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REVIEW ARTICLE

Ontology-Based Information Integration: A State-of-the-Art Review in Road Asset Management

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Abstract

As a novel and efficient method of knowledge management, ontology provides a machine-processable technique to establish structured knowledge/information for effective management. The advantages, disadvantages, and future directions of ontology in road asset management, which relies heavily on acquiring and using data, are attracting much research attention over the past few years. This paper aims to provide a thorough and systematic review of ontology, including its development and implementation, in road asset management. In total, 45 journal papers and 12 conference papers published over the last 14 years were reviewed, sorted, and analysed. It is observed that: (1) most ontologies in road asset management target at traffic service and road assets; (2) most ontologies are designed to support the operation and maintenance stage; and (3) RDF-based language and OWL semantics are the two most popular ontology technique. From the review, it is found that the current development and implementation of ontology in road asset management also have a few limitations, including the lack of specific ontology engineering approach, the lack of an automatic mechanism to capture instances, properties and relationships, limited ontologies techniques in this field, and the lack of sharing and linking ontologies of different domains. This study provides useful reference for the architecture, engineering and construction industry to understand and select the most appropriate ontology techniques for creating structured knowledge bases and making effective knowledge management decisions.

Abbreviations

AEC	Architecture, engineering and construction
BIM	Building information modelling
CL2M	Closed-loop life cycle system management
DL	Description language
EL	Expressing language
GIS	Geographic information system
GPS	Global positioning system
IC-PRO-Onto	Infrastructure and construction process ontology
IDEON	Intelligent systems technology distributed enterprise ontology
IFC	Industry foundation classes
ISO	International standard organization
JADE	Java agent development environment
LPGs	Labelled property graphs
NoSQL	Not only SQL
OWL	The web ontology language
PDA	Personal digital assistant
QL	Query language
RDF	Resource description framework
RDFS	RDF schema
RL	Reasoning language
RTDSS	Roadside tree diagnosis support system
SeRQL	Sesame RDF query language
SLR	Systematic literature review
SPARQL	SPARQL protocol and RDF query language
SQL	Structured query language
SWRL	Semantic web rule language
TDDS	Tunnel defect diagnosis system
VEACON	Vehicle accident ontology
W3C	World wide web consortium
XML	Extensible markup language

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1 Introduction

As road networks are expanding, efficient management of infrastructure and assets is becoming challenging for governments and industries. The design, construction, operation, and maintenance of these road networks require a large amount of data to be collected, stored, transferred, and analyzed [1]. However, massive data and information transformation and exchange among isolated databases in project contractors, private agencies, and public organisations make information sharing rather difficult [2]. Traditional methods or systems of road asset management rely heavily on humans, and they also have other limitations such as being costly and highly uncertain [3]. These problems require a more cost-effective, efficient, and computer-based approach for the integration of databases [4].

Ontology, a term first appearing in the philosophy field, is defined as a description of the types and structures of objects, properties, processes, and relations in computer science and information science [5]. The concepts of Semantic Web and Linked Data, which have the same core as ontology, were also considered to be ontology-based techniques in a few studies. Since Berners-Lee et al. [6] introduced this concept into the computer science field, it has been rapidly applied in the architecture, engineering, and construction (AEC) field to facilitate engineering management [7]. For example, Le and Jeong [8] used ontology to improve the unification and interconnection of life-cycle data to support decision making in highway asset management. As a data-driven technology, ontology has significant value in road asset management because the properties and relationships within all asset objects can be derived directly or through simulations [9]. Ontology can increase efficiency in data management. It can also be used to create a platform for stakeholders, who may have different backgrounds, to share their knowledge and understand asset management concepts more easily. For instance, Merdan et al. [10] applied ontology in the transportation domain to share information among agents and provide agreement and understanding on the commonly used concepts.

Over recent years, isolated review studies have been conducted on the application of ontology in various road asset management subjects [11]. For example, Pauwels et al. [12] reviewed ontology technologies in the AEC industry, observing that ontologies can link domains and offer data interoperability and logical inference functions to the industry. Following this research, Yang et al. [13] reviewed 116 papers and presented a comprehensive summary of the state-of-the-art ontology-based systems in engineering, and they proposed a roadmap to facilitate the application of ontology. As a part of road asset management, Grubic and Fan [14] reviewed ontology-based supply chain management and categorised the studies into six ontology models, including enterprise ontology, Toronto Virtual Enterprise (TOVE) ontologies, Trans-European model, Intelligent Systems Technology Distributed Enterprise Ontology (IDEON), manufacturing system engineering ontology, and the model by Ye et al. [15], which implemented the semantic integration of supply chain management. However, a few research gaps remain. No systematic review for the field of road asset management has been conducted. Over the past few years, the road asset management field has implemented ontologies because of their value in infrastructure management systems [16, 17]. However, existing reviews often focus on specific aspects of road asset management and have relatively narrow scopes. For example, Kiritsis [18] reviewed how ontology aids in different engineering life cycle stages, but the review did not identify other road management aspects. Grubic and Fan [14] focused on ontologies in supply chain management, but they only presented mature models and their application in certain fields. They lack a holistic view of the current development and implementation of the technology.

Therefore, this paper aims to provide the latest advances in the development and implementation of ontologies in road asset management. A comprehensive review can not only help improve the current understanding of ontology languages and techniques in AEC industry, but also help choose the most appropriate approaches to develop new ontologies in relevant transport asset management domains. In addition, the gaps in current development and implementation, as well as future research directions, are also proposed after the comprehensive review. The remainder of this paper is organised as follows. Section 2 introduces the method for the review. Section 3 presents a detailed literature analysis. A discussion section is provided in Sect. 4 to summarise the gaps and future directions of this area. Section 5 concludes this paper.

2 Research Method

2.1 Systematic Literature Review (SLR) Methodology

A systematic literature approach proposed by Yang et al. [13] was used in this study. The review process involved paper selection (filtering), quantitative analysis, qualitative analysis, and result discussion. Such a method has also been adopted by other similar review studies [12, 13, 18].

The scope of the review was confined to the development and implementation of ontology in road asset management. In total, eight steps were adopted during the review process,

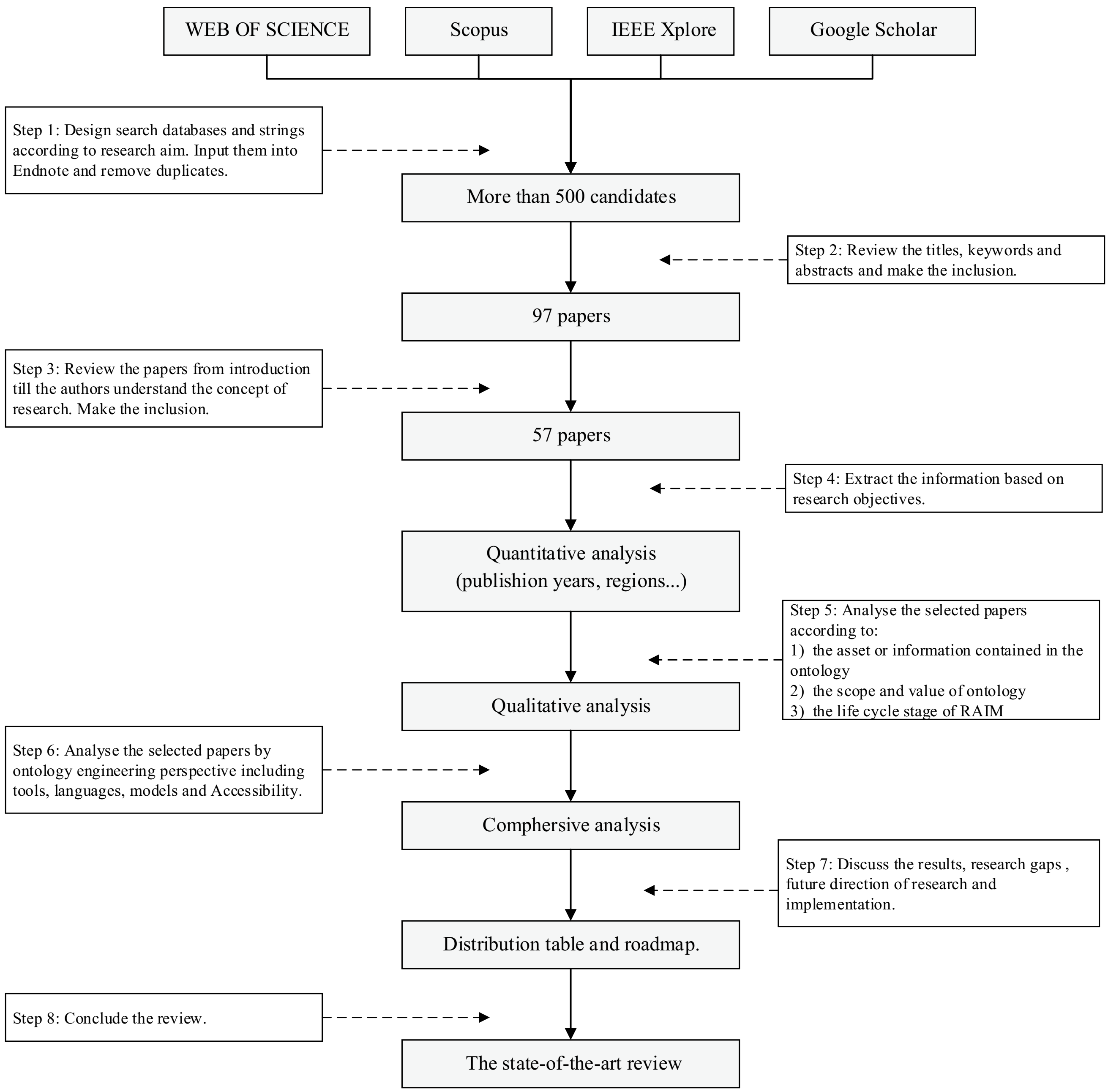

Fig. 1 The process of the systematic literature review

and a detailed explanation of the review process is shown in Fig. 1. Priority was given to the Web of Science database owing to its wide coverage and high quality, while Scopus, IEEE Xplore, and Google Scholar were also considered [19]. The searching strings were defined based on previous studies, e.g. Yang et al. [13], Le and Jeong [8], Kiritsis [18]. Based on these studies, 'semantic' or 'semantic web' and 'Linked data' are the most relevant keywords for ontology, while 'traffic asset' is a typical substitute for 'road asset'. Thus, the final search strings were set as ('ontology' OR 'semantic' OR 'Linked Data') AND ('road' OR 'road asset' OR 'traffic asset'). Note that conference papers from the computer science field were also considered in this study because conferences are also an important means of communicating quality research on ontology in the computer science field [20].

