Formalized Knowledge Representation to Support Integrated Planning of Highway Projects

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Abstract

The objective of this paper is to propose an ontology capable of supporting a structured coordination of spatial-temporal conflicts in highway projects plans. For many highway agencies, there are different functional groups in charge of capital projects planning, safety, design and construction, maintenance and rehabilitation, and short-term operational tasks. However, many of these functional groups tend to have a "siloed" approach to planning. Integrated planning is therefore challenged by the existence of multiple incompatible legacy systems and the lack of a standardized knowledge representation format for planned highway projects information. Current literature and existing formal representations fail to address the level of information coverage and depth to support the integrated planning of highway projects. Accordingly, this study proposes an ontology-enabled knowledge representation which allows relevant planned projects information and inter-project conflicts to be processed in a standard computer interpretable manner. Ontology development was done through the analysis of project attributes of more than 30 highway agencies, review of existing ontologies, and interviews with team leads of different functional groups of highway agencies. The proposed representation was validated via logical consistency checks and competency questions evaluations in the Protégé environment. Future work will aim to employ this ontology to capture and implement tacit integrated projects planning knowledge for improved decision support.

Keywords

Knowledge representation • Ontology • Conflict analysis • Integrated planning • Maintenance and rehabilitation

8.1 Introduction

The planning process for the development and preservation of highway infrastructure is a multi-faceted problem which often involves different information needs for capital projects planning versus maintenance and rehabilitation (M&R) projects planning [1, 2]. Furthermore, different asset classes (like bridges, pavements, safety appurtenances, etc.) may also have different funding categories and project eligibility constraints which needs to be accounted for as part of the decision-making process [3]. Consequently, there are often multiple functional groups within the same agency working on different aspects of the same asset or multiple functions across different assets. This can lead to a "siloed" approach to planning which can have inefficiencies in the form of repetitive information generation, missed opportunities for synergistic projects, and a lack of coordinated decision-making across project information silos [3, 4].

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Additionally, there are often multiple independent legacy information systems being utilized by different functional groups within the same agency [5]. Hence, most State Highway Agencies (SHAs) often have to deal with disconnected databases which result in interoperability barriers and redundant data acquisition efforts [4, 5]. Hence, the data generated tends to have significant heterogeneity in their structure, syntax, and semantics [6]. This is especially the case for projects data that are generated by different functional groups working on the same asset. When it comes to projects data, many SHAs manage hundreds of projects in various phases of development and delivery at any given time. Potential changes in highway funding also mean that projects scheduled to take place within a specified plan period can be moved up or postponed for different reasons depending on funds availability. Furthermore, unpredicted natural and/or man-made (economic) activities in a region can lead to faster deterioration of existing roadways which necessitate new M&R projects that were not initially budgeted for. This can affect the priority list of projects and lead to changes in scope and costs of extant highway projects [4]. To address these issues with data systems, dynamic data updates, and inadequate synergy in what should be a more effective cross-functional process, an integrated planning process is essential. Salient to this process, is establishing a formal standard representation of highway projects data to support cross-functional projects planning.

However, while there have been a number of representations in the form of XML-based schema and other upper-level ontologies about the transportation domain, there is still a deficiency of representations that have the depth and coverage required to support cross-functional projects planning in the highway domain. More specifically, there is a need to represent inter-project (cross-functional project) conflicts knowledge in a computer-interpretable format to ensure timely conflict response and assigned responsibilities. This paper presents a 2-part ontology that formalizes planned highway projects information and inter-project conflicts in highway projects plans.

8.2 Background

Ontologies are a form of standardized knowledge representation which allow for human-readable language (vocabulary) in a structured, and standardized form. An ontology, as used in information science, is an explicit description of concepts in a domain and the relationships that exist between those concepts [7]. It enables complex fuzzy knowledge gained by domain experts to be captured in a standard computer interpretable manner to better support decision-making tasks that target domain experts have to make [6, 8]. There have been several ontologies and other forms of formalized representations proposed in the literature to support processes and concepts in the built environment. A strong theme that runs through several of these representations is the emphasis on data exchange standards in an effort to improve CAD-based software or streamline principal business processes [9]. Some of these studies on the development and application of ontologies are further discussed in the succeeding sub-sections.

