Ontological Base for Concrete Bridge Rehabilitation Projects

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Abstract –

Concrete bridges are important infrastructures, which thus need effective rehabilitation to maintain good condition. Bridge rehabilitation projects often have tight schedules, multiple participants and constraints, and scattered project information. Thus, improving information integration in these projects can be critical. This research develops a concrete bridge rehabilitation project management ontology (CBRPMO) to integrate various project information, e.g. information of constraints, tasks, procedures, project participants, and relations between these project entities. The CBRPMO was built based on domain knowledge collected from various documents and was refined in a focus group. The development followed standard procedures. The CBRPMO was also validated in a case study. It turns out the CBRPMO can effectively integrate information and support effective querying, which can save time to manually search for information from scattered sources. The CBRPMO contributes to industry because it expands the boundary and application of ontologies for bridge maintenance by covering the rehabilitation stage.

Keywords –

bridge rehabilitation; project management; semantic web; ontology

1 Introduction

Bridge rehabilitation projects often have a tight schedule and complex tasks with various constraints, e.g. labour, materials, and equipment [1]. Information of these constraints should be timely integrated to assist constraint removal [2]. Moreover, rehabilitation projects involve participants of different backgrounds, who often have isolated databases. Thus, information for managing the project, e.g. constraints and tasks/procedures, are often scattered in project documents or systems [3]. As such, it is essential to improve information integration and exchange in bridge rehabilitation projects so that information can be timely delivered to the right person, e.g. project managers, to support informed decisions.

Ontology is an emerging semantic web technique (SWT), which is built in a standard format while can link heterogeneous information sources. Ontologies have been increasingly applied in construction projects to enhance information integration and sharing [4]. Compared to traditional relational databases, ontologies are more effective to integrate domain-specific and unstructured information, such as constraints related information [5]. Therefore, this study develops the concrete bridge rehabilitation project management ontology (CBRPMO) to integrate information in bridge rehabilitation projects and address challenges of integrating and exchanging information.

2 Related Work

Concrete bridge maintenance includes four stages: inspection, condition evaluation, maintenance decision-making, and rehabilitation. Rehabilitation can include hazard treating, reinforcement, and replacement. Hazard treating fixes damages. Reinforcement increases the structure load-carrying capacity by adding components or materials. Replacement substitutes severely damaged bridge components. In the digital era, many modern information technologies have been applied to collect, analyse, and store bridge data for bridge inspection, monitoring, and decision-making [6, 7].

However, at the rehabilitation stage, studies focus on engineering techniques (e.g. the confinement technique [8], and grouted splice sleeve [9]) and materials (e.g. ultra-high-performance fibre reinforced concrete [10]). Compared to other stages, the rehabilitation stage is also complex and requires extensive information exchange. Rehabilitation projects have a tight schedule, multiple participants, and complex constraints that need to be removed [11]. Constraints are things that prevent work from being smoothly executed (e.g. delay of materials), and work should not start until all constraints are removed. Constraint removal means required entities of a certain amount and quality are in place on time. The importance of removing constraints is highlighted in other complex projects [12]. Constraint removal relies on identifying constraints based on domain knowledge and sharing constraints related information so that the management attention can be properly directed [11]. However, it can be difficult to access such information in bridge rehabilitation projects because they are often scattered in isolated systems and documents [13]. As such, more efforts are needed to improve information integration in these projects. Bridge management systems (BMSs) and bridge information modelling (BrIM) have been applied for bridge inspection and evaluation and can be used to integrate rehabilitation information as well. However, BMSs are restricted to pre-rehabilitation stages, and they often suffer from the data island problem as they do not adequately consider integration of data of different formats and managed by different parties [14]. Besides, due to features of the industry foundation class (IFC) schema, BrIM tools are good at modelling geometry information rather than semantic information. In this case, SWT-based methods, e.g. ontologies, can be applied.

An ontology is a graphical method for describing domain information and knowledge, which consists of nodes (i.e. classes and instances of classes) and relations (i.e. edges between nodes). Studies of ontologies for information integration focus on building semantic relations between information sources and applying semantic query (e.g. SPARQL) to search for relevant information. Thus, one can not only find contents that match key words textually, but contents semantically related. For instance, a bridge beam can be semantically related to its design drawings. Hence, when searching for the beam, information of the drawing can also be easily explored by navigating the relation between the two ontological instances.