After collecting more than 500 papers in Step 1, a manual process was adopted to filter papers by examining their titles, keywords, and abstracts. Only peer-reviewed journal papers, conference papers from leading conferences, and other papers that use ontology in road asset management were retained. After filtering, 97 publications were identified.

Note that the term 'road' in this review only refers to surface pavements and objects that move on them, such as vehicles [21].

In Step 3, a further filtering process was conducted manually. Only papers closely related to the development and implementation of ontology in road asset management were included. After filtering, 57 papers were identified and included in the analysis.

2.2 Analysis Codes

The 57 selected papers were coded and analysed through codes in Table 1, which were developed from Li et al. [22] and Yang et al. [13]. These codes can be categorised into three groups. The first group is related to the publications, including year, author, journal/conference title, and country/region. The second group is related to the implementation domains, focusing on the asset type and life-cycle stage where the ontology is implemented. Asset type represents what asset types have been targeted at by using ontology techniques, and life-cycle stage represents the life cycle stages of road assets where the ontology techniques are applied. The third group of codes focuses on the ontology techniques, which include the ontology modelling approach, tool, data representation, serialization, querying and accessibility. These codes consist of all necessary processes from knowledge formalization to ontology presentation. In addition, the gaps identified during the review process are analysed, and future directions are discussed.

3 Review Results

3.1 Quantitative Analysis of the Selected Papers

This section presents a statistical analysis of the selected papers. Figure 2 shows the number of papers by publication type. Journal papers accounted for 79% (45 out of 57) of the selected publications, while proceedings from conferences contributed 21%. Note that almost 50% of the studies were published after 2014, which indicates an increasing interest of researchers in this topic.

Figure 3 shows the distribution of studies by country/region from 2006 to 2019. Forty-two out of the 57 publications were from Europe and North America, demonstrating relatively higher research interests in this specific topic from these two regions.

3.2 Qualitative Analysis of the Selected Papers

Based on *International Organization for Standardization (ISO) 55,000: Asset management—overview, principles, and terminology* (ISO, 2014), relevant road asset management guidelines, including *Guide to Asset Management* [23], and peer-reviewed studies on road asset management [13, 18], ontology implementation in road asset management can be described from two perspectives, i.e., asset type and life cycle stage.

3.2.1 Asset Type

Based on the best practice and standards, assets in road asset management are primarily classified into five groups: traffic service assets, road assets, property assets, data assets, and

Table 1 Codes for the review

Area	Code	Description
Publication-related information	Year	Year of publication
	Author	Authors
	Publication venue	Journal/conference at which the paper was published
	Location	Country/region where the study originated
Implementation domains	Asset type	Asset type of ontology implementation
	Life-cycle stage	Life-cycle stage of the ontology implementation
Ontology techniques	Modelling approach	Ontology knowledge collection and formalization
	Tool	Tool and platform used to create ontologies
	Data representation	Data model and description language
	Data serialization	Serializing data into machine interpretable syntax
	Data querying	Information searching and reasoning
	Accessibility	Whether or not the development has open access to readers
	Limitation	Limitation of current ontology implementation

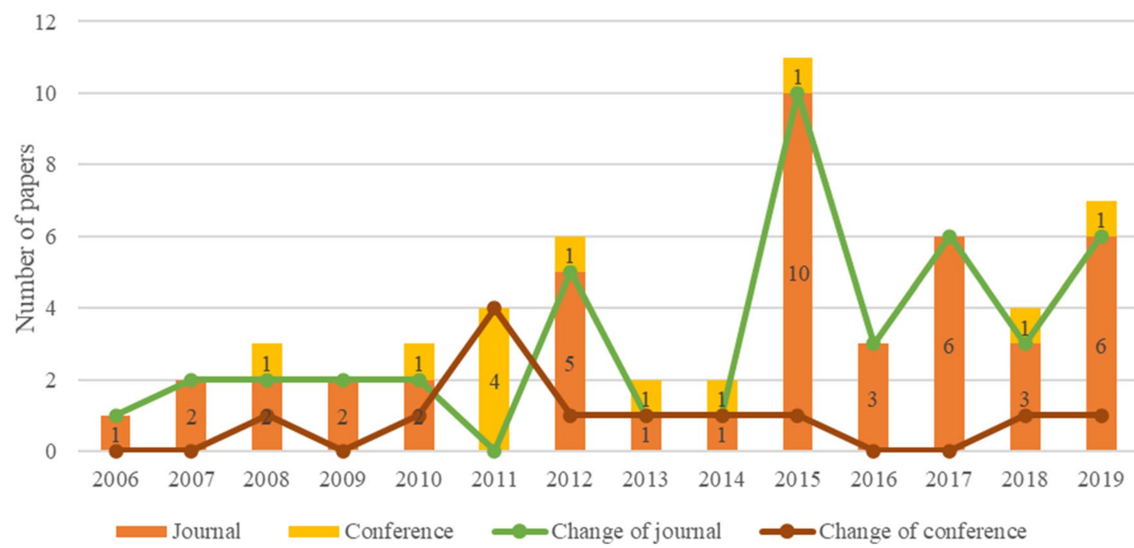

Fig. 2 Trends of publications

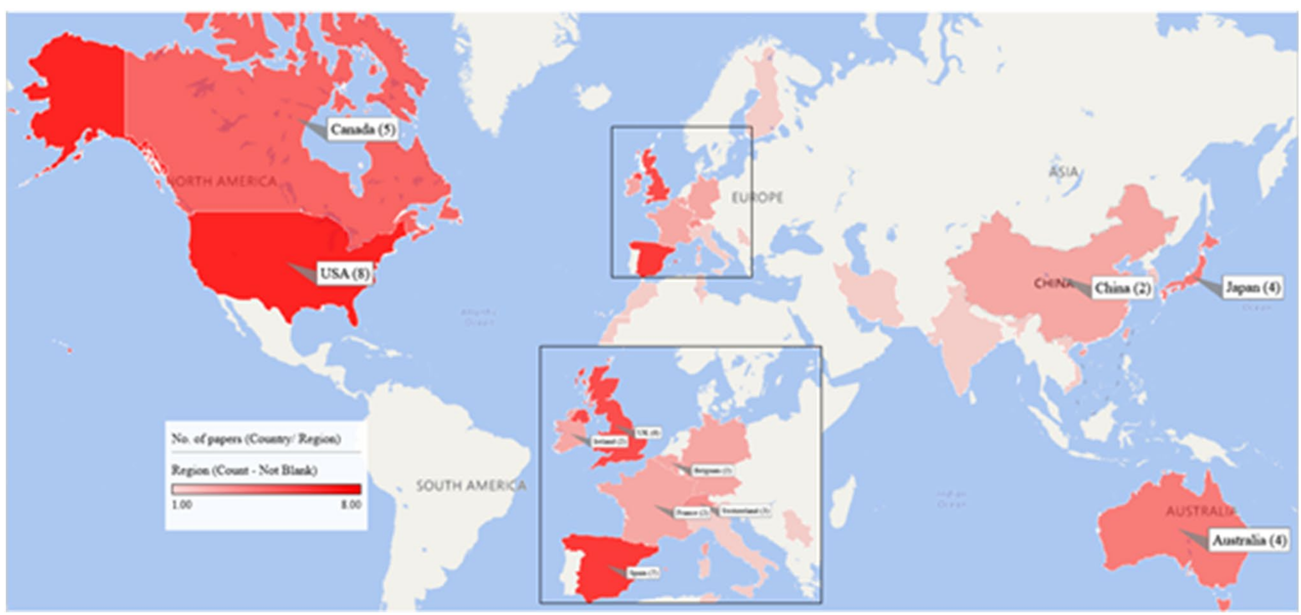

Fig. 3 Distribution of publications by country/region

other assets [18, 24]. Table 2 lists previous studies on road asset management using ontology, categorised by asset type.

- Traffic service assets. These are all assets relevant to traffic systems, such as signals, marking, lighting, and safety devices. Traffic service assets are the most important type of asset in which ontology is implemented.