8.2.1 AEC/FM

Traditionally, the Architectural, Engineering, and Construction (AEC) industry generates large amounts of data throughout the planning, design, construction, and operations phases of building projects. Accordingly, there have been several formal representations to capture project information via the Industry Foundation Classes (IFC) schema, aecXML, agcXML, E-COGNOS ontology, BIM Collaboration Format (BCF), and many other representations that have concentrated on providing a formal structure for data exchange and knowledge reasoning in the AEC domain [6, 10, 11]. The E-COGNOS ontology was developed to support knowledge representation of knowledge items in the construction domain. Additionally, it was built to be IFC complaint and broad enough to capture all the different business scenarios which exist in the construction domain. Several other studies in the literature have developed building-centric ontologies for enhancing interoperability, data integration, and process integration to support many business functions within the AEC domain [7].

8.2.2 Transportation Infrastructure Management

On the other hand, knowledge management practices in the transportation infrastructure domain have been slow compared to the building industry [9]. Formal representations that allow for reasoning and capture of tacit knowledge are scarce in the extant literature. One of the prominent works in formalized representation in this area involves the development of the TransXML (NCHRP Project 20-64) schema which was sponsored by the National Cooperative Highway Research Program

[12, 13]. The aim of this schema was to provide an extensive framework for the exchange of transportation-related data throughout the planning, design, construction, maintenance, and operation phases of transportation infrastructure [13]. The key business areas of this schema were roadway survey/design, transportation construction, highway bridge structures and transportation safety. It was built on key concepts from other schemas like LandXML, Geography Markup Language (GML), and other existing XML-based schema. However, one of the major limitations of this schema is that it lacks sufficient depth for pragmatic function-specific applications [13]. More importantly, like other XML-based schema developed earlier, it primarily serves as a data exchange mechanism but cannot support reasoning and knowledge extraction that can be relevant for pragmatic highway decisions to be made. In spite of this, there have also been other studies that have proposed ontologies for broad and specific applications in the infrastructure management domain. El-Diraby and Kashif [14] proposed a distributed ontology to support knowledge management during highway construction to capture the complex relationships that exist between the design and construction phases of highway projects as well as the role of relevant stakeholders in the process. Le and Jeong [12] also proposed and implemented an ontology-enabled data integration system which was used to support highway asset management. That study demonstrated how ontologies could be used for process integration and seamless information flow from infrastructure condition survey events to supporting M&R projects selection.

8.2.3 Research Gap

These studies notwithstanding, there still remains a lack of formalized knowledge representations which provide a standard format for planned highway projects information exchange and documenting spatial-temporal conflicts analysis. More specifically, there is the need for a representation that supports reasoning about cross-functional inter-project conflicts that may arise from the "silo" approach to planning in highway agencies. Previous works have focused more on design and construction of highway projects without accounting for the cross-functional nature of highway projects planning. Accordingly, the existing representations in the literature fail to acknowledge the potential spatial-temporal conflicts that may arise due to the different schedules of highway projects planned for the same network but proposed by different functional groups working in the same agency on the same network.