Ontologies can be object or process oriented. The former is based on taxonomies of objects, such as building objects like walls and windows; the latter is based on sequences and constraints of tasks [15]. The object-oriented ontologies are the dominant form, which often stores information that is relatively static, such as material and geometry, defects, quantity and cost, risk, and structure condition from project documents and systems (e.g. BIM and BMS) [16]. Some studies have also built process-oriented ontologies (or as a part of their work) to record information of project progress [15].

However, studies of ontologies in the construction sector focus on vertical buildings and bridge inspection and evaluation. Besides, most ontologies are objects oriented. Therefore, the industry still lacks an ontology especially designed for bridge rehabilitation projects to integrate information specific in such projects, e.g. tasks and procedures, constraints, and participants.

3 Development of the CBRPMO

The ontology development 101 published by the Stanford University was adopted to build the CBRPMO. The document is a general and mature guideline to develop different ontologies and has been applied in several projects in the construction sector[17-19]. The key steps are shown in Figure 1.

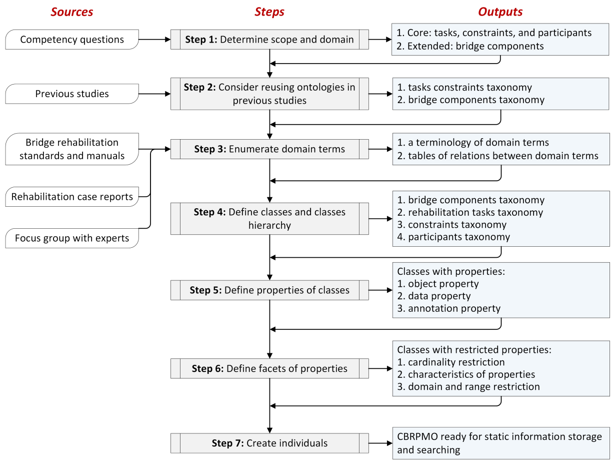

Figure 1. Development process of CBRPMO

3.1 Determine domain and scope

The first step is to define the domain and scope of the ontology. This step can be achieved by answering the following fundamental questions:

Q1: What domain will the CBRPMO cover?

A1: The domain is concrete bridge rehabilitation project management; therefore, the ontological model will cover rehabilitation tasks and procedures, constraints, and project participants.

Q2: For what purpose will the CBRPMO be used?

A2: The CBRPMO aims to improve current project management in bridge rehabilitation projects by integrating project-related information.

Q3: Who will use and maintain the ontology?

A3: The main user is the management team of rehabilitation projects, but other stakeholders, e.g. the bridge owner, can also have access.

Q4: What are the sources for the ontology?

A4: Concrete bridge rehabilitation standards and manuals, case reports, project documents (e.g. work plans and project meeting records), and experts' opinions are the main sources.

Q5: For what types of questions will the CBRPMO provide answers?

A5: The CBRPMO will answers questions that a rehabilitation project manager can ask, e.g. procedures, constraints, detailed activities, precautions of tasks, and methods to address constraints not timely removed.

3.2 Consider reusing existing ontologies

Reusing existing ontologies can save time taken to build the ontology from scratch. Several online ontology libraries were searched, such as the Ontolingua, DAML, and DMOZ; however, no relevant ontologies were found. Current bridge maintenance ontologies focus on the static information of bridge components rather than the rehabilitation project process, and therefore, such ontologies were not adopted [1, 10]. Nevertheless, there are some ontologies including common taxonomies of construction task and constraints [5, 6, 11, 27] which fit the scope of CBRPMO and thus were adopted as reference for the following steps.

3.3 Collecting domain terms

Critical terms of concrete bridge rehabilitation were identified in this step, including project entities, e.g. tasks/procedures, constraints, and project participants, their attributes (e.g. the finish date of a task), and relations between entities. Five types of relations were identified: 1) between tasks and procedures; 2) between procedures and constraints; 3) between constraints, i.e. if one constraint is not removed timely, the removal of its related constraints related may also be delayed; for instance, if design drawings are not provided, working plans depending on the drawings can be delayed; 4) between tasks/procedures and participants supervising the task/procedures; and 5) between constraints and participants responsible for constraint removal.