  The aim of road assets and infrastructure management is to provide services for road users [43]. As a result, more than 58% of the studies were related to traffic service assets. On this specific subject, some studies focused on traffic management, including traffic condition information collection, analysis, and sharing. For example, ontology can be used to structure sensor-based information to predict traffic congestion, which can aid drivers in selecting better routes [39]. In addition, the global positioning system (GPS) information of a road can also be digitised using ontology, which would provide more integrated data for road management authorities [39]. Sensor ontologies can also aid the collection of digital information on weather, road works, events, moving objects, and accidents. Such collected data were processed using a

Table 2 Summary of asset types in ontology studies in road asset management

Areas (Number of studies)	References
Traffic service assets (32)	Ceausu and Despres [25], Hornsby and King [26], Vallejo et al. [27], Zhai et al. [28], Houda et al. [29], Wang and Wang [30], Barrachina et al. [31], Du et al. [32], Gregor et al. [33], Jelokhani-Niaraki et al. [34], Malgundkar et al. [35], Stocker et al. [36], Bermejo et al. [37], Lécué et al. [38], Lécué et al. [39], Corsar et al. [16], Mohammad et al. [40], Toulni et al. [41], Watson et al. [42], Zapater et al. [43], Zhao et al. [44], Gould and Cheng [45], Fernandez et al. [46], Consoli et al. [47], Lee et al. [48], Fernandez and Ito [49], Czarnecki [50], Nguyen and Nguyen [51], Van de Vyvere et al. [52], Wu et al. [53];
Road assets (10)	Halfawy [54], Hülsen et al. [55], Yabuki et al. [56], Kiritsis [18], Zeb et al. [57], Le and Jeong [8], Cordoba et al. [58], Zeb [59], France-Mensah and O'Brien [60], Lim et al. [61];
Property assets (1)	Kaza and Hopkins [62]
Data assets (4)	Koukias et al. [63], Koukias and Kiritsis [64], Niestroj et al. [65], Ali et al. [66];
Other assets (7)	Merdan et al. [10], El-Gohary and El-Diraby [67], Berdier [17], Das et al. (2015), Zhang et al. [2], Beetz and Bormann [68], Niestroj et al. [69];

computer and reused in a traffic system in Dublin city [26, 38]. Moreover, transportation and travel data can be analysed by ontologies for more efficient use of road assets [16, 41, 43].

Most of the risks on roads are related to traffic; therefore, traffic management is also a priority [43]. Accidents on roads can cause significant problems, such as injury to road users, waste of time, increased cost, adverse effects on the environment, and damage to the economy [31, 70]. On this specific topic, Ceausu and Despres [25] built an ontology for accidentology and terminology of on-road accidents. This was a preliminary study, but it confirmed the feasibility of using ontology in this scenario. Road event data [34], road condition data from cameras [40], and traffic accident data [30] were then integrated into ontologies to understand their hierarchy, relations, and interconnections, which can also be reasoned, shared, and reused. The behaviour of road users (e.g. drivers) has a relatively high effect on risks; thus, improving users' behaviour was also investigated to minimise risks [55]. To reduce the chance of accidents involving novice drivers, Nguyen and Nguyen [51] applied a fuzzy ontology to collect road information to simulate traffic situations. By learning and understanding the emergency events on a road, novice drivers can gain extra experience before they actually begin to drive. Ontology can also increase information accuracy after an accident. For example, Watson et al. [42] attempted to correct the under-reporting injuries caused by accidents using Linked Data, which provided implications for road safety research, policies, and funding.

Other fields in traffic service management have also used ontology techniques. For example, to achieve better traffic flow and decision making, an ontology was implemented to provide valuable and efficient information for traffic light systems [52]. Normal data fragments, real-time data, and long-term historical data can be used through traffic light ontologies to predict and minimise accidents on roads [49, 52]. Intelligent or automated transportation systems require a large amount of information and information processing, which ontologies can aid and provide support for informed decision making [33, 44]. Two studies used ontological approaches to plan and record data with vector features, such as determining the shortest path [29] and journey route planning [48].

- Road assets. Road assets are all the facilities and relevant information that belong to road systems, including earthworks, pavements, shoulders, and roadside areas.

The life-cycle management of road structures is important and requires a significant amount of information, and ontology can be applied to increase the efficiency of information storage and extraction [7]. For example, Kiritsis [18] presented a closed-loop life cycle system (CL2M) with ontology techniques for the management of engineering assets. Zeb et al. [57] proposed a semantic web framework with a four-step method to share life-cycle information such as design knowledge and workflow.

Unlike the management of roads, highway management is a specific subject that has been investigated separately because of its high value and strategic significance in the social economy [8]. As multiple agencies and stakeholders are involved in highway projects, the use of ontology can produce benefits by linking different stakeholders, improving the classification and interconnection of life-cycle data of highway assets, and supporting various decision-making procedures in highway asset management [8, 60].

A road crossing is another important road asset that includes multiple asset types, such as vehicles, users, signals, and assets. Studies in this domain typically focus on the decisions made by drivers when they are at a crossing [55, 58]. Ontology techniques have also been used for other road asset types, such as sewage systems [54] and roadside trees [56].

- Property, data, and other assets. This category refers to road management facilities, road information storage and management systems, and other general road systems and information that cannot be grouped into any of the above categories. For example, ontology has been used to provide a uniform understanding of guidelines and standards (e.g. ISO 19115-1 and ISO 55002) through documentational analysis [65]. Some researchers have implemented ontology rules to present document content, which can be used in asset operation, maintenance, and configuration [64]. Merdan et al. [10] attempted to manage the relationships between stakeholders and projects by using a rule-based ontology framework for the cooperation of different tasks. Beetz and Borrmann [68] focused on information integration using Linked Data during asset management.

3.2.2 Life-Cycle Stage

Scholars have widely acknowledged that there are four main management stages throughout the entire life cycle of road assets and products: planning, construction, operation, and maintenance [23]. We categorised studies based on the life-cycle stages that they focus on. The results are shown in Table 3.

- Planning and construction. These two life-cycle stages have attracted limited research interest. The design of work flow was the main purpose for the studies in these two stages. Ontology played a role to ensure that knowledge is standardised. For example, Zhang et al. [2] develope a construction safety knowledge ontology for the workers for fast-training purpose.
- Operation & Maintenance. This stage refers to the operation and maintenance of road-related assets. More than 70% of the papers are related to operations, probably because that this stage requires a significant amount of information for effective decision making [72]. In these studies, ontologies are proven to be effective in supporting fast information and data exchanging. Some notable examples include the management of traffic and asset condition information [29, 35, 41, 50], road equipment management [33], and road structure management [56]. Only a few studies were related to road maintenance. For instance, Berdier [17] developed an urban ontology for maintaining road systems.

  Risk management, as a key topic in operation and maintenance, is listed separately in Table 3 because of the large number of publications on this subject. Researchers have used ontologies to achieve efficient data exchange and build synonymity for accidents and road events to reduce risks [27, 30, 53]. In this domain, streaming real-time data from sites to the management system was a key issue, which can be supported by using formalized ontological information.

- Entire life cycle. Some studies used ontologies for efficient data exchange [54, 68], knowledge sharing among stakeholders [67], documentation sharing [66], and highway management [60] throughout the entire life-cycle of roads. Ontologies have also been used to improve collaboration in supply chain management during the construction of road projects to reduce costs and avoid risks [71].

Table 3 Summary of selected papers by life-cycle stages

Life cycle stages (Number of studies)		References
Planning (2)		Kaza and Hopkins [62], France-Mensah and O'Brien [60];
Construction (2)		Das et al. [71], Zhang et al. [2];
Operation and Maintenance (38)	General (22)	Hornsby and King [26], Zhai et al. [28], Houda et al. [29], Yabuki et al. [56], Stocker et al. [36], Jelokhani-Niaraki et al. [34], Gregor et al. [33], Malgundkar et al. [35], Du et al. [32], Lécué et al. [38], Corsar et al. [16], Koukias et al. [63], Toulni et al. [41], Zapater et al. [43], Zeb et al. [57], Fernandez et al. [46], Fernandez and Ito [49], Czarnecki [50], Van de Vyvere et al. [52], Merdan et al. [10], Berdier [17], Consoli et al. [47];
	Risk management (16)	Ceausu and Despres [25], Vallejo et al. [27], Hülsen et al. [55], Wang and Wang [30], Barrachina et al. [31], Bermejo et al. [37], Lécué et al. [39], Mohammad et al. [40], Watson et al. [42], Zhao et al. [44], Gould and Cheng [45], Cordoba et al. [58], Niestroj et al. [65], Wu et al. [53], Niestroj et al. [69], Nguyen and Nguyen [51];
Entire life cycle (7)		Halfawy [54], El-Gohary and El-Diraby [67], Kiritsis [18], Le and Jeong [8], Zeb [59], Beetz and Borrmann [68], Ali et al. [66];

3.3 Ontology Techniques Analysis

This section aims to analyse ontology techniques from the perspective of ontology engineering, which is related to the process of ontology knowledge formalization and representation [73]. The analysis framework of this paper follows the work of Yang et al. [13] and Ashraf et al. [7], while some adjustments (e.g. specific ontology modelling approach and access situation) have been made. The analysis focuses on the principles, methods, and tools for initiating, developing, and maintaining ontologies [73]. The main components in ontology engineering are ontology modelling approach (knowledge development and formalization), ontology tool, data representation, serialization and querying (ontology implementation and presentation) and accessibility [13]. Ontology modelling approach represents what type of ontologies are used and what domains they target at. After the modelling approach, the tools or platforms to be used for editing ontology from the software engineering perspective need to be selected. These two steps aim to formalize ontologies from documents and digitally represent ontologies. Data representation, serialization and querying refer to professional techniques used to store, form and implement ontology in road asset management. Figure 4 presents the relationships of these steps in ontology engineering. The results of the overall analysis are shown in Table 4.

