, sorted, and extracted according to a pre-determined set of selection criteria (Forsythe, 2014). All personnel involved in a given project can access the information contained in a database in accordance with their needs and the availability of a central source of data can enhance the efficiency of operations. Databases can also help engineers to learn from the accidents that occurred in the past and to develop enhanced knowledge that allows them to more accurately identify and prevent safety hazards in the future work environment (Gambatese et al., 2005). Imhof (2004) developed an online database in which the details of a large volume of cases involving bridge failures were stored. He subsequently used this database to assess how the damage was distributed and present a high-level summary of the core factors that can lead to the collapse of a bridge. Having done so, he generated productive insights on how accidents can be prevented. Furthermore, visual inspection processes are prone to error and are utterly subjective. Poor quality images or lighting conditions may lead to an incorrect evaluation. Kim et al. (2016) proposed the use of 3D laser scanning technology as a means of avoiding the limitations associated with physical inspection. A framework for bridge inspection has been developed that employs a Terrestrial Laser Scanner (TLS) and a strategy by which the TLS point clouds are detected and processed to detect deficiencies and deformations and to reconstruct the 3D scheme as the as-built models are created (Truong-Hong et al. 2016). BIM is often used in the bridge maintenance field too. One of the most significant advantages of BIM is that the digital model allows users to store a large amount of information, which they can subsequently use to visualise the data and, thereby, significantly improve their understanding of the project (Whyte, 2002). One example of this can be observed in the work of McGuire et al.(2016) who created a plug-in for Revit that could collate key information related to several important aspects of bridge inspection operations. The Revit plug-in can be synched with the damage-cube family, which can be subsequently employed to develop insights into the extent and prevalence of a given type of deficiency within a specific area of a component of the bridge. Additionally, it is important to note that regulations are somewhat theoretical and are open to interpretation. As such, the extent to which they are intentionally implemented is subject to the understanding of the personnel conducting the work. Furthermore, the traditional process by which requirement manuals are reviewed and compiled is time-consuming. Automatic rule checking technology has the potential to overcome these issues.

Automatic rule checking involves the use of software to assess the configuration of a set of objects (Eastman et al., 2009). It involves encoding traditional standards and then applying computer-read rules to check the building model. The Semantic Web represents one approach by which rule checking can be implemented and it has demonstrated significant potential in this domain.

The fundamental objective of the Semantic Web is to combine multiple online information sources and generate data that have precise meanings linked with real-world objects in a manner that allows human or computer users to understand and process the information available more efficiently. However, it has not yet been possible to include all the human knowledge that exists in the world in the Semantic Web. As such, semantic terms are employed to provide the computer with access to larger amounts of data. The Semantic Web can be employed in numerous fields (Hou et al., 2015) and it is of significant benefit within research studies, especially those that involve natural language processing, data annotation, information retrieval (Rajput & Haider, 2011), data interoperability and decision support. The aim of the current research is to examine how the Semantic Web can be employed within the rule-checking phase of bridge maintenance processes.

As a critical element of the Semantic Web, ontology plays a significant role in its application, the ontology provides a framework that can be employed to model knowledge and translate the knowledge into a form that can be interpreted by both computers and humans.

The word ontology can be interpreted in numerous ways. Historically, ontology was the philosophical study of existence or being. It is traditionally regarded as belonging to the metaphysics branch of philosophy and it considers what entities exist or are perceived to exist and how these entities can be grouped, structured in a hierarchy, and categorised according to their differences and similarities. Following the emergence of computer science, ontology has developed a whole new meaning, and the term can now also be employed to describe a computational artifact or an information object (Guarino et al., 2009). According to Guber (1993), an ontology is an “explicit specification of a conceptualisation”. Borst (1997) expanded on this definition by describing an ontology as a “formal specification of a shared conceptualisation” that treats a conceptualisation as a universal opinion as opposed to an opinion held by an individual. Additionally, there is a requirement for this conceptualisation to be transformed into a form that computers can read. Studer et al. (1998) combined the two definitions of ontology described above and highlighted how an ontology represents an explicit, formal specification of a shared conceptualisation.

Generally speaking, an ontology consists of a set of concepts and established relationships between those concepts through elements such as properties, data values, class hierarchies, and property restrictions (Hou et al., 2015). Numerous research and applications of ontology have been documented. A large number of domains have been covered, such as transportation, knowledge engineering, safety science, architecture and so on. In the construction field, ontologies are mainly used to aid the information exchange and sharing, which includes rule checking, knowledge management, and project management. According to Yurchyshyn and Zarli (2009), an ontology-based approach has been proposed to semi-automatically check conformance problems in the construction field. To improve the real-time monitoring of a specific building, Dibley et al. (2015) proposed a multi-goal framework based on an ontology that has enormously improved the previous version. Furthermore, Zhang et al. (2017) developed an ontology-based method to assist holistic structural design with the consideration of safety, environmental impact, and cost. It is worth mentioning that ontologies can also be utilised to facilitate the data exchange and sharing in the BIM files. For instance, Park et al. (2013) integrated BIM with ontologies to create a conceptual system for construction defect management, which can greatly improve the effectiveness of the defect management process. Furthermore, an enhancement of conversion patterns to convert IFC to Web Ontology Language (OWL) by adding class expressions was proposed by Terkaj and Šojic (2015). It has been proven to be an effective approach to improve data consistency and applicability for industrial application.

Based on the review of ontology implementation in the AEC field, some conclusions can be drawn: (1) Most ontology research is still at the conceptual stage, which shows that some problems need to be solved before practical use. (2) The potential of ontologies is limitless. For instance, the function of reasoning has not been maximised during the ontology development. (3) Despite significant research related to Semantic Web in the AEC domain, few works have focused on the infrastructure sector, especially in the bridge maintenance domain. Thus, to improve efficiency and combine knowledge regarding bridge maintenance, automatic evaluation, and the selection of suppliers to help engineers make decisions in bridge maintenance, an ontology called Bridge Maintenance Ontology (BrMontology) has been developed. In the next section, the process of developing the BrMontology will be illustrated in detail.

3 Design and development of bridge maintenance ontology

3.1 Underlying resources for ontology development

3.1.1 The method of bridge technical condition evaluation

According to the Code for Technical Condition Evaluation of Highway Bridges (Li, 2011), the bridge technical condition evaluation includes the evaluation of bridge member, component, superstructure, substructure, bridge deck system, and whole bridge. The process of highway bridge evaluations can be shown in Figure 3.

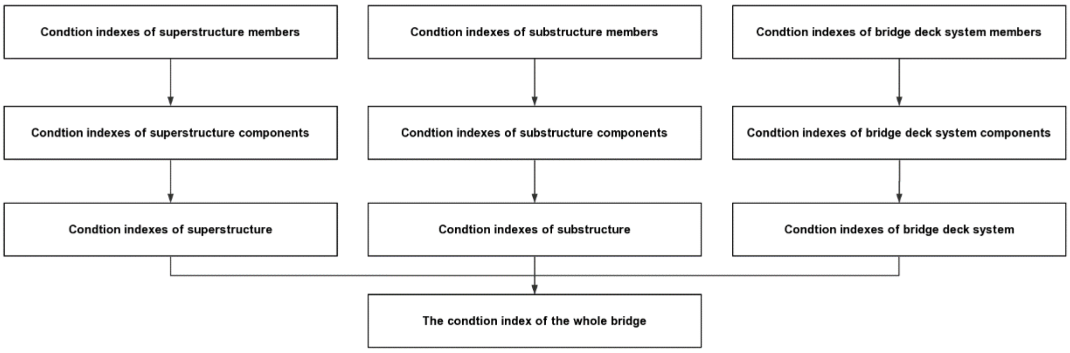


Figure.3 Bridge condition evaluation

The evaluation of highway bridges is implemented by using the combination of stratified condition assessments and 5 levels of independent control index. It evaluates each bridge member first and then evaluates each bridge component. After evaluating bridge components, it will assess the condition of superstructure, substructure and bridge deck system, and then conclude an overall technical condition of the bridge.

3.1.2 Level classifications of bridge technical condition

Bridge components consist of main components and secondary components. The overall technical condition of a bridge can be divided into 5 levels, as Table 1 shows.

Table 1 Overall technical condition of a bridge

Level of technical conditions	Description
1	Brand new and function well
2	With slight damages but no influence on functions
3	With medium damages but can keep normal functions
4	With severe damages and normal functions have been affected
5	With very severe damages and the bridge in a dangerous condition

Similarly, the technical condition of main components and secondary components can be classified into 5 levels (1 to 5) and 4 levels (1 to 4) respectively.

3.1.3 Computation of bridge technical condition

Based on the description in section 3.1.1, the computation process mainly involves 4 steps, starting from evaluating bridge members to evaluating the overall bridge condition, as shown below:

Step 1. Evaluation of bridge members.

When evaluating the technical conditions of bridge members, the formula below can be used (Li, 2011).

$$PMCI_l(BMCI_l \text{ or } DMCI_l) = 100 - \sum_{x=1}^{k} U_x.$$

When x=1, $U_i = DP_{i1}$; $x \geq 2$, $U_x = \frac{DP_{ij}}{100 \times \sqrt{x}} \times (100 - \sum_{y=1}^{x-1} U_y)$;

Where, $PMCI_l, BMCI_l,$ and $DMCI_l$ are the condition index of component i's member l in the superstructure, substructure, bridge deck system respectively. k is the type of deducting points in component i's member l; U, x, y are variables; i is the type of components, such as upper bearing members, bearings, piers; j is the type of detection indicator of component i's member l; DP_{i1} is the deducting points of detection indicator j of component i's member l,the value of deducting point is determined according to Table 2;

Table 2 Deducting point of detection indicator (Li, 2011)

The highest level of detection indicator	**Detection indicator**				
	1	**2**	**3**	**4**	**5**
3	0	20	35	-	-
4	0	25	40	50	-
5	0	35	45	60	100

Take, for example, the evaluation of a bridge pier to show how the technical condition is computed. The bridge pier, as a member of a bridge, may suffer different types of damages, such as cracking, voids and hungry spots, spalling and so on. Each type of damage has a specific standard to describe. In terms of voids and hungry spots, the standard for evaluating them are listed in Table 3.