Table 1. Profiles of focus group participants

Expert No.	Years of experience	Area of expertise
1	8	Application of ICTs in infrastructure projects
2	8	Construction management
3	10	Bridge design and construction
4	11	Bridge maintenance and rehabilitation
5	13	
6	15	

Reviewing related documents is a common approach to realise this step [9, 17, 19]. This study reviewed 11 manuals and 52 cases reports in China, North America, and Australia, because of the large volume and rich experience of bridge maintenance in these regions [1, 13]. A focus group was organised to refine the findings. Six experts from both academia and industry were invited, who were selected based on experience and expertise of bridge maintenance [20] (see Table 1). This is necessary because the initial findings can be biased to the authors' knowledge and thus need to be modified by experts. Moreover, the documents do not adequately reflect the third to fifth relations which are complex to model. For instance, some material constraints can affect removal of equipment constraints, whereas the opposite scenario can occur for other constraints pairs. The relations of supervision and constrains removal also vary among projects. In addition, the documents do not consider the strength of the second and third relation, i.e. a procedure or constraint is more likely to be affected by some constraints if their removal is delayed, which is important to identify critical constraints.

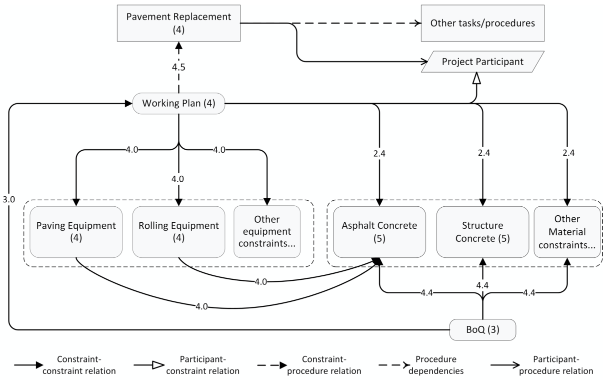

Figure 2. Partial view of the obtained relations (the numbers in this figure indicate the level of the class in the constraint hierarchy in Figure 5)

The results of this step include a terminology and knowledge of relations. The terminology maps tasks and procedures to constraints, and participants while records attributes of these entities. The obtained relations are shown in Figure 2. It should be noted that: 1) constraints are divided into groups (Figure 5) to facilitate relations setting-up; 2) only direct relations are considered; for instance, the bill of quantities directly affects material delivery, but it can also indirectly affect equipment supply by affecting working plans that determine the equipment, but such relation is addressed by the work plan; 3) relation strength ranges from 1 to 5, and larger numbers indicate higher strength; 4) Strength is rated at the most specific sub-classes of the constraint hierarchy under which, according to the experts, constraints have similar impact on others and thus can share the strength (see Figure 2); 5) because of the reliance on project conditions, experts only provide common practices for the fourth and fifth relations; for instance, sub-contractors often provide labour. Thus, such relations can be setup in specific projects.

3.4 Define Classes and Classes Hierarchy

In this step, classes are extracted from domain terms, using a mixed extraction approach where the most salient classes are extracted first, which are generalised and specialised. For instance, the term 'Deck System Replacement' is extracted, and then, 'Replacement' is extracted as its super-class, while terms like 'Pavement Replacement' and 'Auxiliary System Replacement' are extracted as its sub-classes. The classes are divided into four groups: rehabilitation task, constraint, project participant, and procedure. Each group forms a taxonomy and can be expanded up to the fifth level (as shown in the white boxes in Figures 4-6). A high-level overview of the CBRPMO is shown in Figure 3.

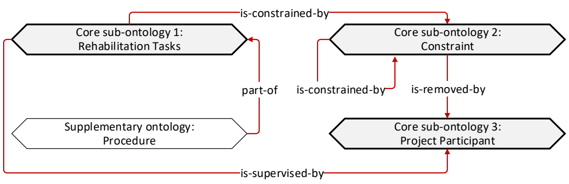

Figure 3. High-level overview of the CBRPMO

The taxonomy of rehabilitation tasks is shown in Figure 4. It should be noted that a task is often formed by procedures so that some procedures can proceed without removing all constraints. Thus, a taxonomy of procedures is built, with four basic classes: preparation, inspection, execution, and acceptance. A task can have some or all of these procedures, and a procedure can be detailed and expanded.