3.3.1 Ontology Modelling Approach

In this review, a total of 23 ontology modelling approaches were identified. Fifteen out of the 23 modelling approaches followed Ontology Development 101, a widely accepted ontology development guide that incorporates three steps, including specification, acquisition and formalization [46]. The first step, specification, determines the ontology scope, which can often be reflected by the name of the constructed ontologies, e.g. Ontology-based traffic accident risk-mapping (Wang and Wang [30]) was for traffic accident risk-mapping and VEhicular ACcident Ontology (Barrachina et al. [31] was for vehicular accident. In the next step of acquisition, knowledge resources are collected to build concepts and relationships. In the context of road asset management, most of the resources are collected from guidance, standards, literatures and project documents. For example, El-Gohary and El-Diraby [67] referenced major enterprise projects (e.g., Industry Foundation Classes) and specific literature about construction management to establish an ontology model (IC-PRO-Onto) for road construction. The final step, formalization, defines taxonomy and lexical term definition to form a final ontology hierarchy.

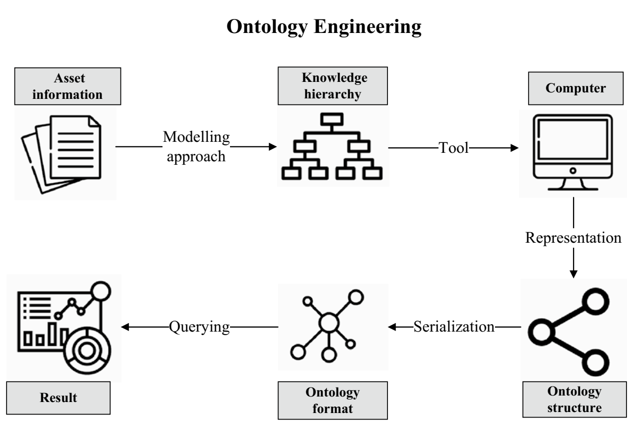

Fig. 4 The processes of ontology engineering in road asset management

Although the modelling approaches often involve the aforementioned three steps, a few differences were noticed. (1) road asset management field has more social properties, thus, ontologies in this field consider more human factors; (2) more informal ontologies were formalized than other engineering domains [18]. In the acquisition step, some studies considered more human participation in knowledge collection. Merdan et al. [10] proposed a multi-agent and knowledge-intensive framework based on the multi-agent system and the material-handling ontology for road agents, which highlighted the valuable opinions from agents. Other works also used focus group to collect first-hand experience to replenish the latest information in ontology framework [56]. As for the formalization step, most studies developed ontology hierarchy directly from knowledge pool and used basic algorithm (e.g., description logics (DL)) and artificial intelligence techniques to form a formal ontology, but there were some special cases that consider semi-formal or informal ontologies. These two types of ontologies contain less explicit information, but they can map various potential links between instances and classes by logic programming [75]. For instance, some of them were created to present more integrated hierarchies (e.g. Kiritsis [18], Koukias and Kiritsis [64]), and others emphasized detailed relationships between instances (e.g. Merdan et al. [10]). Semi-formal and informal ontologies which allow a loose form in natural or restricted language can reduce strict definitions for class and relationship, and they provide flexibility to decision making process with similar accuracy of knowledge extraction [75].

The establishment of specific ontology models has some advantages. First, they provide common setting up steps of ontology from original information to knowledge-meta process, which can be reused by similar research in the future [13]. Second, they provide a clear and intuitive description of the key elements within them [13]. Another minor advantage is the unique naming of ontology models that can provide convenience for people to search, find, refer, and use them [76].

Table 4 Summary of the selected papers from the ontology engineering perspective

Author	Ontology engineering					Open access
	Modelling approach	Tool	Data representation	Data serialization	Data querying	
Ceausu and Despres [25]	ACCident TO Scenarios (ACCTOS)	–	OWL[1]	–	–	–
Kaza and Hopkins [62]	Information System of Plans (ISoP)	–	–	–	–	Y
Merdan et al. [10]	–	JADE[2], Protégé[3]	OWL	–	–	–
Hornsby and King [26]	Suggested Upper Merged Ontology (SUMO)	–	Relational database	–	SQL[4]	–
Zhai et al. [28]	–	–	RDF[5]	–	SeRQL[6]	–
Vallejo et al. [27]	–	Protégé	OWL	–	OWL–to–PROLOG[7]	–
Houda et al. [29]	–	Protégé	RDF	–	SWRL[8]	Y
El-Gohary and El-Diraby [67]	Infrastructure and Construction PROcess Ontology (IC-PRO-Onto)	–	OWL	N-triples	–	Y
Svetel and Pejanović [74]	–	–	RDF	XML[9]	–	–
Berdier [17]	–	–	RDF	XML	–	–
Yabuki et al. [56]	Roadside Tree Diagnosis Support System (RTDSS)	Hozo[10]	MySQL[11]	–	–	Y
Wang and Wang [30]	Ontology-based traffic accident risk-mapping (ONTO_TARM)	–	–	–	–	–
Jelokhani-Niaraki et al. [34]	–	–	OWL	–	–	–
Barrachina et al. [31]	VEhicular ACcident ONtology (VEACON)	–	OWL	–	–	–
Gregor et al. [33]	–	–	RDF	N-triples	–	Y
Du et al. [32]	–	–	OWL	–	–	–
Kiritsis [18]	Linked Design Ontology (LDO)	Protégé	OWL	JSON-LD[12]	–	Y
Lécué et al. [38]	Semantic Traffic Analytics and Reasoning for CITY (STAR-CITY)	–	OWL (OWL2EL[13])	–	–	Y
Lécué et al. [39]	–	–	OWL	–	–	Y
Das et al. [71]	–	Protégé	Cassandra[14]	XML	–	–
Zeb et al. [57]	Ontology-supported asset information integrator system (AIIS)	–	OWL	XML	–	–
Zhao et al. [44]	–	–	–	–	SWRL	–
Zhang et al. [2]	Ontology-based job hazard analysis (JHA)	Protégé	–	–	SWRL	–
Mohammad et al. [40]	–	–	–	–	SWRL	–
Corsar et al. [16]	–	Linked Open Data[15]	RDF	N-triples	–	Y
Zapater et al. [43]	Road traffic information web service (WSs)	–	OWL	–	–	–
Toulni et al. [41]	Vehicular Ad-hoc NETwork (VANET)	–	OWL	–	–	–
Koukias and Kiritsis [64]	Technical Documentation Ontology (TDO)	–	–	–	–	–
Fernandez et al. [46]	–	Protégé	OWL	–	–	–

Table 4 (continued)

Author	Ontology engineering					Open access
	Modelling approach	Tool	Data representation	Data serialization	Data querying	
Gould and Cheng [45]	–	Protégé	OWL	–	–	Y
Le and Jeong [8]	–	–		XML	–	Y
Fernandez and Ito [49]	The Semantic Sensor Network	Protégé	OWL	Turtle	–	–
Consoli et al. [47]	–	–	RDFS[16]	N-triples	–	Y
Cordoba et al. [58]	SesToCross	–	–	–	–	–
Lee et al. [48]	University activity ontology (UAO)	–	–	–	–	Y
Zeb [59]	Eco asset ontology (EA_Onto)	Protégé	OWL	–	–	–
Niestroj et al. [65]	–	–	OWL	–	–	–
Beetz and Borrmann [68]	–	–	OWL	–	SPARQL[17]	Y
Wu et al. [53]	Topological semantic trajectory (TOST)	–	MySQL	–	–	–
Niestroj et al. [69]	The OpenStreetMap (OSMAP) ontology	Protégé	OWL	–	–	Y
Van de Vyvere et al. [52]	–	–	RDFS	–	–	–
Ali et al. [66]	Ontology and latent Dirichlet allocation (OLDA)	Protégé	OWL	–	–	Y
France-Mensah and O'Brien [60]	Integrated highway planning ontology (IHP-ONTO)	Protégé	OWL	–	SWRL	Y
Nguyen and Nguyen [51]	–	Protégé	OWL	–	–	–

[1]OWL = The Web Ontology Language

[2]JADE = Java Agent Development Environment

[3]https://protege.stanford.edu/

[4]SQL = Structured Query Language

[5]RDF = Resource Description Framework

[6]SeRQL = Sesame RDF Query Language

[7]http://www.jiprolog.com/

[8]SWRL = Semantic Web Rule Language

[9]XML = Extensible Markup Language

[10]http://www.hozo.jp/

[11]https://www.mysql.com/

[12]JavaScript Object Notation for Linked Data

[13]https://www.w3.org/TR/owl2-profiles/

[14]https://cassandra.apache.org/

[15]https://www.w3.org/egov/wiki/Linked_Open_Data

[16]RDFS = RDF schema

[17]SPARQL = SPARQL Protocol and RDF Query Language

3.3.2 Tool

After ontologies has been formed, they require a development environment to implement, and many tools, either for research or business, have been developed. The selected papers were remarkably consistent that most of the studies used Protégé, which is a tool developed by researchers from Stanford University. It can be run on a variety of platforms, manage many standard data formats such as RDF and Turtle, and support extensions [77].

In the early application stage, Houda et al. [29] used Protégé as a validation tool in their research to check if a new ontology improved the information management process of travel planning. After years of development, the latest version of Protégé has embedded many useful functions such as information querying, reasoning, and visualisation. Being applied in practices and research, Protégé has demonstrated its advantages including ease for the beginner, open for the secondary development, and vast popularity among researchers for ontology establishment in road assets and other AEC projects [71]. According to an online survey, Protégé is the most frequently used tool [78].