Table 3 Standard for assessing voids and hungry spots (Li, 2011)

Grade	Standard for assessing	
	Qualitative description	Quantitative description
1	Intact	—
2	Light voids or hungry spots	Cumulative area≤ 20% of member area, single area≤1.0 m^2
3	Many voids or hungry spots	Cumulative area> 20% of member area, single area>1.0 m^2

As we can see, when the cumulative area is larger than 20% of the member area, or the single area is larger than 1.0 m^2, the level of voids and hungry spots on this member can be marked as grade 3. It is easy to see that the cumulative area of voids and hungry spots on the bridge piers, which are shown in Figure 4, is larger than 60% of the pier area. Therefore, we can mark the grade of voids and hungry spots on this bridge member as 3, according to Table 2, the deducting point can be identified as 35. After evaluating the voids and hungry spots, we can use similar methods to evaluate other types of damages. After evaluating all the damages on this pier, the formula mentioned above can be used to compute the technical condition of this pier. Similarly, we can use the same approach to compute the technical condition of other members, components, structures, and then compute the overall technical condition of the bridge.

Figure.4 Voids and hungry spots on bridge piers (Voids on Lishui River Bridge, 2016)

Step 2. Evaluation of bridge components

When evaluating the technical conditions of bridge components, the formulas below can be used (Li, 2011),

$$PCCI_i = \overline{PMCI} - (100 - PMCI_{min})/t$$
$$\text{or } BCCI_i = \overline{BMCI} - (100 - BMCI_{min})/t$$
$$\text{or } DCCI_i = \overline{DMCI} - (100 - DMCI_{min})/t\ .$$

Where, $PCCI_i, BCCI_i,$ and $DCCI_i$ are the grade of component i in the superstructure, substructure, and bridge deck system respectively; $\overline{PMCI}$, $\overline{BMCI}$, and $\overline{DMCI}$ are the average grade of each component i's member in the superstructure, substructure, and bridge deck system; $PCCI_{min}, BCCI_{min},$ and $DCCI_{min}$ are the lowest grade of component i's members in the superstructure, substructure, and bridge deck system respectively; t is the coefficient which varies with the number of members.

Step 3. Evaluation of bridge superstructure, substructure, and deck system.

When evaluating the technical conditions of bridge superstructure, substructure, and deck system, the formulas below can be used (Li, 2011),

$$SPCI(SBCI_l \text{ or } BDCI) = \sum_{i=1}^{m} PCCI_i(BCCI_i\ or\ DCCI_i) \times W_i$$

Where, $SPCI,\ SBCI$, and $BDCI$ are the technical conditions of the bridge superstructure, substructure, and bridge deck system respectively; m is the number of the bridge superstructure (substructure or deck system) types; W_i is the weight of the component i.

Step 4. Overall evaluation of bridge

The formula below can be used to evaluate the overall bridge condition (Li, 2011),

$$D_r = BDCI \times W_D + SPCI \times W_{SP} + SBCI \times W_{SB}$$

Where, D_r is the grade of the bridge's overall technical condition; W_D, W_{SP}, W_{SB} are the weight of the bridge deck system, superstructure, and substructure respectively. The classification of the bridges' overall technical condition is listed in Table 4.

Table 4 The classification of the overall technical condition (Li, 2011)

The grade of technical condition	Level of technical condition				
	1	2	3	4	5
$\boldsymbol{D_r}$	[95,100)	[80,95)	[60,80)	[40,60)	[0,40)

3.2 System Framework and Vital Components

The BrMontology includes four key components: (1) The knowledge base stores ontology models and all the SWRL rules. It is the most important component of the framework. (2) The ontology management system, which helps editors establish and modify the ontology. In the case of the current study, Protégé 5.2 was employed. (3) The rule engine, which reads the existing facts and rules created by knowledge engineers and infers new facts in this system; for example, JESS engine in this ontology. (4) The query interface, which is often used to interact with the knowledge management system. The collaboration of these four crucial components allows the whole ontology system to work seamlessly and effectively. Furthermore, the reasoning engine, which can check the consistency of the developed ontology to eliminate errors, is also an important part.

A workflow of the BrMontology framework is provided as follows: Firstly, knowledge engineers translate knowledge regarding bridge maintenance, evaluation, and decision support into ontology and SWRL rules. Secondly, the ontology and SWRL rules defined via Protégé and SWRLTab are stored in a knowledge base. Then, the rule engine executes SWRL rules and generates new facts in the ontology management system. Finally, the decision-maker can obtain useful information by setting multiple constraints from Semantic Query-Enhanced Web Rule Language (SQWRL) query interface. More details are illustrated below.

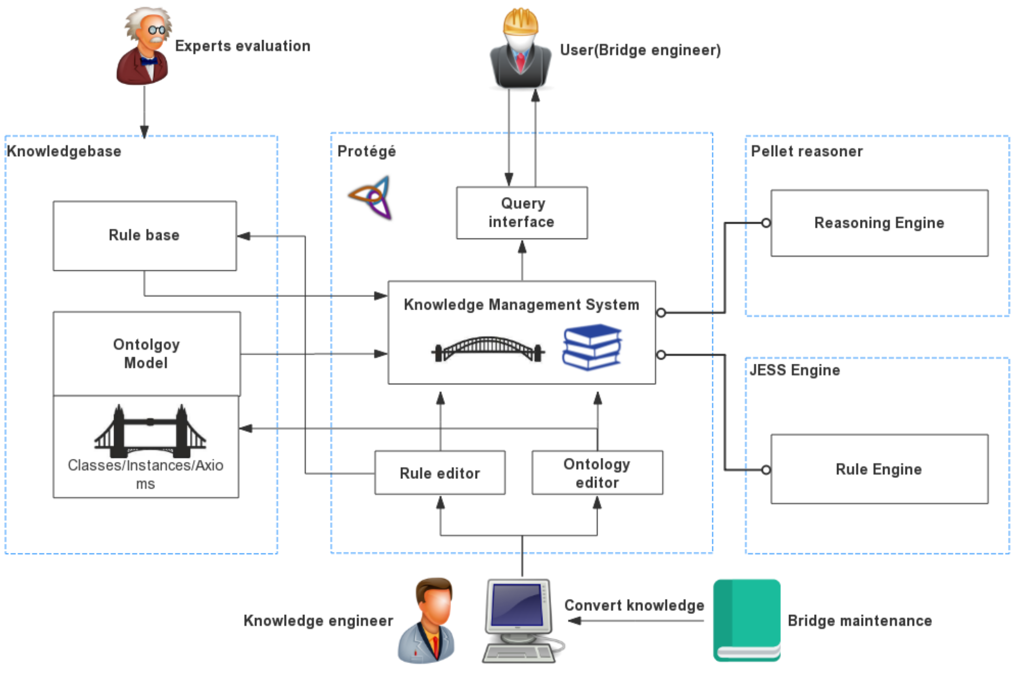


Figure.5 The workflow of the BrMontology framework

- Ontology editor

Protégé 5.2 was adopted for the ontology because it is open-source software. It allows the ontology to be created and updated by users and it is compatible with most OWL syntax validators. Additionally, various plugins can be used in combination with Protégé. □

- Rules engine

The Jess engine is a vital tool for the development of rules that can be repeatedly applied to a set of facts or executed to create new facts. □

- Ontology reasoner

Pellet is a vital reasoner in the ontology. It can provide important standards and advanced reasoning services. □

- Plug-ins

SWRL Tab: can help write SWRL rules.

SWRL Editor: can help edit and save various SWRL rules.

SWRL Jess Bridge: facilitates communication between the ontology and rule engines. SQWRLQueryTab: can offer a graphical interface through which users can interact with SQWRL queries.

SWRLJessTab: can provide a graphical interface to work with the SWRLJessBridge.

3.3 Development of BrMontology

3.3.1 Methodology and key steps

To establish a knowledge-based decision support system, it is first necessary to identify the complex field knowledge before incorporating it into the knowledge base. Collecting domain knowledge is a vital preparation step in the creation of an ontology. To acquire domain knowledge, a large number of knowledge engineering methods have been developed, for example, MIKE, CommonKADS, and PROTEGE-II. However, each of them has employed a different emphasis (Hou et al. 2015).

In the current study, the CommonKADS knowledge engineering method was used to support the preparation procedure for two main reasons. First, it represents the leading standard for the analysis of knowledge and the development of a knowledge-intensive system (Schreiber, 2000). Second, the CommonKADS method incorporates many of the activities that are considered to be essential for knowledge engineering, from knowledge analysis and management to knowledge-intensive system development (Sure et al., 2009). During the process of system development, the CommonKADS is a useful tool for early knowledge collection and it primarily consists of three activities: (1) Knowledge identification. It involves identifying the problems in relevant domains, the purpose the knowledge will serve, and the scope of the ontology. The main task of this activity involves reviewing and analysing the existing literature and semantic sources. All related terms are then compiled in a list before a glossary of the key terminology is constructed. (2) Knowledge specification. During this step, a template is selected and a semi-formal model is developed. The purpose of these activities is to create a specification for the knowledge model. (3) Knowledge refinement. It is the last phase of the knowledge modelling process, and it typically consists of two tasks: validation and refinement of the knowledge model. More details of these activities are shown in Figure 6. In this case, numerous existing literature, specifications, and semantic sources related to bridge maintenance were studied and reviewed, and a large number of potential terminologies were listed for reuse before a glossary of the key terminology was constructed during the first stage. In the knowledge specification phase, a template bridge model was selected and all relevant key terms were identified. Besides, the initial knowledge model, i.e., ontology, and relevant SWRL, SQWRL were constructed according to corresponding bridge maintenance regulations. Furthermore, in knowledge refinement stage, data in an actual bridge maintenance report was inputted into the ontology and outcomes generated by running the ontology were compared with actual results to validate the knowledge model. Meanwhile, the whole knowledge base was continuously broadened and adjusted.