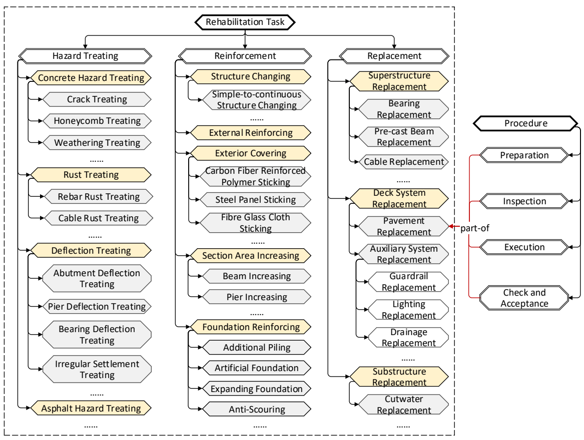

Figure 4. Overview of the tasks' taxonomy

The constraints taxonomy is shown in Figure 5. The engineering constraints refer to the absence of drawings and approvals, supply chain constraints include late delivery of materials and equipment, and site constraints hinder work of on-site crews [2].

The project participant taxonomy is shown in Figure 6. This taxonomy is mainly divided by responsibilities of participants, while project-level participants are first divided by project phases.

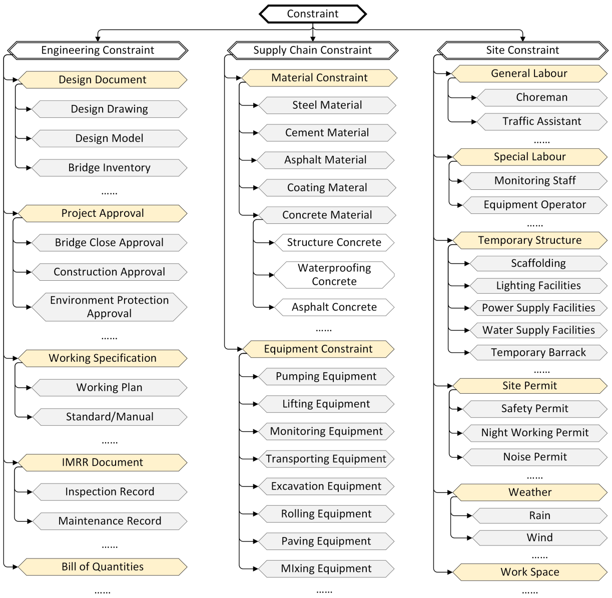

Figure 5. Overview of the constraints' taxonomy

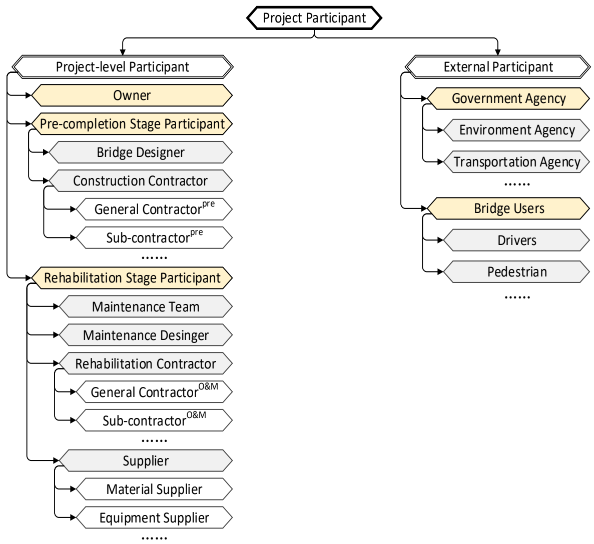

Figure 6. Overview of the taxonomy of project participants

3.5 Define Properties

Properties are relations that connect two classes or a class and its attributes, forming a subject-property-object triple [21]. There are three types of properties, i.e. object, datatype, and annotation properties. Object properties describe relations among classes and instances of classes (Step 7), e.g. the 'is-constrained-by' relation between procedures and constraints and between two constraints. Datatype properties describe quantitative or qualitative attributes of classes and their instances. For instance, the 'Constraint' class has a 'has-planned-removal date' property linking the constraint to its expected date of removal. Annotation properties add explanations of classes, instances, and other properties. They can be applied to set relation strength between constraints and between procedures and constraints. Figure 7 shows examples of object properties while Figure 8 shows examples of datatype and annotation properties.