Despite it is easy and interesting to use, some researchers argued that the functions of it is limited [79]. For applications in industry or government, the functionalities of tools, such as live streaming data, may require additional expansion. Thus, Yabuki et al. [56] developed the platform HOZO to edit the ontology for roadside trees. Since Protégé is based on OWL and might encounter some problems when using external modules that were developed for other languages [77]. However, the general recommendation is that these tools must be used with caution, and users must fully understand the purpose of the target ontology.

Other tools are also used to build ontologies in road asset management areas. For instance, Merdan et al. [10] proposed a multi-agent and knowledge-intensive ontology through Java Agent Development Environment (JADE), which is a well development platform. Outside the road asset domain, there are many tools available for developing ontologies. For instance, SWOOP is a light-weight ontology editor used in the area of biology and bio-tech, which is based on Web and easy to use for beginners. NeOn Toolkit is another tool which has an extensive set of plug-ins to support engineering ontology, especially heavy-weight projects (e.g., multi-modular ontologies and ontology integration in building projects). Possible reasons for not using these tools in road asset management includes: 1) Protégé is a mature platform; and 2) the tendency to follow existing practices.

3.3.3 Data Representation

Data representation refers to how formalized knowledge from ontology engineering stage can be stored as computer readable information. It contains both data structure and database types used when implementing ontology [6]. The resource description framework (RDF) store and Web ontology language (OWL) were found as the most widely used storage model and representation languages.

- RDF core

The RDF was developed as a standard data model for data exchange and storage on the web [80]. With the feature of being a stable data format and facilitating data integration, it was selected as the core of the ontology and semantic web [80]. By presenting instances or objects as nodes that are identified by a unique resource identifier (URI) and linked by edges (relationships), such a data format makes information reusable by both humans and computer applications [81]. Or in other word, a 'subject-predict-object' relation can be defined by RDF, and this is the first step to formalize engineering information to ontology.

In other words, RDF is the basis of many developed ontologies in road asset management. Because of its long development history, many studies may have common processes and similar steps, which is convenient for researchers and engineers to share and use their ontologies [80]. However, the extension of functions is limited, and users require more complex abilities to satisfy the requirements [81]. Thus, RDF-based techniques can be used in most of conditions and road assets, and they are a good starter for any ontology study.

- RDFS and OWL

The RDF Schema (RDFS) and OWL were designed to enrich the default classes and relationships in RDF. Two of the selected studies specifically highlighted RDFS as their data representation language. RDFS was subsequently created as an evolution of the traditional RDF. It consists of definitions for classes, comments, and elements, and expand the presentation ability of RDF. For instance, RDFS can develop extra subclasses for existing RDF class, which cannot be defined by default RDF-based language. The first study that used RDFS is the work conducted by Consoli et al. [47], who provided a road maintenance RDFS with more available vocabularies. However, studies using RDF or RDFS frequently focused only on the basic framework establishment for a new domain because of its powerful class definition function. While other functions such as various relationship between class and subclass (rather than the simple definition as 'is subclass of'), or automatically information mapping by logics, were not considered [82].

Over twenty-two of the selected studies used OWL-based ontology in their research. OWL was developed by the World Wide Web Consortium (W3C) Web Ontology Working Group and published as a standard and recommended ontology language in 2004 [83]. It expanded the functions of RDFS to provide more embedded elements, such as complex class expressions for ontology [84]. In the field of road asset management, some studies attempted to use OWL. For instance, Kiritsis [18] created a closed-loop life-cycle management platform for road assets. By using OWL, it provided a wider understanding of ontology in this domain and the ability to apply ontology techniques in a complex environment. Moreover, it extended the resections function of RDFS, which became the rules for defining particular relationships. Another study was conducted by Jelokhani-Niaraki et al. [34], who observed that the OWL classes in spatio-temporal ontology can be reasoned, shared, and reused by the rules.

The new version of OWL, OWL2 has a series of evolution such as OWL2 Expressing Language (EL), OWL2 Query Language (QL), and OWL2 Reasoning Language (RL), for different contexts [85]. Compared with OWL, the OWL2 series can be considered as a whole, reasoning algorithms for the OWL profiles, and they exhibit higher performance and are easier to implement in road asset management. For example, Lécué et al. [38] selected OWL2 EL to improve city road management ontology in the data transformation process, which achieved easy updating and flexible composition of stream operations.

In other words, OWL semantics provide more possibilities than RDF for ontology. It provides a more mature and professional vocabulary for ontology and extends functions such as reasoning for the road asset management process. OWL-based techniques allow ontology to have extra development potential and more uniform data than before. However, with the development of OWL, its compatibility with the original RDF is increasingly limited. As a result, because some of the important plug-in modules (e.g. online module) from computer science are based on RDF, OWL ontologies cannot benefit from these extra and useful functions [86].

Other storage and representation formats have also been used in road asset management domain. For instance, MySQL is an open-source relational database management system that structures data by using information in tables. Cassandra is a NoSQL database, with an aim to provide relation (e.g. graph database) other than the tabular relations used in MySQL. NoSQL databases can handle large volume of data, support high-speed querying and plug-ins. With ontologies being increasingly established in road asset management domain, integrating ontologies in NoSQL databases is also possible [87].

3.3.4 Data Serialization

After data representation, instances, relationships and classes need to be serialized into different syntaxes for general use. Extensible markup language (XML) syntax for RDF, usually referred to as RDF/XML, is the most classic and easy-to-use format. For instance, an ontology (VEACON) created XML-based messages to provide flexible and expressive relationships between instances [31].

Additionally, other syntaxes have also been developed for RDF, such as N-Triples, JSON-LD and Turtle [80]. N-triples have a simple line structure which consists of a subject, predicate and object separated by a space. Four of the selected studies used this syntax, which is easy to parse and can assist compression. JSON-LD is an attempt to store new ontology using an existing format JSON. As for Turtle, it is more readable to human users, and it also has the ability to provide data stream to the management system [68]. Only two studies mentioned that they chose JSON-LD and Turtle to provide more professional RDF data in their road management process. Different syntaxes can provide more features to ontology such as easy to read by human and higher dynamic performance [81].

3.3.5 Data Querying

Data querying refers to searching required information in ontology by certain languages. In this work, extra reasoning languages implemented to improve current data interpretation are also discussed in this section.

SPARQL Protocol and RDF Query Language (SPARQL) is a query language designed and trimmed for all RDF formats. It enables schema-instance inconsistencies to be queried through the formulation of corresponding codes [68]. If an ontology is implemented using relational databases, the structured query language (SQL) languages are required for its data query, manipulation, and control. Only one study in the literature used SQL queries to derive the relationships between road objects [26]. The limited query function narrowed the SQL application in road asset management [88].

Some of the other languages listed in Table 4, e.g. SeRQL (Sesame RDF Query Language), are variants of SQL, while the other, e.g. OWL-to-ProLog (Programming in Logic), are specific functional languages to convert data formats. Similar to OWL, for which its variants, i.e., OWL2, OWL2 RL, and OWL2 EL, have their own characteristics and suit different use contexts, these extension languages have their own application contexts. For example, OWL2EL provides a more efficient classes definition [38]. In summary, the less used languages may fit specific knowledge domains or engineering scenarios better, but also have higher application requirements. Moreover, subsequent research in the same field may have to revert to other popular techniques such as OWL [86].

A special language is Semantic Web Rule Language (SWRL), which is a combination of OWL Description Language and the rule markup language. The extension of rules for OWL enables ontology to understand road information without extra input, which saves space and time to achieve a more efficient ontology [44].

3.3.6 Accessibility

Only eighteen ontologies have been shared online for public access, which can benefit road engineers and researchers in understanding and reusing these models [68]. Some of the datasets are shared on GitHub (an online forum for sharing projects). The ontologies that used the Linked Data techniques also have their own online databases, i.e., the Linked Open Data (a cloud website). It provides a place to update and upgrade the ontologies as well as a cloud that uses Linked Data to link the nodes of different datasets [89]. Thus, information from different domains can be automatically read by computers [90]. However, researchers from the road ontology field have seemingly not fully considered accessibility.

3.3.7 Ontology in Road Asset Management

- Ontology modelling in various life-cycle stages

The overall process for developing and implementing ontologies in various life-cycle stages of roads follows the widely accepted ontology modelling guide, i.e., Ontology Development 101, with a few adjustments.

Planning. Ontology engineering in the planning phase focuses on hierarchy and relationship design because of the importance of information structure, such as identifying a detailed hierarchy for decision making during the planning phrase [62]. Because of this specific feature, there was a heavy focus on ontology acquisition and formalization. In these two steps, detailed and complete knowledge for preparation is collected and implemented in ontology for usage. Researchers also chose language and tool that can highlight the relationships between instances, such as OWL in data representation and querying [60].

Construction. Numerical and physical properties of materials and structures in the construction stage pose new requirements on the ontology modelling. Thus, ontology structures were designed to be concise to directly reveal the construction process, and the properties were linked with instance properly for easy reading and querying by human [2]. In addition, ontology modelling in this stage also starts to consider engineers' experience. However, the acquisition step is still often implemented within the concepts and procedures from industry standards. To present as much property information as possible, the implementation always needs tools that have complex property coding and storing abilities. A case was the work completed by Das et al. [71], which chose Protégé to finish a construction supply chain management ontology.