8.3 Research Objective and Approach

To address this gap in knowledge representation, this paper proposes an ontology to serve as a formal representation for planned highway project information and identified inter-project conflicts in highway plans. An ontology is used because it provides a unifying framework within an organization via reducing the conceptual and terminological confusion in the vocabulary used in a certain domain or application context. In the context of this problem, the use of ontologies will enable a shared understanding and communication between relevant decision-makers/functional groups with varying application needs but common information requirements concerning highway projects planning [15]. The proposed approach to ontology building is based on a hybrid systematic framework which combines the ontology building approach by Uschold and Gruninger [15] and the "methontology" approach by Fernández-López et al. [16]. The former provides a useful set of guidelines for developing the purpose, scope, and approach of the ontology to be built whereas the latter method provides a detailed approach for knowledge acquisition, conceptualization, and implementation (as shown in Fig. 8.1). Accordingly, the ontology building began by answering questions about why the ontology was being built, the target domain information to be represented, the intended users, and scenarios of use. After the ontology scope specification, the authors identified the relevant concepts and relationships for the ontology via reviewing publicly available projects information (transportation plans, online highway project portals, and project databases) from over 30 SHAs, existing XML-based schema, and prior ontologies in the literature. This was followed by ontology conceptualization and formal implementation of the ontology via the Web Ontology Language (OWL) in the Protégé 5.2.0 Ontology Editor environment. Finally, ontology verification was done via the built-in Pellet Logic Reasoner [17] in the Protégé environment whiles the competency evaluation included the use of SPARQL, a query language for Resource Description Framework (RDF) graphs, in answering select competency evaluation questions [12].

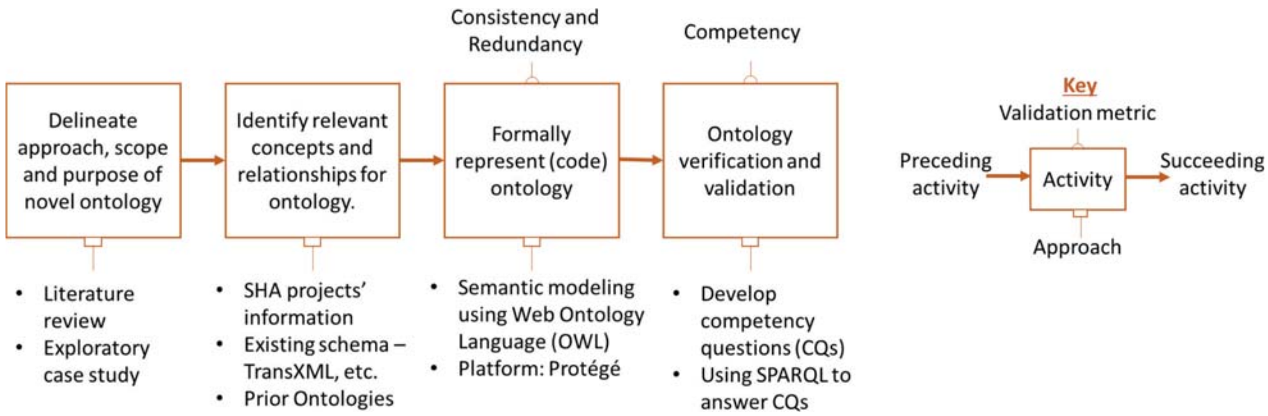

Fig. 8.1 Research methodology for proposed ontology

8.4 Proposed Ontology

The ontological model proposed for this study builds on the Actor-Process-Product-Attribute model which has been utilized in several upper-level ontologies in the transportation infrastructure delivery domain [7, 9, 11]. Hence, the model in Fig. 8.2 can be interpreted as an "actor" performs a "process" that has an output that can be a "knowledge item, decision action or physical product" that has "attributes." These concepts are supported by a "constraint" and/or "mechanism." Within this context, a highway project is represented as a decision action (product) which is as a result of a prior "planning process" (not included in this ontology). In this paper, the attributes of a planned highway project (Product | Decision Action) and an inter-project conflict (Product | Knowledge Item) are presented in detail.