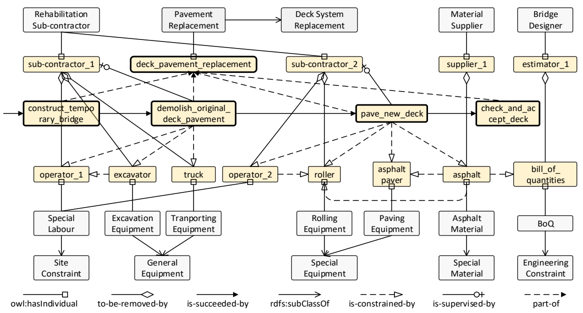

Figure 7. Properties in the CBRPMO

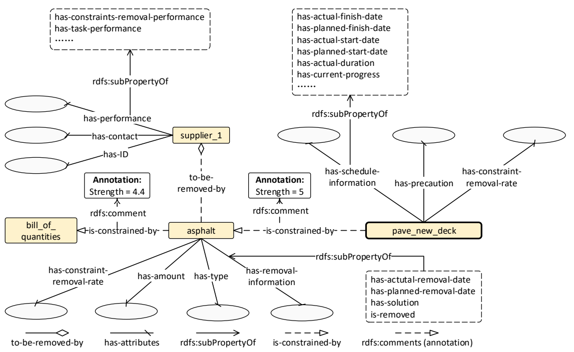

Figure 8. Properties in the CBRPMO

3.6 Define facets of properties

Facets can enrich semantics of properties, including cardinality restrictions, characteristic settings, and domain and range restrictions. Cardinality restrictions specify the number of values that a property can have, for instance, the 'has-actual-finish-date' property has a single cardinality because a task has only one actual finish date. For characteristics, object properties in the CBRPMO can be normal (no characteristics), transitive, symmetric, asymmetric, and invertible. A detailed introduction of characteristics can be found in [22]. Domain and range restrictions specify the type of the subject and object of a property, respectively. The type can be either datatypes or classes. For instance, the domain of 'has-actual-finish-date' and 'is-constrained-by' should be 'Date' datatype and 'Constraint' class, respectively. Properties and their facets are defined at the class level, which are inherited by instances of the class. For instance, during instance creation (Step 7), a task instance cannot be connected to a constraint instance through the 'is-supervised-by' because the property's range, i.e. object, is restricted to 'Project Participant'.

3.7 Create Instances

Instances represent specific and physical entities of abstract classes. For instance. the 'asphalt paver' and 'roller' in Figure 7 are instances of the class 'Special Equipment'. Instances creation is project dependent and should be performed during ontology implementation. The number of instances depends on the complexity and scale of the project whereas the names of instances can be flexible as long as they are consistent. Finally, as mentioned, properties of instances should comply with definitions of their classes.

4 Case Study

For a new ontology, its semantic and syntactical correctness must be verified. Semantic validation should be completed before implementing CBRPMO in real projects. This can be realised by asking competency questions, consulting experts, and ontology alignment. CBRPMO is a new ontology and there are no similar ontologies for cross comparison. Hence, the first two methods were adopted. Asking competency questions is a simple way to check semantics of CBRPMO[23]. Such questions should echo questions in A5 of Step 1 and cover both classes and instances, such as: 1) how many sub-classes do certain constraint classes have; 2) what are the constraints of certain constraints and procedures; 2) what are the planned/actual finished date of certain procedures; and 4) who are the participants responsible for removing certain constraints? Artificial instances (created by the authors for validation) can be created, and the CBRPMO is checked if it contains enough information to answer the questions.

Above self-checking was performed by the authors periodically during ontology development, which to some extent ensured semantic correctness of CBRPMO. In addition, the initial CBRPMO (i.e. without instances which should be created during implementation in practice) was sent to experts of the focus group mentioned before. The authors explained each class and property, e.g. the definition of the class and reasons to setup the property, to the experts to further validate semantic correctness and modify the ontology.