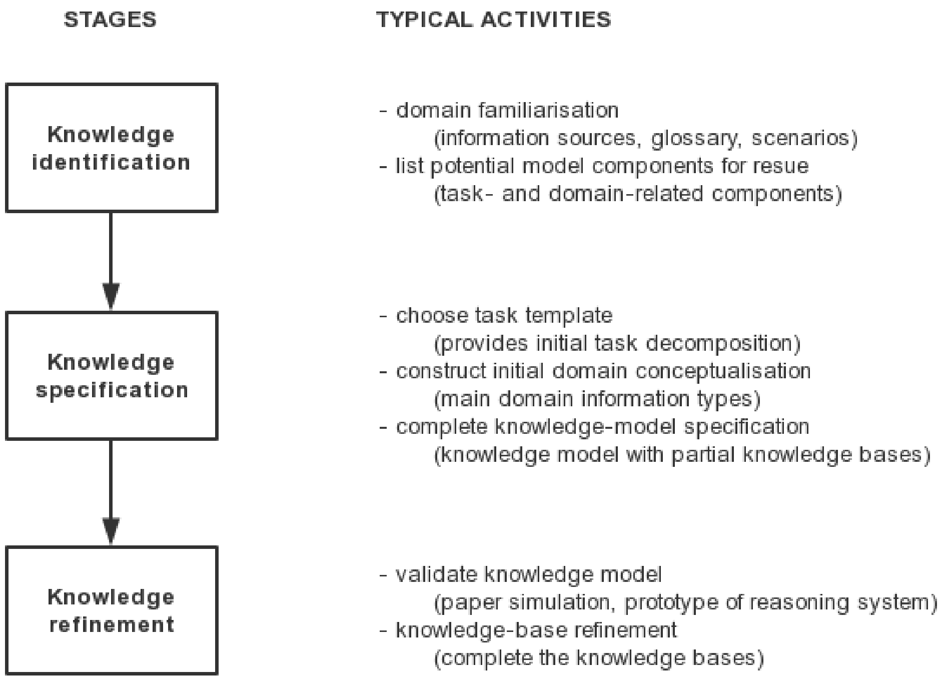


Figure.6 The CommonKADS methodology

Based on the acquired domain knowledge, knowledge engineers can start to develop the ontology. According to the previous literature (Sure et al. 2009), several approaches can be adopted to develop an ontology, such as Uschold and King, Grüninger and Fox, Methodology, KACTUS and Ontology Development 101. Each method has its own merits and shortcomings. In the current research, the Ontology Development 101 is adopted due to the following reasons: (1) This methodology was designed for beginners. As such, it is easy to learn and operate. (2) The detailed activities involved in this approach have been specified. The process of establishing an ontology is described in detail in this methodology. (3) It can be integrated with other tools. This method contains detailed instructions on how to implement the ontology in the Protégé environment.

The steps by which BrMontology was achieved are discussed in detail below:

Step 1. Define the domain and scope of the BrMontology.

The domain and scope of an ontology play significant roles in its development and has a major influence on its quality. As such, it is important to define the domain and scope at an early stage of the ontology development. Answering competency questions functions as a good approach so that knowledge engineers can determine the scope of the ontology. Some of the questions that were asked to create the ontology that was employed in this study, together with the respective answers, were as follows:

Q: Why develop the BrMontology?
A: To improve the management of multi-domain knowledge, to help bridge engineers reduce repetitive work tasks, and provide more valuable information to support effective decision making.
Q: What domains will the BrMontology cover?
A: Bridge evaluation and maintenance (including evaluation standard, maintenance code, required materials, cost, and the selection of supplier).
Q: Who is going to use the BrMontology?

A: Bridge engineers.
Q: What are sources for the knowledge base?
A: Bridge maintenance code, the specification of bridge evaluation, websites, and so on.
Q: How can the technical condition of a bridge be evaluated?
A: The evaluation of highway bridges is achieved through the implemented combination of stratified condition assessments and the five levels of independent control index. Each bridge member is evaluated first then followed by each bridge component. After evaluating the bridge components, the technical condition of the superstructure, substructure and bridge deck system is assessed before the overall technical condition of the bridge is calculated.

Answering competency questions and updating the knowledge model is an interactive process that can help knowledge engineers continually improve the quality of the ontology.

Step 2. Consider reusing or extending existing ontologies.

Evaluating the extent to which existing ontologies can be reused or extended is an important step that can save time and energy. In the case of the current research, after reviewing a large amount of literature, we were able to identify only a small number of ontologies related to the bridge maintenance domain. However, these ontologies' primary goal is not about bridge inspection and evaluation, and most classes and class hierarchy defined in these ontologies are not relevant so that it is difficult to reuse an existing ontology. Therefore, a new ontology has been developed.

Step 3. List crucial terms in BrMontology.

As previously mentioned, a glossary of essential terms was generated during the knowledge identification phase by reviewing and analysing relevant literature. Hence, in this step, all the key concepts associated with bridge evaluation and maintenance were listed. This list included both the relevant terms and the associated cost. Since concepts (e.g., DMCI, DCCI, BDCI, etc.) related to bridge evaluation have been listed in the previous section, Table 5 demonstrates an example of some crucial information about material suppliers, which has been inputted in BrMontology. Based on this data, BrMontology can help automatically select the most suitable supplier with different considerations, such as price, rating, time, etc.

Table 5 Information about material suppliers

Supplier	Company name	Address	Price	Delivery time	Rating	Phone
1	ZhengXiang Technology Co.,Ltd	International Financial building 22, Bei Cheng, Tian Jing, China	80	3d	Very good	18888888
2	Zhi Pan Industry Co.,Ltd	JuTai road 1221, Baoshan district, Shanghai, China	40	5d	good	28888888
3	Miao Han Industry Co.,Ltd	Songhu road 2511, Songjiang District, Shanghai, China	30	5d	good	38888888

Step4. Define classes and class hierarchy

Three methods can be employed to define class hierarchy (Uschold and Gruninger, 1996): The Top-Down method, The Bottom-Up method, The Mixed method. Each of them has its own inherent strengths and weaknesses. In this study, the Top-Down approach was used. This involved adding the general classes first and then the subclasses. Starting with a super-class in which structure, material, hazard, etc., are listed, this super-class is broken down into classes and then into sub-classes. The latter are very specific as to what may be included in them. For instance, the structure class includes superstructure, substructure, and bridge deck system, these sub-classes include bridge deck pavement, abutment, main arch ring etc. More detailed classes are illustrated in Figure 7.