8.4.1 Highway Project

The highway project component of the ontology focuses on the representation of planned highway projects and their attributes as needed in mid- to long-term transportation plans of SHAs. The major attributes presented include the project type, project location, project schedule, project cost, project status, and the overseeing project entities as shown in Fig. 8.3. The project type can have instances (individuals) based on the Federal Highway Administration's (FHWA) classification [12] or locale-specific statewide project classifications. This ontology also allows planners to connect the project type to the funding category since

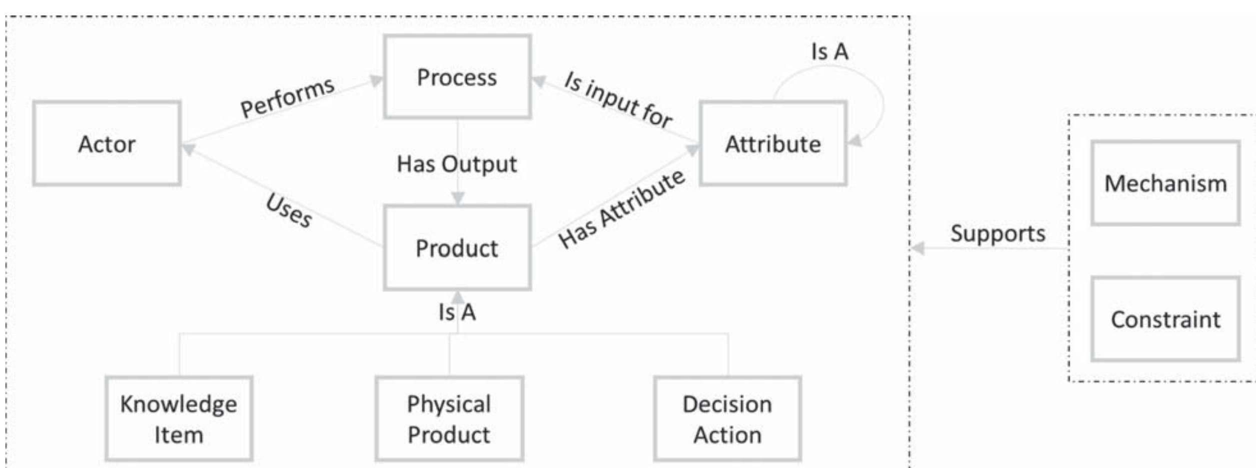

Fig. 8.2 Parent ontological model Adapted from El-Gohary and El-Diraby [7]