Operation & Maintenance. Since ontology has advantages in efficient information exchange and processing, most of the attempts were focused on the fields that have high data demand and liquidity, such as traffic information management or other activities in this stage [30, 40, 72]. Comparing with construction stages, the influence from human experience in this stage is significant [91]. In addition, more complex hierarchies were developed from ontology formalization since more supporting knowledge was required on decision making. The importance of manual works in road asset management caused the selection of semi-formal and informal ontologies in formalization step, since they provide more flexibility on information management. As for ontology representation stage, because of the requirement on high-speed data exchanging, some innovative techniques (e.g., NoSQL databases) which have outstanding performance in data exchanging started to be adopted. In this stage, querying and reasoning functions were also highlighted by works. Although ontology can do part of reasoning work, current computer logic may not reliable enough, and the cost would be higher as well [91].

Road assets and their whole lifecycle management can benefit from ontology in three ways: (1) it can form abundant and critical knowledge pool for road asset management, which provides both standard and up-to-date information in a fast-changing environment; (2) it can help interpret human experience and further integrate human experience with existing knowledge, which provides solid background for informed decision making; and (3) it can improve data exchange efficiency and help achieve real-time information reporting and responding with reduced time, cost and potential risks.

- Other ontology engineering techniques in road asset management

The implementation of ontologies needs supporting techniques of data representation, serialization and querying. The most commonly used data structure for now remains to be RDF. It achieves basic ontology functions such as searching for different types of relations in the traffic information area. Ontology needs describing languages to present full information. RDFS and OWL can enrich RDF by complex classes and direct description, which significantly improves the ability to store and present road asset information [18, 34]. The number of studies using other supporting languages, such as OWL2 EL and OWL2 DL, is limited. Specific reasons are that MySQL performs inefficiently when large volumes of data with complex data structures are involved, but it is good at structuring information and exaction efficiency, which is suitable for simple but repeating ontology building process such as instance and relationship in traffic lights system [92]. In contrast, databases of NoSQL can provide alternative opportunities to overcome obstacles related to scalability and flexibility, and they have attracted interest from researchers [87]. It is suitable for areas such as traffic flow and road condition monitoring which requires large volume and streaming data.

In data serialization, most studies used the basic RDF/XML as the syntax. Other syntaxes have not been used often because the completeness of ontology framework is usually first priority, and this can be fully presented by XML. Additional advantages such as easy to read, are not as important as completeness [78]. The ultimate aim of ontology is to search relevant information for informed decision making in road asset management. Thus, querying and reasoning functions are developed to automatically extract the required information. SWRL is found as the mostly used querying and reasoning language with an advantage of expressing potential relationship and property. In emerging areas in road asset management filed, such as hazard analysis and smart city management, many latest techniques (e.g. SWRL and OWL2) have been implemented to improve the ability in data querying and reasoning [2, 38].

4 Major Gaps and Future Directions

Based on the analysis and findings from previous sections, the major gaps in the implementation of ontology in road asset management include the lack of ontology automatic mechanism, limited options of ontology techniques, lack of online sharing of ontologies for easy access and discussion, lack of a link between ontology and other engineering techniques to obtain necessary cooperation, and limited consideration of user convenience. In addition, recommendations for further research on ontologies in certain domains are also presented. A detailed analysis for limitations and future direction can be seen in following sections.

4.1 Lack of Specific Ontology Engineering Approach for Road Asset

Based on the review in Sect. 3.3.1, it is found that although the general ontology development process is defined by widely accepted document and other well-known publications, some specific features of road asset management may require special attention. For instance, a more static situation (e.g., in the design and planning stage) requires a standard and formal knowledge acquisition for ontology [71]. On the other hand, dynamic situations (e.g., operations and maintenance stage) require efficient data storage and high-performance data exchanging. However, existing studies have not identified the unique characteristics of these life-cycle stages and formed typical ontology engineering approaches to accommodate these challenges. The lack of best practice in this domain caused sporadic problems in knowledge collection and weak ontology integration for linked data. Other engineering fields have already piloted some wide-accepted models to improve the understanding and building of ontologies, such as TOVE and IDEON ontology model for supply chain management [14].

4.2 Lack of an Automatic Mechanism

Based on the review from Sects. 3.3.1, 3.3.2 and 3.3.3, ontology techniques aids in the transfer of road asset management data into machine-processable information. However, the initial transition from traditional datasets into ontology data formats still requires much manual work. An automatic mechanism to capture instances, properties, and relationships is required [45]. Some of the research groups are trying to address this specific problem. For example, Nyulas et al. [93] created batch imprinting plug-ins for Protégé, which can automatically convert spreadsheet information into triples. However, such attempts are insufficient because of the increasing mega data scale and structural complexity. Meanwhile, from the perspective of ontology creation, the rule-based automatic mechanism can achieve new data creation and mapping in the current ontology during the use process. In some relevant fields, such as tunnel and bridge maintenance, an automatic mechanism has been conducted for years. For instance, a semantic web-based tunnel defect diagnosis system (TDDS) was used to automatically set up the link within structural defects in underground transpiration tunnels [94]. However, current new rules for automatic reasoning must be translated and manually input into the software.

In future research, an automatic rule-creation method is recommended to further reduce manual work [94]. Future research can elicit and formalise both explicit and implicit rules on integrated instances and relationships via a specific rule language. The first research to use SWRL in this field was conducted by Houda et al. [29], who used rules to automatically provide a proper travelling plan. In 2015, Zeb et al. [57] and Zhang et al. [2] extended the automatic creation and reasoning ontology to asset integration and analysis of site working hazards, respectively. In the next stage, machine learning techniques can be included in the rule-creation system to facilitate the semantic annotation process and reduce human intervention. Currently, relevant applications can be observed in auto-creating rules and guidelines on computers for road assets [66].

4.3 Limited Ontology Techniques

The selection of suitable ontology techniques depends on the aim and scope of the implementation. For instance, ontology is a more efficient approach for searching the target information in a documentational dataset, such as finding a special requirement for traffic lights in road asset management standards [95]. However, current ontologies on road asset management have not provided sufficient reasons for RDF or OWL being the most suitable representation approach instead of other approaches (such as

OWL2). Note that all of the selected studies within the review used RDF, even RDF serialisation syntax stores (e.g. RDF/XML, Notation3, N-Triples, and Turtle) as the data models. As an important conclusion from Table 4, when researchers attempt to establish an ontology, the option of tools appears to be singular. More than 80% of ontologies under road asset management (which mentioned the tool used in their research) selected Protégé.

Other ontological data models have been introduced in information management systems. Some of the latest studies in other fields have begun to use more efficient and performable storage syntaxes such as RDF* and labelled property graphs (LPGs) [96]. These novel formats are graph-based models, which have advantages such as using less storage space and having faster query paths [97]. Gong et al. [96] compared LPGs and RDF triples models using an oilfield ontology and observed that LPGs have advantages over RDF in query efficiency for large datasets. The friendly interface, low programming requirements, and open resources are the reasons it is popular in this field [98]. However, while the homogenisation of ontology techniques may provide more opportunities for cooperation and comparison between ontologies, it also limits the opportunity of benefiting from the innovation with other approaches [99].

Future studies are encouraged to focus on the latest techniques, or their latest version, based on their advantages (such as professional vocabulary and better reasoning function) in relevant fields. For example, the OWL2 language can formalise ontologies and automatically correct logic errors in the ontology mining process [100]. Other mentioned storage approaches (e.g. MySQL and databases of NoSQL) can also be adopted in the road asset management field, depending on the specific requirements of projects (such as roadside tree management) Yabuki et al. [56].

Another finding is that a few studies did not apply existing ontology modelling approach and created their own ontology development methods, such as IC-PRO-Onto [67]. Beginning from scratch might cost researchers more effort, but such a strategy is still recommended for future research because it can expand the current research body and provide a more detailed roadmap for subsequent research in the relevant road management or asset management domains [14]. However, the models should be reasonable, using best practices to avoid the risk of mistakes. The above finding is drawn based on the review from Sects. 3.3.3, 3.3.4, 3.3.5 and 3.3.7.

4.4 Lack of Sharing Ontologies

Ontologies of different domains can be linked by advanced techniques (e.g. Linked Data) to form a large ontology cloud even if they have been built in their specific domains [101]. If a research group transferred open access information (such as traffic flow, asset management guidance, and standards) into an ontology, an option to share the ontology online for public read, reuse, and develop it is available [102]. However, as mentioned in Sect. 3.3.4, the majority of the selected papers have not shared their database online. A consensus in the computer science field is that researchers should provide open access to their outcomes to collect feedback and update the versions [102]. Although ontology is also a computer-based technique, not all researchers have made their ontologies publicly available. By interlinking the nodes in different datasets, even in different formats, the range of ontological information can be expanded and developed in a more friendly manner for all stakeholders and parties in a large road project [90]. Moreover, Beetz and Borrmann [68] made analysing the different road models from various projects feasible by linking them in an integrated ontology. Studies that have not conducted the Linked Data technique to interlink the databases can also upload the ontologies online for other purposes such as permanent storage, maintenance, and communication with users [103].

According to these findings and gaps, the authors suggest that a final ontology study should be published online, which can aid researchers to gain a better understanding. This step also provides a platform for the developer to upgrade and fix bugs if there are any. For instance, Lécué et al. [39] first established a traffic congestion prediction model and then opened it to the public in 2014, sooner after another study that updated and implemented the model in an actual city [38]. Moreover, the Linked Data also requires the ontology dataset to be published online to benefit the future development of relevant techniques. However, researchers may have other concerns, for example, over the secrecy of the research; thus, researchers do not need to make ontologies publicly available. Such finding is drawn based on the review from Sect. 3.3.6.