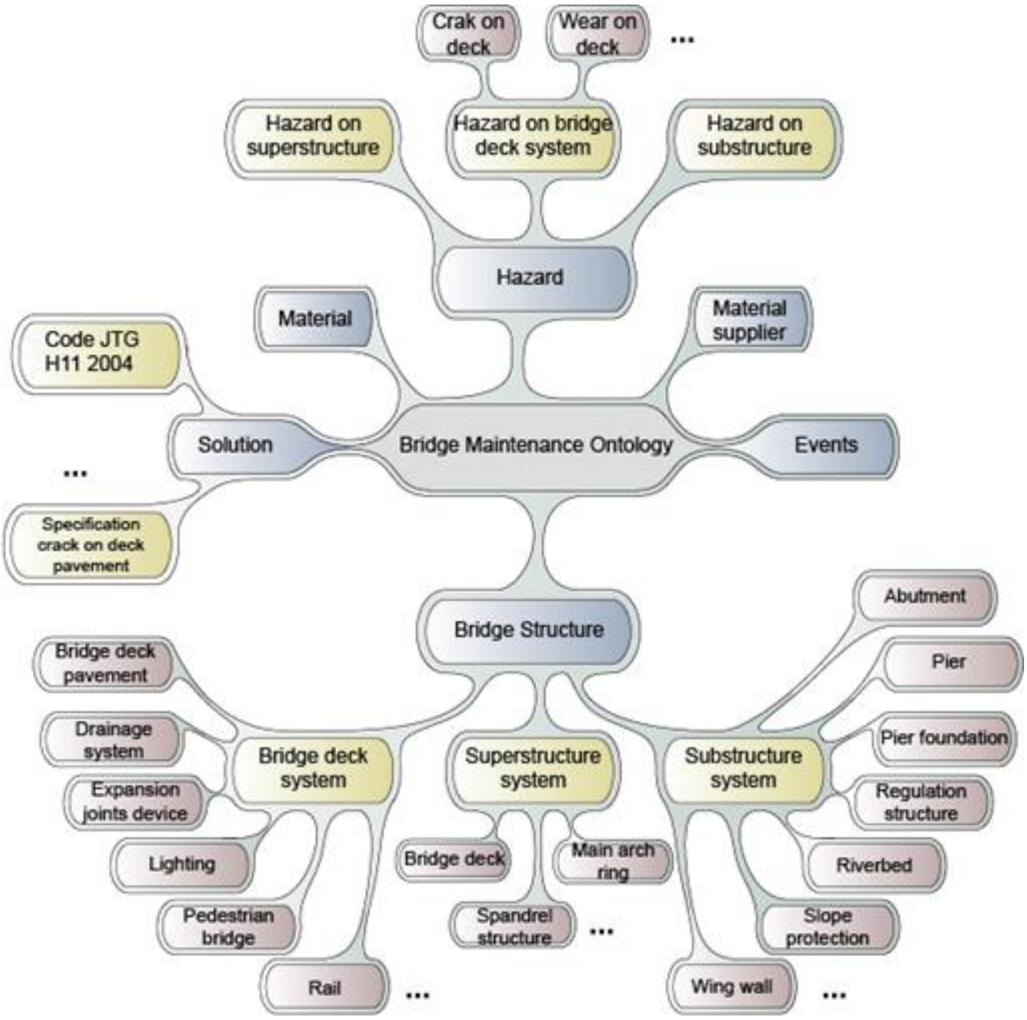


Figure 7 Detailed classes and class hierarchy

Step5. Define the properties of classes

A class hierarchy in isolation cannot represent knowledge accurately; as such, the properties of classes are also incorporated, the relationship between classes and properties is shown in Figure 8. Generally speaking, three different kinds of properties are used in ontologies: object properties, data properties, and annotation properties. The object property describes the relationship between different classes; for instance, has hazard and is_supplier_of. Using these object properties can connect various classes. Following this, a statement such as “Structure has_hazard Crack” and “MaterialSupplier is_supplier_of Material” can be formulated. Figure 9(a) presents the main classes’ object properties of the BrMontology. The data property describes the characteristics of various instances in both a quantitative and qualitative way. It incorporates multiple datatypes that can describe different types of information. For instance, the width of a crack is 5 mm. In the BrMontology, this statement can be represented as follows: An instance of Crack class has a data property named “max_width” with data value “5”. All the data property defined in the BrMontology are shown in Figure 9(b). The annotation property is often used to describe or explain specific instances. For example, pressure_infusion method has a workflow. In the current study, it can be represented as follows: An instance of Solution has an annotation property, which includes the detailed workflow of pressure_infusion, as shown in Figure 9(c)

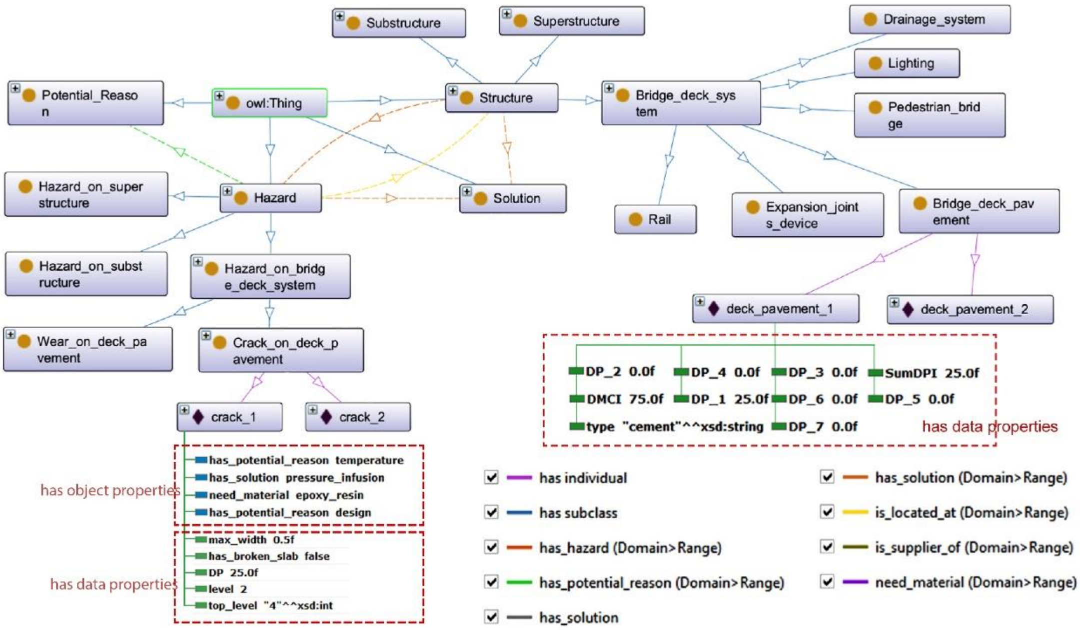
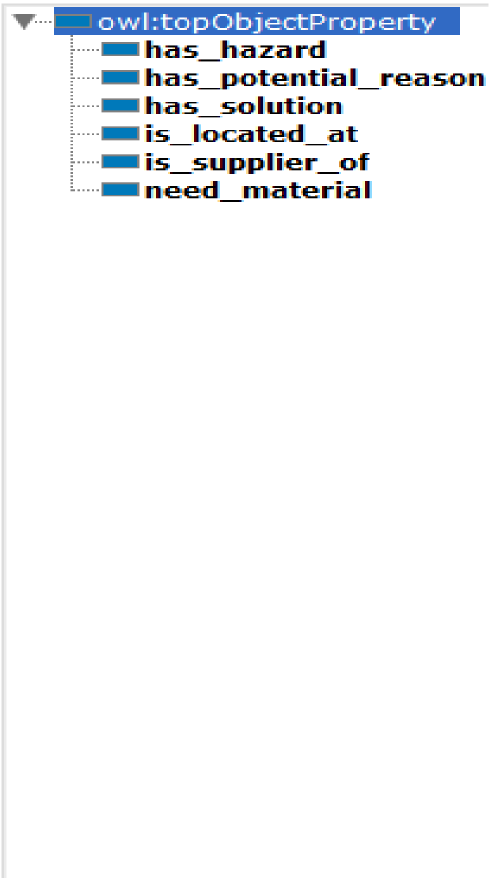
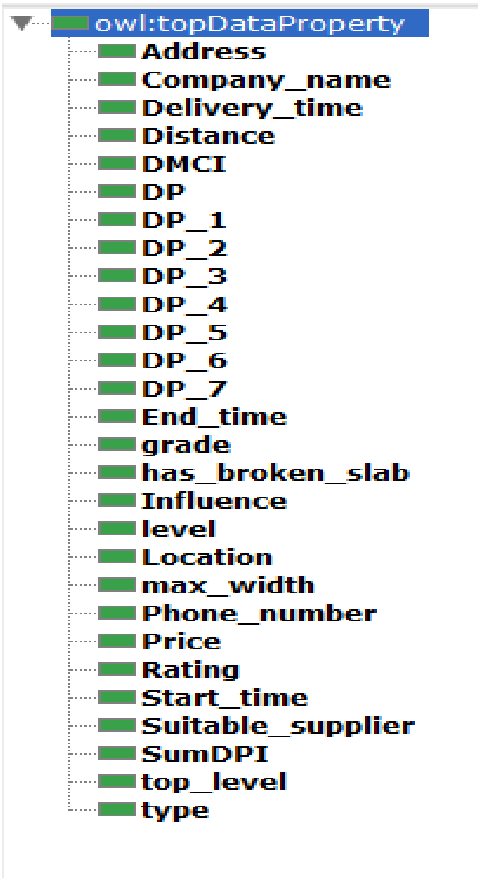
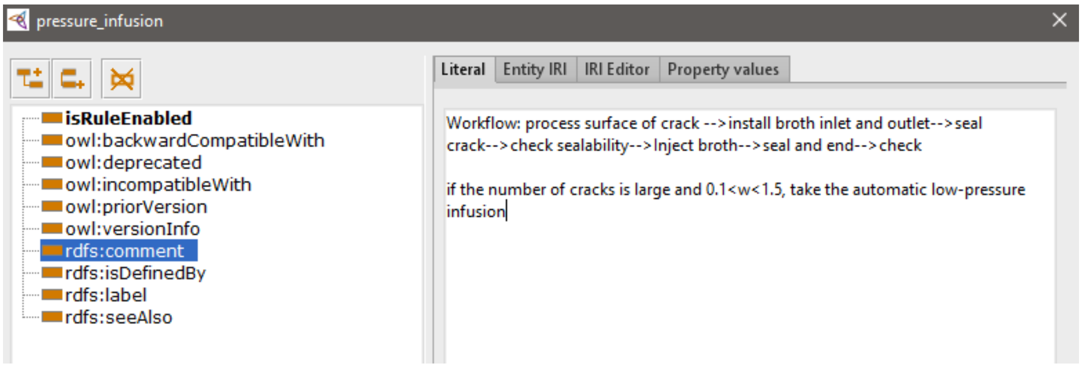


Figure 8 A high-level overview of BrMontology





(a) *(b)*



(c)

Figure.9 The developed ontology in the Protégé

Step6. Define the facets

Facet refers to the value of a property. Frequent kinds of value types can be attached to classes, such as string, int, float, and Boolean. For instance, the rating of MaterialSupplier can be described qualitatively using strings like bad, good, very good. Moreover, the price of Material can be attributed using a float like 80.0.

Step7. Create instances

Different individual instances are added in the class hierarchy. Three activities are carried out to create an instance: Selecting a class, adding a specific instance of this class, and attaching facets to the instance. For example, individual instances of the MaterialSupplier class are a list of companies. The company name, address, rating, price, and phone number are input as the facets of data properties, as shown in Figure 10

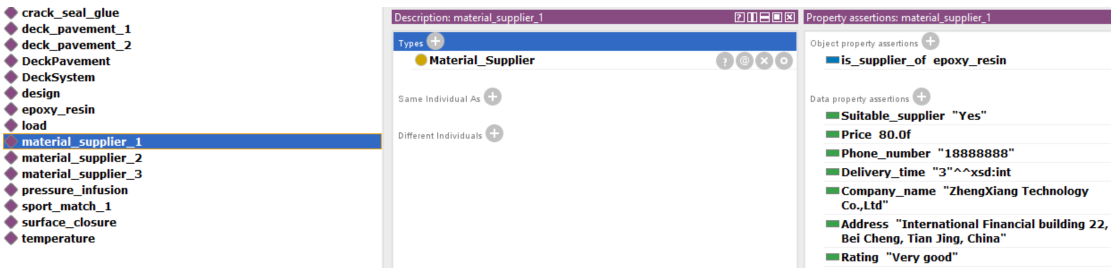


Figure 10 An instance of material supplier

Step8. Create rules: SWRL and SQWRL rules

To realise the Semantic Web, integrating various layers of its conceived architecture is an essential problem. In practice, a lot of proposals for integrating rules and ontologies have been developed; for example, hybrid and homogeneous methods (Hou et al., 2015). In the ontology that was developed for the current research objective, a homogeneous method was adopted that offered a seamless semantic integration of the rules and the ontology.