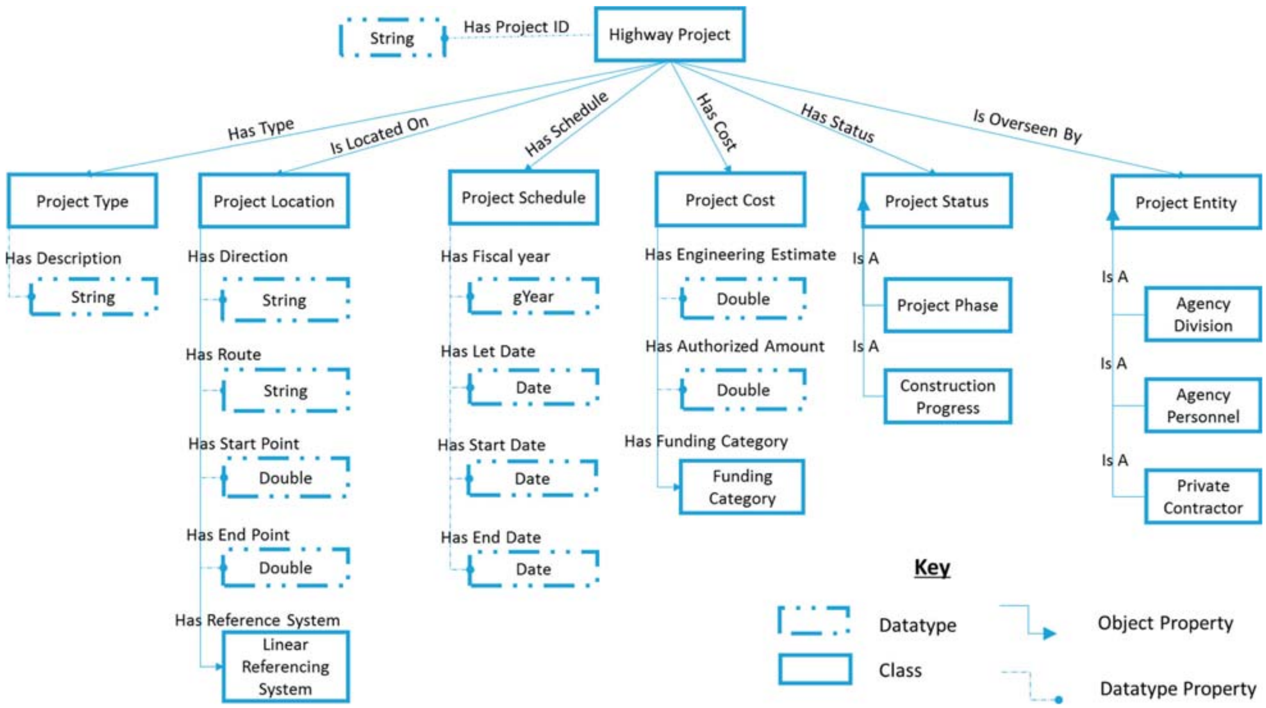

Fig. 8.3 Proposed ontology (highway project component)

some funding categories have restrictions on project type eligibility. Additionally, unlike El-Diraby and Osman [9] which represented infrastructure products spatially using the latitude/longitude coordinate system, this representation accounts for a more dominant description of highway project locations. SHAs typically use linear referencing systems (LRS) like the Mile-point, Milepost and other state-specific LRSs. The project cost also accounts for the difference in the engineering estimate of the project and the authorized amount from the agency since these figures are not always the same.

Furthermore, the "Project Status" class allows for decision-makers to track the current phase of the highway construction project. For example, the relevant phases for major capital projects (new construction as classified by FHWA), may include the preliminary engineering phase (environmental review, geotechnical studies, traffic studies, etc.), design, and construction phases. More often than not, before capital projects are added to highway projects plans, they have already undergone the initial problem screening and concept development phases. Finally, this ontology accounts for the responsible actors for highway projects including when they are outsourced (Private contractor) or when they are done using in-house forces (Agency Personnel and Division). This specification in practice is also important because it can have implications as to the eligible funding categories and reasoning after the inter-project conflict detection is conducted.

8.4.2 Conflict Detection Process

The conflict detection process can be conducted via a Geographic Information System (GIS) visualization, traditional database operations, or a hybrid of both. The inter-project conflict detection process used in this study was based on a prior study by France-Mensah et al. [4]. The study presented a GIS-based approach for the detection of conflicts in proposed highway projects by different functional groups within the same agency. The major steps included (1) Data processing which involved converting all the planned projects data to a common syntactic and semantic format; (2) Conducting spatial checks to see if any number of projects occur on the same road section via the highway name and specified project limits; (3) Checking for a close temporal sequence among projects that have spatial conflicts and (4) Checking the project types to ensure that the identified spatial-temporal conflicts are not complementary highway projects. Complementary highway projects are projects that are scheduled to be executed in the same location but in a close temporal sequence. Accordingly, if there are spatial-temporal conflicts in an integrated highway projects plan which are unintentional, these conflicts are referred to as inter-project conflicts (in this study). To enable an efficient documentation and coordination of these identified conflicts, it is important to develop a formal structure to capture key aspects about the spatial-temporal context of the conflict as well as a structured evaluation and response to resolve these errors in projects plans.