4.5 Lack of Coordination with Other Techniques

As a novel concept, the implementation of ontology in road asset management is still relatively independent and lacks coordination with other new road asset management techniques. Although many knowledge domains and ontology tools appeared in this review, a limitation was also identified in that current ontologies lack cooperation with other latest and computer-based techniques. For instance, with the development of Industry 4.0 and Intelligent Cities, data flow from the bottom (e.g. construction sites) to top (e.g. departments of government) is required [104]. Ontology, as a novel machine-based information management process, should have borne advantages in coordinating with other computer-based techniques to improve efficiency [105].

Surprisingly, this is not evident, and other techniques are improving in this field. In the road building and maintenance sector, building information modelling (BIM) and the industry foundation classes (IFC) data model are applied to a uniform data format and a digital information sharing platform [106]. Many papers on integrating BIM and classical the geographic information system (GIS) to achieve better functions such as locating the structure elements have been published [107, 108]. Moreover, with a similar development aim and history, BIM, GIS, and ontology could be coordinated by using some plug-ins [109, 110]. However, attempts have rarely been made to coordinate these approaches with ontology. For instance, the ontology built based on a BIM model does not consider the construction site layout because of the incompatibility between two techniques (ontology and BIM) [109]. Thus, updating BIM and IFC information frequently to reflect the current condition and schedule in ontology is not currently possible, which would improve the accuracy of planning time [2]. Future studies could provide more opportunities for the cooperation between ontology and AEC relevant tools, which also improves the acceptability of ontology in these industries. The above finding is drawn based on the review from Sects. 3.3.5, 3.3.6 and 3.3.7.

4.6 Not Considering Human Users

Although ontology is based on computers and the Internet, its final aim is to provide services to human users. Several studies have mentioned interactions with human users. For example, an ontology built for single-lane road crossing considered experience from experts and then optimized the option of drivers [58]. However, few of them consider human users as an important and separate consideration when establishing ontologies. Similar to other concepts in computer science, there is a problem of how to effectively make the techniques practical in a friendly manner to human users [111]. To achieve this, the knowledge pool on ontology must be developed from a human logic perspective. Currently. Most existing ontologies were extracted from project documents directly and missed out on the investigation involving humans [12]. This method may cause the logic of human beings to lack in the ontology and leave the problems to the future ontology users [111]. To solve this problem, an expert system can be used to collect the instances and relationships by providing the knowledge input [58]. The event data from end users may also be considered to be regularly updated to the ontology as an adjustment.

Another reason for this gap is that some of the studies used existing software (e.g. Protégé) that have available user interfaces, while some of the studies were based on original programming software. The outlook of the ontology is also important for users from industry to accept this novel approach [13]. Only a few of the studies discussed these performance scenarios, such as the visualisation function of ontology. Improving these aspects should be considered in future research.

5 Conclusion

This paper contributes to the current knowledge body by providing a systematic review on the state of the art of ontologies in road asset management. First, it investigates and highlights the road asset management areas where ontologies have been implemented. Compared with previous studies which focus on the investigation of ontologies in isolated road asset management areas, such a holistic review can help provide a better picture for the development and use of ontologies in the whole life cycle of road asset management. This paves the way for developing an ontology-based asset management system where information is structured and linked. Second, this work analysed previous studies from the perspective of ontology engineering (which includes ontology modelling, ontology tool, ontology representation, serialization and querying) and the use of ontology in road asset management. Readers can clearly understand how to identify and build the most appropriate ontology in various road asset management stages. Third, this review is also one of the first attempts targeting at various ontology techniques and their implementations in road asset management. The contribution to new knowledge at this level includes the advantages and disadvantages of various ontology techniques which will be useful to identify the most appropriate approach for each road asset management area and life cycle stage.

The results indicate that as an emerging technique, ontology has been implemented in many road asset management fields since 2006. However, most of the research focused on traffic service sand road assets, while other knowledge areas have not been comprehensively studied. In terms of the life-cycle stage, over half of the studies focused on the operation stage of road asset management. From an engineering perspective, the adoption of standard techniques (e.g. RDF and OWL) in ontology has been increasing, and various models and languages have been developed. Among the tools, Protégé is the most frequently used, as it has many functions such as creating, editing, and presenting ontologies. Finally, five main gaps were identified in the review process. The authors suggest that ontology development in road asset management fields should consider automatic mechanisms, multiple techniques, sharing and linking ontologies coordination with other technologies, and considering user-friendliness.

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References

1. Najafi M, Bhattachar DV (2011) Development of a culvert inventory and inspection framework for asset management of road structures. J King Saud Univ Sci 23(3):243–254
2. Zhang S, Boukamp F, Teizer J (2015) Ontology-based semantic modeling of construction safety knowledge: towards automated safety planning for job hazard analysis (JHA). Autom Constr 52:29–41
3. Möller B, Beer M (2008) Engineering computation under uncertainty–capabilities of non-traditional models. Comput Struct 86(10):1024–1041
4. Liu P, Chetal A (2005) Trust-based secure information sharing between federal government agencies. J Am Soc Inf Sci Technol 56(3):283–298
5. Smith B (2012) Ontology. In: Hurtado G, Nudler O (eds) The furniture of the world: essays in ontology and metaphysics. Brill, Leiden, Netherlands. pp 47–68
6. Berners-Lee T, Hendler J, Lassila O (2001) The semantic web. Sci Am 284(5):34–43
7. Ashraf J, Chang E, Hussain OK, Hussain FK (2015) Ontology usage analysis in the ontology lifecycle: a state-of-the-art review. Knowl Based Syst 80(May):34–47
8. Le T, Jeong HD (2016) Interlinking life-cycle data spaces to support decision making in highway asset management. Autom Constr 64:54–64
9. Reddy KR, Veeraragavan A (2011) Application of highway development and management tool in rural road asset management. Transp Res Rec 2204(1):29–34
10. Merdan M, Koppensteiner G, Hegny I, Favre-Bulle B (2008) Application of an ontology in a transport domain. In 2008 IEEE international conference on industrial technology. IEEE
11. Wu C, Wu P, Wang J, Jiang R, Chen M, Wang X (2021) Ontological knowledge base for concrete bridge rehabilitation project management. Autom Constr 121:103428
12. Pauwels P, Zhang S, Lee YC (2017) Semantic web technologies in AEC industry: a literature overview. Autom Constr 73:145–165
13. Yang L, Cormican K, Yu M (2019) Ontology-based systems engineering: a state-of-the-art review. Comput Ind 111:148–171
14. Grubic T, Fan IS (2010) Supply chain ontology: review, analysis and synthesis. Comput Ind 61(8):776–786
15. Ye Y, Yang D, Jiang Z, Tong L (2008) An ontology-based architecture for implementing semantic integration of supply chain management. Int J Comput Integr Manuf 21(1):1–18
16. Corsar D, Markovic M, Edwards P, Nelson JD (2015) The transport disruption ontology. In: International semantic web conference. Springer
17. Berdier C (2011) Road system ontology: Organisation and feedback. In: Falquet G, Métral C, Teller J, Tweed C (eds) Ontologies in urban development projects. Springer, London, pp 211–216
18. Kiritsis D (2013) Semantic technologies for engineering asset life cycle management. Int J Prod Res 51(23–24):7345–7371
19. Jiang R, Wu P (2019) Estimation of environmental impacts of roads through life cycle assessment: a critical review and future directions. Transp Res Part D Transp Environ 77:148–163
20. Freyne J, Coyle L, Smyth B, Cunningham P (2010) Relative status of journal and conference publications in computer science. Commun ACM 53(11):124–132
21. Park JY, Lee DE, Kim BS (2016) A study on analysis of the environmental load impact factors in the planning stage for highway project. KSCE J Civ Eng 20(6):2162–2169
22. Li X, Shen GQ, Wu P, Yue T (2019) Integrating building information modeling and prefabrication housing production. Autom Constr 100:46–60
23. Austroads (2016) Guide to asset management. Australia
24. ISO (2014) 55001: asset management in overview, principles and terminology
25. Ceausu V, Despres S (2006) Case based reasoning to analyze road accidents. Int J Comput Commun Control 1:118–123
26. Hornsby KS, King K (2008) Modeling motion relations for moving objects on road networks. GeoInformatica 12(4):477–495
27. Vallejo D, Albusac J, Jimenez L, Gonzalez C, Moreno J (2009) A cognitive surveillance system for detecting incorrect traffic behaviors. Expert Syst Appl 36(7):10503–10511
28. Zhai J, Chen Y, Yu Y, Liang Y, Jiang J (2009) Fuzzy Semantic retrieval for traffic information based on fuzzy ontology and RDF on the semantic web. J Softw 4(7):758–765
29. Houda M, Khemaja M, Oliveira K, Abed M (2010) A public transportation ontology to support user travel planning. In: 2010 4th international conference on Research Challenges in Information Science (RCIS). IEEE
30. Wang J, Wang X (2011) An ontology-based traffic accident risk mapping framework. In: International symposium on spatial and temporal databases. Springer
31. Barrachina J, Garrido P, Fogue M, Martinez FJ, Cano JC, Calafate CT, Manzoni P (2012) VEACON: a vehicular accident ontology designed to improve safety on the roads. J Netw Comput Appl 35(6):1891–1900
32. Du H, Anand S, Alechina N, Morley J, Hart G, Leibovici D, Jackson M, Ware M (2012) Geospatial information integration for authoritative and crowd sourced road vector data. Trans GIS 16(4):455–476
33. Gregor D, Toral SL, Ariza T, Barrero F (2012) An ontology-based semantic service for cooperative urban equipments. J Netw Comput Appl 35(6):2037–2050
34. Jelokhani-Niaraki MR, Sadeghi-Niaraki A, Kim K (2012) An ontology-based approach for managing spatio-temporal linearly referenced road event data. Road Transp Res J Aust N Z Res Pract 21(4):38–49
35. Malgundkar T, Rao M, Mantha SS (2012) GIS driven urban traffic analysis based on ontology. Int J Manag Inf Technol 4(1):15
36. Stocker M, Rönkkö M, Kolehmainen M (2012) Making sense of sensor data using ontology: a discussion for road vehicle classification
37. Bermejo AJ, Villadangos J, Astrain JJ, Córdoba A (2013) Ontology based road traffic management. In: Intelligent Distributed Computing VI. Springer, pp. 103–108
38. Lécué F, Tallevi-Diotallevi S, Hayes J, Tucker R, Bicer V, Sbodio M, Tommasi P (2014) Smart traffic analytics in the semantic web with STAR-CITY: scenarios, system and lessons learned in Dublin City. J Web Semant 27:26–33
39. Lécué F, Tucker R, Bicer V, Tommasi P, Tallevi-Diotallevi S, Sbodio M (2014) Predicting severity of road traffic congestion using semantic web technologies. In: European semantic web conference. Springer, Cham, pp 611–627