When this approach is employed, both the ontology and rules are represented in the OWL. Since SWRL is developed as a supplement to OWL, the interaction between OWL and SWRL is based on valuable semantic integration. Hence, there is no difference between the rule predicate and the ontology predicate. Both classes and properties of classes can be defined through the use of these rules.

The SWRLTab in Protégé is used to develop rules for the BrMontology. Two types of semantics are often used in the development of rules: SWRL and SQWRL. The first is often utilised to reason function and the second to query OWL ontologies. As previously described, the SWRL syntax includes two main parts: the antecedent and the consequent. An implicit symbol '→' is used to connect these two parts. Additionally, the conjunction symbol '∧' is used to connect different atoms. Variables in atoms are represented by the interrogation identifier '?'. The seven types of atoms provided by SWRL are as follows:

- The Class atom, which includes a named class in the OWL ontology with a variable or a named class with an individual in the OWL ontology.
- The Individual Property atom, which includes an object property in the OWL ontology and two variables representing two individuals in the OWL ontology.
- The Data Valued Property atom, which includes data property in the OWL ontology and two variables. The first represents an OWL individual and the second represents a data property or value.
- The Different Individuals atom, in which every variable is a different OWL individual.
- The Same Individual atom, in which two variables are the same OWL individuals.
- The Built-in atom, which can support a lot of complex predicates. This is a particularly useful feature of SWRL.
- The Data Range atom, which consists of a data range and either a literal or a variable name.

Example rules in SWRL and SQWRL can be defined as:

Rule example: Evaluate the technical condition of bridge damage

SWRL	Crack_on_deck_pavement(?C) ^ max_width(?C, ?y) ^ has_broken_slab(?C, false) ^ swrlb:lessThan(?y, 3) -> level(?C, 2)

Query example: Select the material supplier by considering Rating

SQWRL	Material_Supplier(?x) ^ is_supplier_of(?x, epoxy_resin) ^ Company_name(?x, ?CN) ^ Rating(?x, ?R) ^ Address(?x, ?A) ^ Phone_number(?x, ?PN) ^ Price(?x, ?PR) ^ Delivery_time(?x, ?DT) -> sqwrl:select(?x, ?CN, ?A, ?PN, ?R, ?PR, ?DT) ^ sqwrl:orderBy(?R)

Table 6 below illustrates the meaning and function of each atom by using an instance rule used in the BrMontology.

Table 6 Meaning and function of each atom

Atom type	Atom	Corresponding OWL element
Class atom	Crack_on_deck_pavement(?C)	Crack on deck pavement(class)
	Material_Supplier(?x)	Material supplier(class)
Data Valued Property atom	max_width(?C, ?y)	Maximum width (data-type property)
	has_broken_slab(?C, false)	Broken slab(data-type property)
	level(?C, 2)	level(data-type property)
	Company_name(?x, ?CN)	Company name(data-type property)
	Rating(?x, ?R)	Rating(data-type property)
	Address(?x, ?A)	Address(data-type property)
	Phone_number(?x, ?PN)	Phone number(data-type property)
	Price(?x, ?PR)	Price (data-type property)
	Delivery_time(?x, ?DT)	Delivery time(data-type property)
Individual Property atom	is_supplier_of(?x, epoxy_resin)	is_supplier_of (object property)

Built-in atom	sqwrl:select(?x, ?CN, ?A, ?PN, ?R, ?PR, ?DT)
	swrlb:lessThan(?y, 3)
	sqwrl:orderBy(?R)

3.3.2 Applications of BrMontology

In this paper, due to limited time and numerous bridge regulations, BrMontology emphasises on one specific type of bridge damage, i.e., crack. A thorough ontology will be developed in future work. Based on the created knowledge model and the defined SWRL, SQWRL, main functions of BrMontology are listed below; more details are shown in Table 7a-d:

- Automate bridge evaluation.

According to the information of a specific crack, the ontology can automatically identify the level of the crack and evaluate the deducting point, thereby calculating the technical condition of the bridge member, component, and structure, then the overall bridge condition can be computed;

- Provide information related to bridge maintenance.

Based on features of cracks and corresponding regulations, the developed ontology can generate and list potential reasons of different cracks, maintenance suggestions of the crack, and required materials for fixing. The detailed workflow of the maintenance approach is also included in the annotation property.

- Assist selecting material suppliers

The knowledge model contains a list of material suppliers and their essential information, such as company names, addresses, phone numbers, prices, ratings, and so on. Therefore, identifying a suitable resource supplier based on the priorities of the ontology's user can be facilitated by the system, with price or rating selected to identify a preferred resource supplier,

- Assist arranging big events

BrMontology can be used to help decision-makers check information about big events, which might cause a sharp increase in traffic flow, such as a concert, a popular sport match, and a marathon etc, and assist them to arrange time to conduct bridge inspections and maintenance. For instance, all crucial information about big events will be selected and listed, such as the location, distance, start time, end time, and the influence on the bridge. Decision-makers can sort these big events in chronological order so that they can reasonably start bridge maintenance to avoid the influence caused by big events.

Table 7a Application 1: SWRL rules for bridge evaluation

Rule 1	Determine the level of crack
Rule 1-1	If the maximum width of the crack is less than 3mm and there is no broken slab, the level of crack is 2. *Crack_on_deck_pavement(?C) ^ max_width(?C, ?y) ^ has_broken_slab(?C, false) ^ swrlb:lessThan(?y, 3) -> level(?C, 2)*
Rule 1-2	If the maximum width of the crack is no less than 3mm and no greater than 10mm and there is no broken slab, the level of crack is 3. *Crack_on_deck_pavement(?C) ^ max_width(?C, ?y) ^ has_broken_slab(?C, false) ^swrlb:greaterThanOrEqual(?y, 3) ^ swrlb:lessThanOrEqual(?y, 10) -> level(?C, 3)*
Rule 1-3	If the maximum width of the crack is greater than 10mm and there is no broken slab, the level of crack is 4. *Crack_on_deck_pavement(?C) ^ max_width(?C, ?y) ^ has_broken_slab(?C, false) ^ swrlb:greaterThan(?y, 10) -> level(?C, 4)*
Rule 2	Determine the deducting point
Rule 2-1	If the top level and actual level of the specific crack is 4 and 1 respectively, the DP of this crack is 0. *Crack_on_deck_pavement(?C) ^ top_level(?C, ?x) ^ level(?C, ?z) ^ swrlb:equal(?x, 4) ^ swrlb:equal(?z, 1) -> DP(?C, "0.0"^^xsd:float)*
Rule 2-2	If the top level and actual level of the specific crack is 4 and 2 respectively, the DP of this crack is 25.

	Crack_on_deck_pavement(?C) ^ top_level(?C, ?x) ^ level(?C, ?z) ^ swrlb:equal(?x, 4) ^ swrlb:equal(?z, 2) -> DP(?C, "25.0"^^xsd:float)
Rule 2-3	If the top level and actual level of the specific crack is 4 and 3 respectively, the DP of this crack is 40. *Crack_on_deck_pavement(?C) ^ top_level(?C, ?x) ^ level(?C, ?z) ^ swrlb:equal(?x, 4) ^ swrlb:equal(?z, 3) -> DP(?C, "40.0"^^xsd:float)*
Rule 2-4	If the top level and actual level of the specific crack is 4 and 4 respectively, the DP of this crack is 50. *Crack_on_deck_pavement(?C) ^ top_level(?C, ?x) ^ level(?C, ?z) ^ swrlb:equal(?x, 4) ^ swrlb:equal(?z, 4) ->DP(?C, "50.0"^^xsd:float)*
Rule 3	Calculating the sum of DP. SumDPI= $\sum_{x=1}^{k} DP_x$ *Bridge_deck_pavement(?B) ^ DP_1(?B, ?a) ^ DP_2(?B, ?b) ^ DP_3(?B, ?c) ^ DP_4(?B, ?d) ^ DP_5(?B, ?e) ^ DP_6(?B, ?f) ^ DP_7(?B, ?g) ^ swrlb:add(?x, ?a, ?b, ?c, ?d, ?e, ?f, ?g) -> SumDPI(?B, ?x)*
Rule 4	Calculating the value of DMCI. $DMCI_l = 100 - \sum_{x=1}^{k} U_x$ *Bridge_deck_pavement(?B) ^ SumDPI(?C, ?x) ^ swrlb:subtract(?z, 100, ?x) -> DMCI(?B, ?z)*
Rule 5	Calculating $DCCI_i$: $DCCI_i = \overline{DMCI} - (100 - DMCI_{min})/t$. *Bridge_deck_system(?B) ^ DMCI_1(?B, ?x) ^ DMCI_2(?B, ?y) ^ DMCI_min(?B, ?min) ^ t(?B, ?z) ^ swrlb:add(?sum, ?x, ?y) ^ swrlb:divide(?ave, ?sum, 2) ^ swrlb:subtract(?b, 100, ?min) ^ swrlb:divide(?c, ?b, ?z) ^ swrlb:subtract(?ci, ?ave, ?c) -> DCCI(?B, ?ci)*
Rule 6	Calculating BDCI: $BDCI = \sum_{i=1}^{m} DCCI_i \times W_i$ *Structure(?S) ^ DCCI_1(?S, ?ci1) ^ DCCI_2(?S, ?ci2) ^ DCCI_3(?S, ?ci3) ^ DCCI_4(?S, ?ci4) ^ DCCI_5(?S, ?ci5) ^ DCCI_6(?S, ?ci6) ^ W1(?S, ?w1) ^ W2(?S, ?w2) ^ W3(?S, ?w3) ^ W4(?S, ?w4) ^ W5(?S, ?w5) ^ W6(?S, ?w6) ^ swrlb:multiply(?a, ?ci1, ?w1) ^ swrlb:multiply(?b, ?ci2, ?w2) ^ swrlb:multiply(?c, ?ci3, ?w3) ^ swrlb:multiply(?d, ?ci4, ?w4) ^ swrlb:multiply(?e, ?ci5, ?w5) ^ swrlb:multiply(?f, ?ci6, ?w6) ^ swrlb:add(?bd, ?a, ?b, ?c, ?d, ?e, ?f) -> BDCI(?S, ?bd)*
Rule 7	Calculating D_r: $D_r = BDCI \times W_D + SPCI \times W_{SP} + SBCI \times W_{SB}$ *Structure(?S) ^ BDCI(?S, ?bd) ^ Wd(?S, ?wd) ^ SPCI(?S, ?sp) ^ Wsp(?S, ?wsp) ^ SBCI(?S, ?sb) ^ Wsb(?S, ?wsb) ^ swrlb:multiply(?a, ?bd, ?wd) ^ swrlb:multiply(?b, ?sp, ?wsp) ^ swrlb:multiply(?c, ?sb, ?wsb) ^ swrlb:add(?dr, ?a, ?b, ?c) -> Dr(?S, ?dr)*