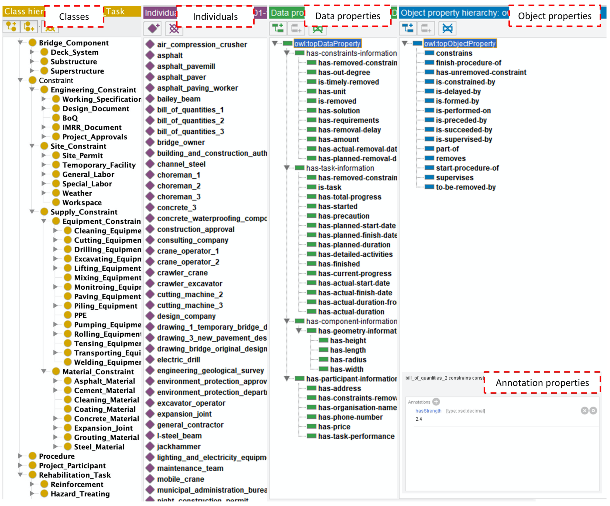

Figure 9. Partial review of the CBRPMO in the Protégé

On the other hand, syntactical validation checks the CBRPMO against ontology syntax, e.g. subsumption, equivalence, and consistency. Syntactical validation should be performed in both ontology creation and implementation phases. The validation can be realised by the Pellet reasoner which can detect syntactic errors in ontologies automatically. Whenever the CBRPMO was modified because of either self-checking or specific project conditions, the reasoner was ran to ensure the CBRPMO can pass syntactical validation [23].

The CBRPMO was implemented in a real project to demonstrate its usefulness for information management. This requires three components. 1) The ontological base. 2) A tool that can edit the ontology, where Protégé 5.50 was adopted. 3) A reasoner, i.e. Pallet, which interacts with the ontology by sending and interpret queries.

A rehabilitation project performed on the Jinghu bridge in Zhejiang, China, was selected to validate the CBRPMO. The bridge is a suspension bridge which is 415-m long. The rehabilitation took about five months (May to October 2018). The CBRPMO was implemented by creating instances and setting up and modifying properties between the instances by combing domain knowledge previously obtained and project specific information, such as information provided by the project team and information in project documents, e.g. work plans and equipment and material inventories. The resultant ontology in Protégé is shown in Figure 9.

The case focused on the deck pavement replacement task because it was the most time-consuming (more than 4 months) and labour-intensive task and it required more constraints than other tasks. It was assumed that the project manager wanted to search for information of the task. Instead of looking for information scattered in project documents or systems manually, the CBRPMO encoded relevant information to support efficient queries using SPARQL, which is demonstrated in Figure 10. To reflect the traditional method of searching information, the same information was manually searched by the authors in project documents and management systems. Then, the searching time was cross compared to show capability of the ontology.

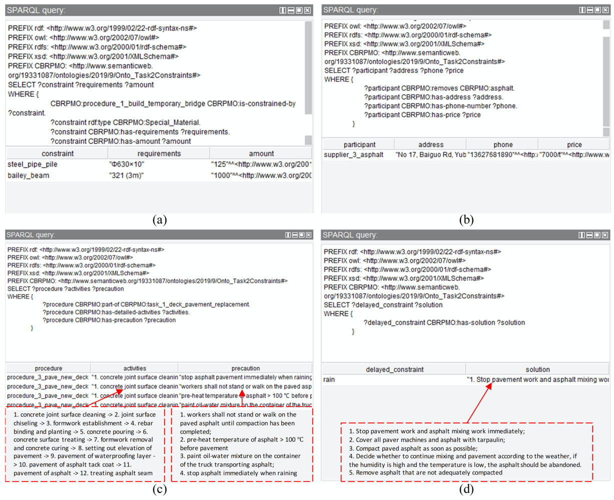

Figure 10. SPARQL queries and results

Query 1 (Figure 10 (a)) not only shows constraints of a procedure (e.g. steel materials for temporary bridge construction) but also requirements (e.g. type and amount) of constraints, so that the manager can arrange constraint removal more easily.

Query 2 (Figure 10 (b)) can rapidly retrieve related information (e.g. contact information) of project participants (e.g. asphalt supplier), which can facilitate communication between the participants.

Query 3 (Figure 10 (c)) can show detailed activities and precautions of a procedure (e.g. new deck pavement). Such information can be generally required by onsite foreman and supervisors to supervise work sequences and quality.

Query 4 (Figure 10 (d)) can answer questions related to solutions to unremoved constraints (e.g. rain), serving as remedial actions when delay occurs.