8.4.3 Inter-project Conflict

The inter-project conflict component of the ontology provides a formalized structure for representing the context and response to addressing identified conflicts in highway projects plans. It consists of classes including the conflicting project (s), conflict location, conflict period, conflict evaluation and the conflict response (Fig. 8.4). First, it is important to identify which highway projects (originally residing in disparate databases) are having spatial-temporal conflicts. The connection of these projects to the "Highway Project" class allows us to re-use all the information known about these projects during reasoning about the conflict and how to best resolve it. For example, knowing the details about the types of projects that have been identified as conflicts can inform an agency about lapses in communication between the responsible functional groups for these projects. The "Funding Category" information also allows decision-makers to ascertain extra funds that have become available for other candidate projects not considered earlier. The data from the "has Time Gap" datatype property is the time difference between the start times of a pair of conflicting projects. This information can be useful to planners in assessing the suitable conflict response options based on the time gap between the conflicting projects. Conflict evaluation also informs the responsible group about the cause and type of the conflict and consequently, how urgent a solution is needed. Lastly, the "Conflict Response" class captures information on what action has to be taken to resolve the conflict, the status of conflict response, and who has the responsibility to perform this action. This allows for accountability in conflict response and ensures that there is a formal approach to tracking all the identified inter-project conflicts in a highway projects plan.

8.5 Implementation and Validation

The validation of an ontology usually has two major parts; internal and external validation. Internal validation also referred to as ontology verification is a test on the internal consistency of the Description Logic (DL) inherent in the proposed ontology. However, this test does not check for comprehensiveness or the pragmatic usability of the ontology to support typical decision-making tasks. The use of competency questions (CQs) is therefore used to demonstrate how the ontology can be used to answer select questions which are useful for the pragmatic decision-making process that an ontology is intended to support [12, 16]. External validation often involves focus groups or one-on-one interviews with Experts to gain

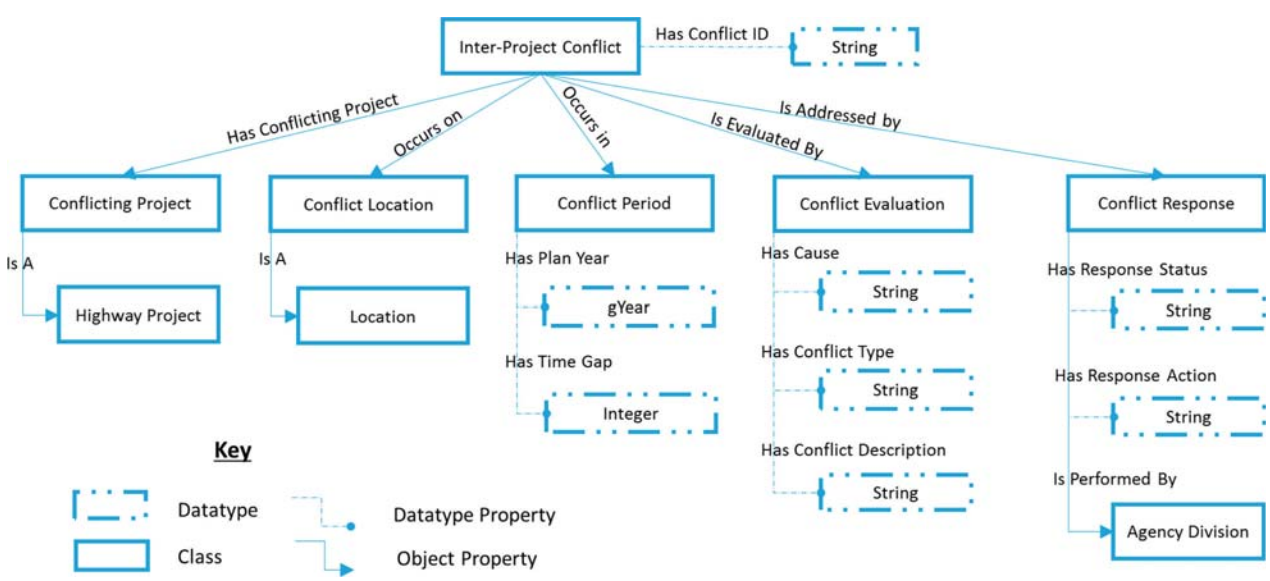

Fig. 8.4 Proposed ontology (inter-project conflict component)

their perspective on the comprehensiveness and pragmatism inherent in the proposed ontology. In this paper, the logical consistency checks and evaluation through CQs are presented.