Table 7b Application 2: SWRL rules for bridge maintenance

Rule 1	Listing the potential reasons of the crack if the bridge deck pavement is made of cement and the DP of crack is not zero *Crack_on_deck_pavement(?C) ^ DP(?C, ?x) ^ Bridge_deck_system(?B) ^ type(?B, "cement") ^ swrlb:greaterThan(?x, 0) -> has_potential_reason(?C, temperature) ^ has_potential_reason(?C, load) ^ has_potential_reason(?C, design) ^ has_potential_reason(?C, construction)*
Rule 2	Providing the maintenance suggestions if the bridge deck pavement is made of cement and the DMCI is less than 100 *Bridge_deck_system(?B) ^ type(?B, "cement") ^ DMCI(?B, ?x) ^ swrlb:lessThan(?x, 100) -> has_solution(?B, bridge_deck_system_maintenance)*
Rule 3	Presenting the method for fixing crack and the required material when the maximum width of the crack is less than 0.15mm *Crack_on_deck_pavement(?C) ^ max_width(?C, ?y) ^ swrlb:lessThan(?y, 0.15) -> has_solution(?C, surface_closure) ^ need_material(?C, crack_seal_glue)*
Rule 4	Presenting the method for fixing crack and the required material when the maximum width of the crack is greater than or equal to 0.15mm *Crack_on_deck_pavement(?C) ^ max_width(?C, ?y) ^ swrlb:greaterThanOrEqual(?y, 0.15) ->has_solution(?C, pressure_infusion) ^ need_material(?C, epoxy_resin)*

Table 7c Application 3: SQWRL rules for selecting material suppliers

Rule 1	Selecting the material supplier with consideration of rating *Material_Supplier(?x) ^ is_supplier_of(?x, epoxy_resin) ^ Company_name(?x, ?CN) ^ Rating(?x, ?R) ^ Address(?x, ?A) ^ Phone_number(?x, ?PN) ^ Price(?x, ?PR) ^ Delivery_time(?x, ?DT) -> sqwrl:select(?x, ?CN, ?A, ?PN, ?R, ?PR, ?DT) ^ sqwrl:orderBy(?R)*
Rule 2	Selecting the material supplier with consideration of price *Material_Supplier(?x) ^ is_supplier_of(?x, epoxy_resin) ^ Company_name(?x, ?CN) ^ Rating(?x, ?R) ^ Address(?x, ?A) ^ Phone_number(?x, ?PN) ^ Price(?x, ?PR) ^ Delivery_time(?x, ?DT) -> sqwrl:select(?x, ?CN, ?A, ?PN, ?R, ?PR, ?DT) ^ sqwrl:orderBy(?PR)*
Rule 3	Selecting the material supplier with consideration of delivery time *Material_Supplier(?x) ^ is_supplier_of(?x, epoxy_resin) ^ Company_name(?x, ?CN) ^ Rating(?x, ?R) ^ Address(?x, ?A) ^ Phone_number(?x, ?PN) ^ Price(?x, ?PR) ^ Delivery_time(?x, ?DT) -> sqwrl:select(?x, ?CN, ?A, ?PN, ?R, ?PR, ?DT) ^ sqwrl:orderBy(?DT)*
Rule 4	Selecting the material supplier with multiple constraints *Material_Supplier(?x) ^ Rating(?x, "Very good") ^ Price(?x, ?PR) ^ swrlb:lessThan(?PR, 100) ^ Delivery_time(?x, ?DT) ^ swrlb:lessThan(?DT, "5"^^xsd:int) -> Suitable_supplier(?x, "Yes")*

Table 7d Application 4: SQWRL rules for arranging big events

Rule 1	Selecting information about big events with consideration of distance *Big_event(?B) ^ Location(?B, ?Lo) ^ Distance(?B, ?Ds) ^ Influence(?B, ?In) ^ Start_time(?B, ?ST) ^ End_time(?B, ?ET) ->sqwrl:select(?B, ?Lo, ?Ds, ?In, ?ST, ?ET) ^ sqwrl:orderBy(?Ds)*
Rule 2	Selecting information about big events with consideration of start time *Big_event(?B) ^ Location(?B, ?Lo) ^ Distance(?B, ?Ds) ^ Influence(?B, ?In) ^ Start_time(?B, ?ST) ^ End_time(?B, ?ET) ->sqwrl:select(?B, ?Lo, ?Ds, ?In, ?ST, ?ET) ^ sqwrl:orderBy(?ST)*
Rule 3	Selecting information about big events with consideration of influence level *Big_event(?B) ^ Location(?B, ?Lo) ^ Distance(?B, ?Ds) ^ Influence(?B, ?In) ^ Start_time(?B, ?ST) ^ End_time(?B, ?ET) ->sqwrl:select(?B, ?Lo, ?Ds, ?In, ?ST, ?ET) ^ sqwrl:orderBy(?In)*
Rule 4	Selecting big events which have *severe* influence on bridge *Big_event(?B) ^ Location(?B, ?Lo) ^ Distance(?B, ?Ds) ^ Influence(?B, "severe") ^ Start_time(?B, ?ST) ^ End_time(?B, ?ET) -> sqwrl:select(?B, ?Lo, ?Ds, ?ST, ?ET) ^ sqwrl:orderBy(?ST)*

4. Validation of the developed ontology

4.1 semantic and syntactical validation of the ontology

Vrandečić (2009) suggested that it is imperative for any new ontology to be thoroughly evaluated. The validation process includes ensuring the semantic and syntactical correctness of the ontology and verifying whether the ontology meets the intended requirements. In the following sections, the first two validation activities will be examined: (1) Semantic validation. During this stage of the process, two main approaches can be adopted to complete the validation process: Consulting domain experts and using ontology alignment, merging and comparison techniques to realise the validation. The latter of these approaches is often used when the ontology is established by reusing or extending existing ontologies. Therefore, considering the fact that BrMontology is a brand-new ontology, the first method will be adopted in this study. Each concept that is incorporated into the BrMontology was analysed and semantically evaluated by domain professionals. (2) Syntactical validation. Once the semantic validation process is complete, another necessary step will be syntactically checking the consistency of the ontology. The developed ontology must be checked against subsumption, equivalence, instantiation, and consistency. Similarly, the syntactical validation can be conducted via the use of two main approaches: manually checking and automatically checking. The automatic checking process is achieved through the use of ontology reasoners, such as Pellet. The Pellet, which is a plug-in for Protégé, can be used to check and eliminate errors in the syntax of the ontology. The reasoning process, as shown in Figure 11, presents that no errors are occurring when running the reasoner, thereby producing a positive result of syntactical validation.

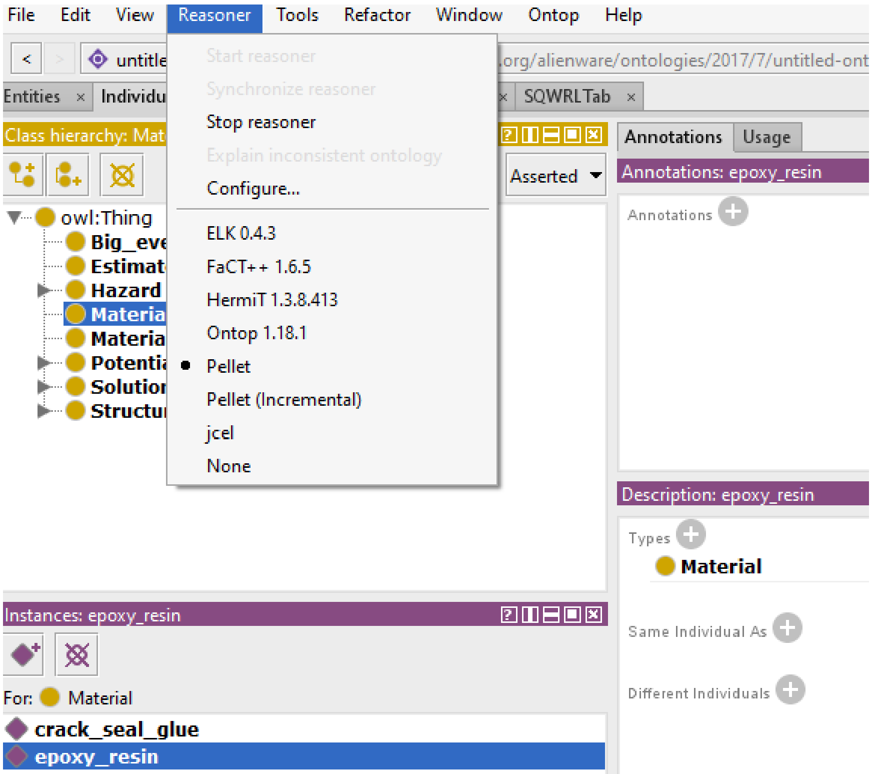


Figure.11 Reasoning process in BrMontology

After semantic validation and syntactical validation, the BrMontology's purpose was validated through the use of a case study.