The information of query 1, 2 and 3-4 was scattered in a project meeting record, an address book, and a work plan, respectively. A few information (e.g. certain steel materials to construct the temporary bridge) needed consulting the project team, which further increased the searching time. Table 2 compares the searching time through the CBRPMO and manual approach. It turns out searching time can be reduced significantly when the information from scattered sources is integrated.

Table 2. Comparison of searching time

Query	CBRPMO	Manual searching

1	0.13s	562s
2	0.08s	116s
3	0.09s	77s
4	0.11s	108s

In addition, the CBRPMO can also identify critical constraints of procedures and tasks. Specifically, the ontology forms a network with classes and instances as nodes and properties (i.e. relations) as edges. Hence, network measures (i.e. in-degree and out-degree) can be computed for every constraint instance, where the former reflects vulnerability (i.e. how many constraints can affect it), while the latter reflects its impact (i.e. how many other entities it can affect). The in- and out-degree of a constraint instance is computed by counting the number of inward and outward properties, weighted by the relation strength stored in annotation properties. Constraints with high degree are regarded as critical.

Figure 11 illustrates critical constraints at different levels. Figure 11(a) shows results at the procedure (i.e. new deck pavement) level. The vulnerable constraints include workspace, approvals, and equipment. Thus, more attention should be given to their constraints and responsible participants to minimise delay. Figure 11(b) shows constraints with greater impact on others at task (i.e. deck replacement) level, including engineering drawings, approvals, permits, and temporary facilities. Thus, they should be closely monitored, additional buffer should be assigned to procedures constrained by them, and remedial solutions should be proposed to mitigate impact when their removal is delayed.

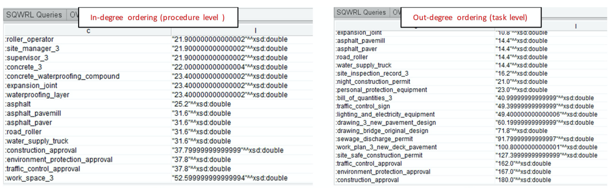

Figure 11. Identification of critical constraints

5 Discussion and Conclusion

Successful rehabilitation projects are important for bridge maintenance. Such projects require effective integration of project information. The challenge is that such information is often buried and scattered in project documents and systems. However, studies on bridge rehabilitation are limited to engineering techniques and methods, which do not cover information management. In addition, although ontologies are effective tools to manage heterogenous and unstructured information, previous ontologies in the construction sector focus on integrating information of static objects of vertical building and bridge inspection and evaluation [4, 16]. However, bridge rehabilitation projects have specific information, e.g. specific constraints and tasks. Thus, existing ontologies cannot be directly applied. The proposed CBRPMO focuses on the rehabilitation stage therefore can bridge the gap. The CBRPMO was built by reviewing rehabilitation knowledge in case reports, manuals, standards, and related studies, which was refined through a focus group. As such, the CBRPMO covers sufficient knowledge in the bridge rehabilitation domain and can integrate scattered information of constraints, tasks and procedures, and participants in a software neutral environment.

The CBRPMO is an effective tool to integrate and search for various information in scattered sources, such as constraints of procedures, information of participants, solutions of unremoved constraints, as well as critical constraints. Moreover, extensibility and flexibility are important for ontologies. The CBRPMO can be merged with existing ontologies without major modifications. For example, the 'Procedure' class can be linked to bridge components in ontologies developed by [16, 17] through an object property 'is-performed-on'. However, currently, the CBRPMO was built manually, which can be time-consuming and inefficient. Therefore, the future studies will focus on automating development of the CBRPMO. For instance, information extraction methods can be employed to extract information from source documents for ontology development (e.g. manuals and standards) then automatically identify relevant classes and properties. Nevertheless, this study still lays a basis (e.g. the basic framework of the ontology) to implement those advanced techniques.

To this end, it can be argued that the CBRPMO has made a contribution by expanding ontologies in the bridge sector to cover the rehabilitation stage while it is also compatible with previously developed ontologies. As demonstrated in the case study, when the CBRPMO was implemented in projects, the project teams can access critical information for project management quickly rather than manually searching the scattered documents. Thus, enormous time can be saved, and the efficient exchange of information can also facilitate informed management decision-making.

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