8.5.1 Logical Consistency (Ontology Verification)

The proposed ontology was coded in the Protégé Ontology Editor Environment [17] using OWL language. The in-built Description Logic (DL) reasoner, Pellet, was used for reasoning to ensure consistency in the class hierarchy and the asserted relationships between the concepts in the proposed ontology. It also checks for implicit subclass relationships induced from the asserted class relationships within the ontology. Having satisfied the conditions for consistency by the Pellet Reasoner, the ontology was confirmed to be internally consistent.

8.5.2 Competency Evaluation

The next validation step aimed at demonstrating that the ontology can be used to answer certain competency questions in line with the intended purpose of the ontology. The CQs included, but was not limited to, queries about where an inter-project conflict was occurring? What were the conflicting projects? What was the cause of the identified conflict? What was the conflict response action? Who was responsible for taking the action to resolve the conflict? The ability for the proposed ontology to answer these questions were demonstrated via SPARQL. A set of instances (individuals) were added to the proposed classes to demonstrate how the ontology was used to extract useful information in an example conflict scenario. Hence, Fig. 8.5 shows the result of an inter-project conflict with ID: C0001 which occurs on route: IH0020 and was caused by a "project location change." The conflict was classified as a "Hard Conflict" and was resolved by the Maintenance Group of the agency by removing the conflicting resurfacing project from the projects plan. It is important to note that the instances used in this example case are not necessarily a part of the proposed ontology.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX onto: <http://www.semanticweb.org/ontologies/2018/integratedprojects#>

SELECT ?ID ?route ?cause ?type ?status ?action ?responsible_actor

        WHERE { onto:Conflict_1   onto:has_Conflict_ID        ?ID.
                onto:Conflict_1   onto:occurs_On              ?section.
                ?section          onto:has_Route              ?route.
                onto:Conflict_1   onto:is_Evaluated_By        ?evaluation.
                ?evaluation       onto:has_Cause              ?cause.
                ?evaluation       onto:has_Conflict_Type      ?type.
                onto:Conflict_1   onto:is_Addressed_By        ?response.
                ?response         onto:has_Response_Status    ?status.
                ?response         onto:has_Response_Action    ?action.
                ?response         onto:is_Performed_By        ?responsible_actor}
```

ID	route	cause	type	status	action	responsible_actor
"C0001"	"IH0020"	"Project location change"	"Hard Conflict"	"Resolved"	"Remove Resurfacing Project"	Maintenance_Group

Fig. 8.5 Results of a SPARQL query on inter-project conflict information

8.6 Conclusion

Planning for highway infrastructure involves several functional groups working in tandem with each other to propose and execute projects for optimal infrastructure delivery and asset management. Since several of these groups tend to use silo information systems for planning, the resulting projects' information between planning groups tends to suffer from semantic and syntactic heterogeneity. This paper proposes an ontology which supports formally representing and capturing information concerning planned highway projects and inter-project conflicts in highway plans.

The validation tests demonstrate that the proposed ontology is internally consistent and is also able to support the intended pragmatic objectives for the development of the ontology. While ontologies about infrastructure delivery tend to be extensive and hence, difficult to comprehensively validate, this proposed ontology focuses on a specific application which makes it more feasible to validate. Future validation will include feedback from domain experts via one-one interviews on the usefulness, coverage, and ease of implementation. Additionally, future work will include the capture of tacit knowledge on inter-project conflict planning and decision-making by highway Engineers. This will enable information reasoning with rules via the Semantic Web Rule Language (SWRL) in the proposed ontology.

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