4.2 Case study validation

In this section, a practical bridge inspection and evaluation report w introduced to validate the BrMontology and illustrate how this ontology works for the bridge maintenance process. The inspected bridge is the Hetang Xijiang Bridge, which is located in Jiangmen, a city in the Guangdong, China. BrMontology's features will be illustrated by considering a particular bridge member and a particular type of damage due to the limited time available and the wide breadth of the bridge maintenance field.

With this ontology, the computer can evaluate the level of damage and calculate the technical condition of the corresponding bridge member according to the information of a specific damage on a particular bridge member. Based on these condition indexes, the ontology can compute the overall condition of the bridge. Taking the evaluation of cracks on bridge deck pavement as an example, the maximum width of a crack and the number of broken slabs are manually inputted and regarded as initial facets while the level of a crack can be assessed automatically according to the JTG/T H21-2011 and initial data, which are shown in Table 8 and Table 9. Then, based on the inferred facts, the deducting points of specific damages and the technical condition of the bridge member, component, and structure can be computed. After inputting all of the damage data from Table 8 and running the SWRL rules, the system can automatically calculate the grade of the bridge deck pavement. From there, the technical conditions of other parts can be worked out based on the results, as shown in Figure 13. The values of DMCI and Dr, which are 75 and 74.7 respectively, are the same as the values in the bridge inspection report, shown in Table 10, and, therefore, positively validating the BrMontology.

Table 8 Cracks on the bridge deck pavement

No.	Component	Shape	Max width(mm)	Length(m)

crack 1	pavement	longitudinal crack	0.5	100
crack 2	pavement	longitudinal crack	0.3	7
crack 3	pavement	longitudinal crack	0.4	6.5
crack 4	pavement	longitudinal crack	0.5	9
crack 5	pavement	longitudinal crack	0.5	15
crack 6	pavement	longitudinal crack	0.5	15
crack 7	pavement	longitudinal crack	0.5	9
crack 8	pavement	longitudinal crack	0.5	9
crack 9	pavement	longitudinal crack	0.45	9
crack 10	pavement	longitudinal crack	0.5	6
crack 11	pavement	longitudinal crack	0.5	8

Table 9 Classification of the level of crack

Maximum width of the crack	Level of crack
x=0	1
x<3mm	2
3mm≤x≤10mm	3
x>10mm	4

Similarly, according to the SWRL rules and features of the specific damage, the BrMontology can generate the potential reasons for damage, required materials for fixing, and maintenance methods of the damage automatically. The detailed workflow of the maintenance method is also included in the annotation property. Besides, the developed ontology created a list which contains different kinds of information about material suppliers and ranked them by price from low to high. This function can provide decision-makers more direct information regarding cost. Likewise, the BrMontology can help users identify a suitable material supplier via a combination of multiple constraints. For example, they can limit the search to a suitable supplier who is described as having a rating of at least “very good”, a price less than 100/kg, and a delivery time less than 5 days. It is convenient for engineers to view and choose key information and make decision more efficiently. Furthermore, all crucial information about big events, which will happen near the target bridge will be selected and listed, such as the location, distance, start time, end time, and the influence on the bridge. The ontology can conveniently sort them by various criterions so that decision-makers can arrange properly the bridge operation and maintenance, as shown in Figure 12.

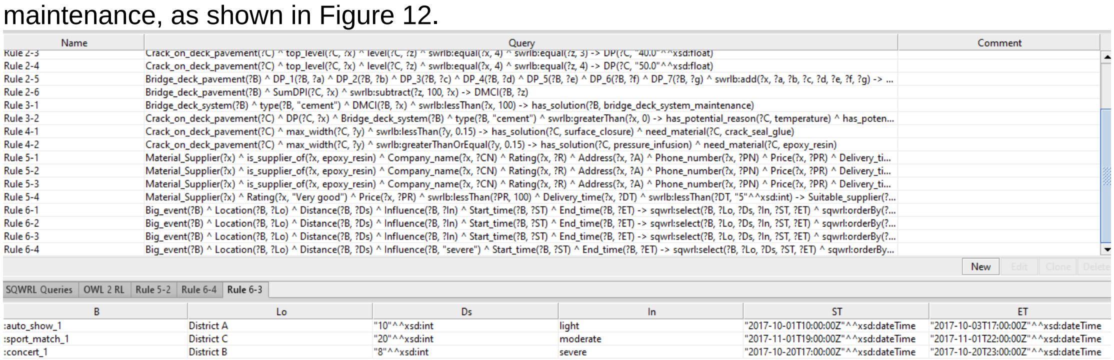


Figure.12 Execution and results of rule 3 in application 4

Table 10 Results of bridge evaluation

Name	Grade	Level
DCI:	69.4	3
Bridge deck pavement(DMCI)	75.0	3
Expansion joint	41.2	4
Pedestrian	56.0	4
Railing	85.0	2
Drainage system	100.0	1
Lighting and marking	100.0	1
SPCI:	79.6	3
Arch rib	61.8	3
Horizontal linkage	78.8	3
Sag tie	61.2	3
Tied bar	100.0	1
Bridge deck	88.6	2
Bearing	100.0	1
SBC:	72.4	3
Pier	64.5	3
Abutment	66.1	3
Pier foundation	78.8	3
Riverbed	100.0	1
Bridge technical condition：	3	
Dr:	74.7	

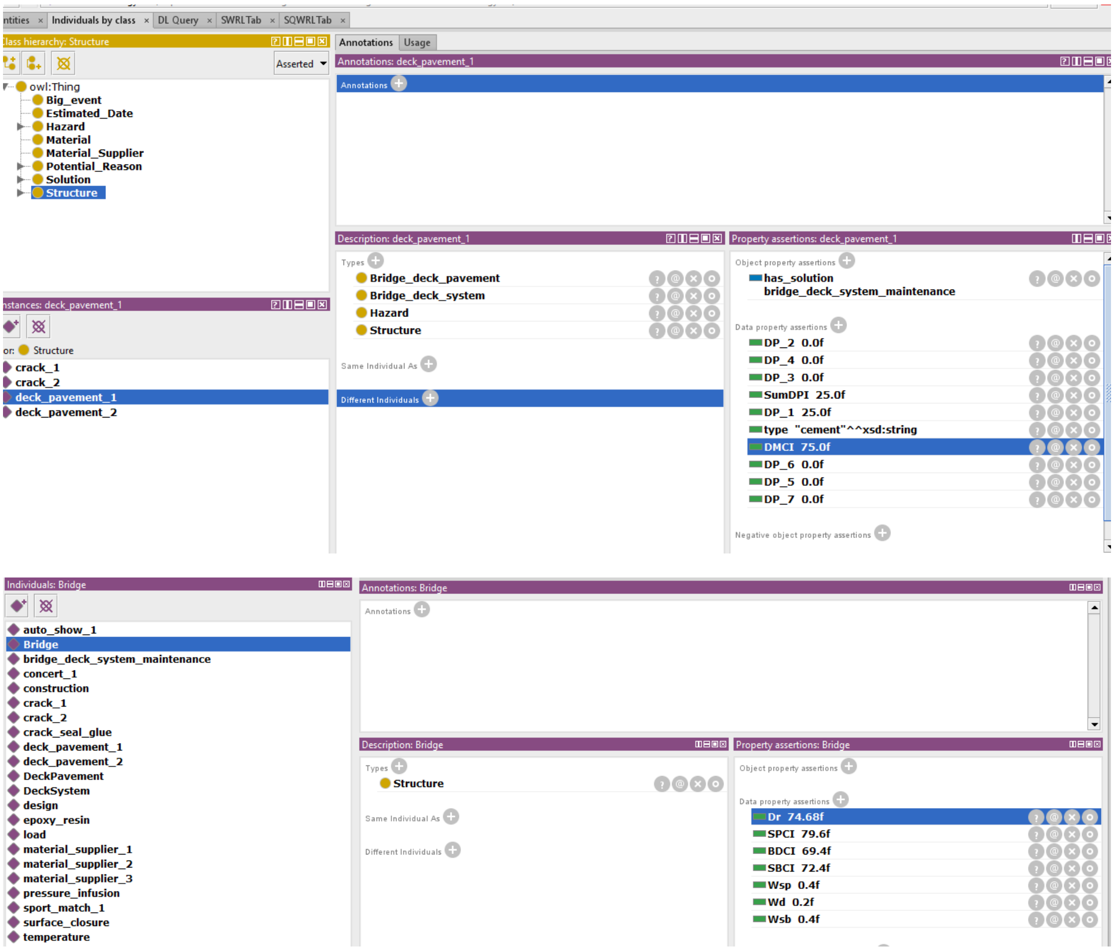


Figure.8 Execution and results of application 1

4.3 Discussion

As an initial attempt, this paper discusses how to utilise ontology, SWRL, and SQWRL rules to assist bridge evaluation and improve the information management of bridge maintenance. The defined SWRL and SQWRL rules are regarded as specification checking tools to automatically calculate and assess the technical condition of a bridge. It presents a new method of working for engineers to achieve the digitalisation and automation of bridge maintenance. The developed ontology also combined knowledge regarding specifications for bridge maintenance, the selection of material suppliers, and the arrangement for big events to provide valuable information with the consideration of cost, time, and rating. BrMontology has demonstrated a new approach of assisting bridge engineers to increase the efficiency of bridge maintenance with the help of an intelligent knowledge base.

Despite some interesting findings, there still exists some limitations in the research. They are as follows:

- Hundreds of types of damages need to be considered in a practical engineering project. However, in this research, only one particular type of damage was considered, due to the restricted time available and the wide breadth of the bridge maintenance field. More detailed classes and instances need to be added into the BrMontology to supplement the evaluation process.
- Only a small set of basic computational operations can be provided by the built-in mathematical functions of SWRL in the ontology. Some complex bridge evaluation formulas must be first converted into simple formulas and then placed in the SWRL

rule format. It is necessary to develop more built-in functions to improve SWRL rules and further fill the bridge maintenance section.

- There still exist several parameters which need to be manually input in this ontology, which means the whole evaluation process cannot be fully automated. It is expected that integration between the BrMontology and BIM can improve the ability of automation.
- The developed ontology is limited in the Protégé context. Bridge engineers with little knowledge regarding ontology engineering might have difficulties using SWRLTab to define bridge rules and query the knowledge base. It is necessary to explore other user-friendly programmes to support bridge maintenance.

For the next stage, the knowledge base is planned to be developed by further defining SWRL and SQWRL rules. Therefore all the practical specifications can be covered. Additionally, it is necessary to explore how to extract Structural information and damage information from a Revit model and import these data into the ontology to execute and infer so that all relevant programmes (e.g. Revit, Naviswork, Protégé) can be linked to develop an integrated process. What's more, as some artificial vision technologies has been applied to collect structural defects, it is reasonable to pay closer attention in automating the manual inspection using similar techniques and automatically populate defect instances in ontologies.

5. Conclusion

Semantic Web and ontology are the proper methodologies to achieve automatic rule checking in bridge maintenance. In this article, a knowledge model called BrMontology was developed to manage the existing knowledge related to bridge maintenance. In the BrMontology, OWL was used to construct a knowledge model and SWRL rules were adopted to represent checking constraints. Then, the bridge maintenance rule checking process was conducted in the JESS engine. Furthermore, to evaluate the ontology, three approaches: semantic validation, syntactical validation, and case study validation were adopted. The results showed that the BrMontology was validated against the purpose for which it was designed. 4 main functions have been achieved by BrMontology: (1) automation of bridge evaluation process (2) sorting and providing information about bridge maintenance (3) assisting selecting material suppliers (4) assisting arranging big events. From results listed by the ontology, it is easier for engineers to make decisions since results offer outcomes of the bridge evaluation, valuable information regarding material suppliers and big events, and provide a quantitative comparison between various choices. Compared with the traditional manual and paper-based method, the proposed approach has following advantages: (1) Bridge maintenance regulations are translated into a machine-read language and imported into the ontology to realise automatic rule checking so that time for manual reviewing and calculating can be saved, meanwhile, unnecessary subjective errors can be avoided. (2) Providing information from all aspects of bridge maintenance (e.g. evaluation, potential reasons, maintenance suggestions, required materials, big events, etc.) allows engineers and decision-makers to have a thorough view to deal with specific issues. (3) It is an open-source software. Based on existing ontologies and user's different requirements, people are able to modify, supplement, and share the ontology, which can save the time for constructing a new ontology and improve efficiency.

Although these outcomes are inspiring, the domain of ontology-based bridge maintenance is just beginning to emerge and, to date, there is no "complete answer" to current issues. Most research associated with this field is still at the conceptual stage and cannot be extensively implemented into the real world. This domain is significant and might provide numerous opportunities in the future. To limit research gaps, the future work should: (1) supplement the intelligent knowledge base, SWRL and SQWRL rules; (2) study how to realise automation in different phases, for example,3D laser scanner or artificial vision technologies can be utilised to capture structural and hazard information (3) investigate how to convert information, including structural information and damage information, from Revit models into ontologies without data loss; (4) develop a multi-disciplinary thinking mode to discover a better facilitation of bridge maintenance.

6. Reference

BORSTW, N. 1997. Construction of engineering ontologies. University of Twenty, Enschede, Center for Telematica and Information Technology.

CHAN, B., GUAN, H., HOU, L., JO, J., BLUMENSTEIN, M. & WANG, J. 2016. Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments. Journal of Civil Structural Health Monitoring, 6, 703-714.

CHIU, C.-T., HSU, T.-H., WANG, M.-T., CHIU, H.-Y., 2011. Simulation for steel bridge erection by using BIM tools. In: 28th International Symposium on Automation and Robotics in Construction, ISARC 2011, IIT Madras, Seoul, Republic of Korea, pp. 560–563.

Dibley M, Li H, Rezgui Y, Miles J. An integrated framework utilising software agent reasoning and ontology models for sensor based building monitoring. J Civil Eng Manage 2015;21(3):356–75.

DOSSICK, C.S., NEFF, G., 2011. gMessy talk and clean technology: communication, problem-solving and collaboration using Building Information Modellin. Eng. Proj. Org. J. 1, 83–93.

EASTMAN, C., LEE, J.-M., JEONG, Y.-S. & LEE, J.-K. 2009. Automatic rule-based checking of building designs. Automation in construction, 18, 1011-1033

FORSYTHE, P., 2014. Proactive construction safety systems and the human factor. Proc. Inst. Civ. Eng.: Manage., Procurement Law 167, 242–252.

GAMBATESE, J.A., BEHM, M., HINZE, J.W., 2005. Viability of designing for construction worker safety. J. Constr. Eng. Manage. 131, 1029–1036.

GROUP, C. I. C. R. 2010. BIM Project Execution Planning Guide Version 2.0. Pennsylvania State University.

GUARINO, N., OBERLE, D. & STAAB, S. 2009. What is an Ontology? Handbook on ontologies. Springer.

GUBER, T. 1993. A Translational Approach to Portable Ontologies. Knowledge Acquisition, 5, 199-229.

HOU, S., LI, H. & REZGUI, Y. 2015. Ontology-based approach for structural design considering low embodied energy and carbon. Energy and Buildings, 102, 75-90

IMHOF, D.2004. Risk Assessment of Existing Bridge Structures. PhD Thesis, University of Cambridge.

KIM, M.-K., WANG, Q., PARK, J.-W., CHENG, J. C. P., SOHN, H. & CHANG, C.-C. 2016. Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM. Automation in Construction, 72, 102-114.

LI CHANGZHU. 2011. Standards for Technical Condition Evaluation of Highway Bridges. JTG/T H21-2011. Ministry of Transport, Highway Science Research Institute

MCGUIRE, B., ATADERO, R., CLEVENGER, C. & OZBEK, M. 2016. Bridge information modeling for inspection and evaluation. Journal of Bridge Engineering, 21, 04015076.

Park CS, Lee DY, Kwon OS, Wang X. 2013. A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. Automation Constr; 33:61–71.

RAJPUT, Q. & HAIDER, S. 2011. A comparison of ontology-based and reference-set-based semantic annotation frameworks. Procedia Computer Science, 3, 1535-1540.

REZGUI, Y., HOPFE, C. J. & VORAKULPIPAT, C. 2010. Generations of knowledge management in the architecture, engineering and construction industry: An evolutionary perspective. Advanced Engineering Informatics, 24, 219-228

SCHREIBER, G. 2000. Knowledge engineering and management the CommonKADS methodology, Cambridge, Mass., MIT Press.

STUDER, R., BENJAMINS, V. R. & FENSEL, D. 1998. Knowledge engineering: principles and methods. Data & knowledge engineering, 25, 161-197.

Sure Y, Staab S, Studer R. 2009. Ontology engineering methodology. In: Handbook on ontologies. London: Springer; p. 135–52.

Terkaj W, Šojic´ A. 2015. Ontology-based representation of IFC EXPRESS rules: an enhancement of the ifcOWL ontology. Automation Constr;57:188–201.

USCHOLD, M. & GRUNINGER, M. 1996. Ontologies: Principles, methods and applications. Knowledge Engineering Review, 11, 93-136.

VRANDEČIĆ, D. 2009. Ontology Evaluation. In: STAAB, S. & STUDER, R. (eds.) Handbook on Ontologies. Springer Berlin Heidelberg

Voids on Lishui River Bridge [Diagram]. 2016. Retrieved from: http://news.sina.com.cn/c/nd/2016-10-18/doc-ifxwviay0001924.shtml

TRUONG-HONG, L., FALTER, H., LENNON, D. & LAEFER, D. F. 2016. Framework for Bridge Inspection with Laser Scanning. EASEC-14 Structural Engineering and Construction, Ho Chi Minh City, Vietnam, 6-8 January 2016.

W3C Help and FAQ. W3C. 2009. What is the difference between the Web and the Internet? [Online Available at: https://www.w3.org/Help/#webinternet [Accessed: 20 April 2017]

WHYTE, J. 2002. Virtual reality and the built environment, Routledge.

Yurchyshyna A, Zarli.2009. An ontology-based approach for formalisation and semantic organisation of conformance requirements in construction. Automation Constr;18(8):1084–98.

ZHANG, J., LI, H., ZHAO, Y. & REN, G. 2018. An ontology-based approach supporting holistic structural design with the consideration of safety, environmental impact and cost. Advances in Engineering Software, 115, 26-39.

ZHAO,L., YUE,G. 2011. Application and practice of BIM. Civil engineering information technology, 3(4), 51-57

ZOU, Y., KIVINIEMI, A. & JONES, S. W. 2016. A review of risk management through BIM and BIM-related technologies. Safety Science.