40. Mohammad MA, Kaloskampis I, Hicks Y, Setchi R (2015) Ontology-based framework for risk assessment in road scenes using videos. Proc Comput Sci 60:1532–1541
41. Toulni H, Nsiri B, Boulmalf M, Sadiki T (2015) An ontology based approach to traffic management in urban areas. Int J Syst Appl Eng Dev 9:54–59
42. Watson A, Watson B, Vallmuur K (2015) Estimating under-reporting of road crash injuries to police using multiple linked data collections. Accid Anal Prev 83:18–25
43. Zapater JJS, Escrivá DML, García FRS, Durá JJM (2015) Semantic web service discovery system for road traffic information services. Expert Syst Appl 42(8):3833–3842
44. Zhao L, Ichise R, Yoshikawa T, Naito T, Kakinami T, Sasaki Y (2015) Ontology-based decision making on uncontrolled intersections and narrow roads. In: 2015 IEEE intelligent vehicles symposium (IV). IEEE
45. Gould N, Cheng J (2016) A prototype for ontology driven on-demand mapping of urban traffic accidents
46. Fernandez S, Hadfi R, Ito T, Marsa-Maestre I, Velasco JR (2016) Ontology-based architecture for intelligent transportation systems using a traffic sensor network. Sensors 16(8):1287
47. Consoli S, Presutti V, Recupero DR, Nuzzolese AG, Peroni S, Gangemi A (2017) Producing linked data for smart cities: the case of Catania. Big Data Res 7:1–15
48. Lee K, Lee J, Kwan MP (2017) Location-based service using ontology-based semantic queries: a study with a focus on indoor activities in a university context. Comput Environ Urban Syst 62:41–52
49. Fernandez S, Ito T (2017) Semantic integration of sensor data with SSN ontology in a multi-agent architecture for intelligent transportation systems. IEICE Trans Inf Syst 100(12):2915–2922
50. Czarnecki K (2018) Operational world model ontology for automated driving systems–part 1: road structure. Waterloo Intelligent Systems Engineering Lab (WISE) Report
51. Nguyen TS, Nguyen HK (2019) Fuzzy ontology based model for supporting safe driving. Int J Comput Sci Netw Secur 19(7):111–115
52. Van de Vyvere B, Colpaert P, Mannens E, Verborgh R (2019) Open traffic lights: a strategy for publishing and preserving traffic lights data. In: Companion proceedings of the 2019 World Wide Web Conference
53. Wu T, Qin J, Wan Y (2019) TOST: a topological semantic model for GPS trajectories inside road networks. ISPRS Int J Geo Inf 8(9):410
54. Halfawy MR (2008) Integration of municipal infrastructure asset management processes: challenges and solutions. J Comput Civ Eng 22(3):216–229
55. Hülsen M, Zöllner JM, Weiss C (2011) Traffic intersection situation description ontology for advanced driver assistance. In: 2011 IEEE intelligent vehicles symposium (IV). IEEE
56. Yabuki N, Kikushige Y, Fukuda T (2011) A management system of roadside trees using RFID and ontology. Comput Civ Eng 2011:307–314
57. Zeb J, Froese T, Vanier D (2015). An ontology-supported asset information integrator system in infrastructure management. Built Environ Proj Asset Manag 5(4):380–397
58. Córdoba A, Astrain JJ, Villadangos J, Azpilicueta L, López-Iturri P, Aguirre E, Falcone F (2016) SesToCross: semantic expert system to manage single-lane road crossing. IEEE Trans Intell Transp Syst 18(5):1221–1233
59. Zeb J (2017) An eco asset ontology towards effective eco asset management. Built Environ Proj Asset Manag 7(4):388–399
60. France-Mensah J, O'Brien WJ (2019) A shared ontology for integrated highway planning. Adv Eng Inf 41:100929
61. Lim T, Porras-Alvarado JD, Zhang Z (2019) Pricing of highway infrastructure for transportation asset management. Built environ proj asset manag 9:64–79
62. Kaza N, Hopkins LD (2007) Ontology for land development decisions and plans. In: Teller J, Lee JR, Roussey C (eds) Ontologies for urban development. Springer, Berlin, Heidelberg, Vol 61, pp 47–59
63. Koukias A, Nadoveza D, Kiritsis D (2015) Towards ontology-based modeling of technical documentation and operation data of the engineering asset. In Engineering Asset Management-Systems, Professional Practices and Certification. Springer, Cham, pp 983–994
64. Koukias A, Kiritsis D (2015) Rule-based mechanism to optimize asset management using a technical documentation ontology. IFAC-PapersOnLine 48(3):1001–1006
65. Niestroj M, McMeekin D, Helmholz P, Kuhn M (2018) A proposal to use semantic web technologies for improved road network information exchange. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol 4, pp 147–154
66. Ali F, Kwak D, Khan P, El-Sappagh S, Ali A, Ullah S, Kim KH, Kwak KS (2019) Transportation sentiment analysis using word embedding and ontology-based topic modeling. Knowl Based Syst 174:27–42
67. El-Gohary NM, El-Diraby TE (2010) Domain ontology for processes in infrastructure and construction. J Constr Eng Manag 136(7):730–744
68. Beetz J, Borrmann A (2018) Benefits and limitations of linked data approaches for road modeling and data exchange. In: Workshop of the European Group for Intelligent Computing in Engineering. Springer, Cham, pp 245–261
69. Niestroj MG, McMeekin DA, Helmholz P (2019) Introducing a framework for conflating road network data with semantic web technologies. ISPRS Ann Photogramm Remote Sens Spat Inf Sci IV-2/W5:231–238
70. Thakkar A, Lohiya R (2021) A review on machine learning and deep learning perspectives of IDS for IoT: recent updates, security issues, and challenges. Arch Comput Methods Eng 28(4):3211–3243
71. Das M, Cheng JC, Law KH (2015) An ontology-based web service framework for construction supply chain collaboration and management. Eng Constr Archit Manag 22(5):551–572
72. Bennett CR, De Solminihac H, Chamorro A (2007) Data collection technologies for road management. The World Bank
73. Scheuermann A, Leukel J (2014) Supply chain management ontology from an ontology engineering perspective. Compute Ind 65(6):913–923
74. Svetel I, Pejanovic M (2010) The role of the Semantic Web for knowledge management in the construction industry. Informatica, 34(3):331–337
75. Stephan G, Pascal H, Andreas A (2007) Knowledge representation and ontologies logic, ontologies and semantic web languages. CiteSeerX
76. Baldwin RW (1990) Naming and grouping privileges to simplify security management in large databases. In: IEEE symposium on security and privacy
77. Noy NF, Crubézy M, Fergerson RW, Knublauch H, Tu SW, Vendetti J, Musen MA (2003) Protégé-2000: an open-source ontology-development and knowledge-acquisition environment. In: AMIA... Annual Symposium proceedings. AMIA Symposium
78. Asim MN, Wasim M, Khan MUG, Mahmood W, Abbasi HM (2018) A survey of ontology learning techniques and applications. Database, J Biol Databases Curation 2018:1–24

79. Khondoker MR, Mueller P (2010) Comparing ontology development tools based on an online survey. World Congress on Engineering 2010 (WCE 2010), London, UK
80. Decker S, Melnik S, Van Harmelen F, Fensel D, Klein M, Broekstra J, Erdmann M, Horrocks I (2000) The semantic web: the roles of XML and RDF. IEEE Internet Comput 4(5):63–73
81. Horrocks I, Patel-Schneider PF, Van Harmelen F (2003) From SHIQ and RDF to OWL: the making of a web ontology language. J Web Semant 1(1):7–26
82. Haase P, Broekstra J, Eberhart A, Volz R (2004) A comparison of RDF query languages. In: The semantic web, pp. 502–517
83. McGuinness DL, Van Harmelen F (2004) OWL web ontology language overview. W3C Recomm 10(10):2004
84. W3C (2020) Semantic Web Standard
85. Neumann T, Weikum G (2010) x-RDF-3X: fast querying, high update rates, and consistency for RDF databases. Proc VLDB Endow 3(1–2):256–263
86. Motik B, Horrocks I (2006) Problems with OWL syntax. In: OWLED
87. Saikaew KR, Asawamenakul C, Buranarach M (2014) Design and evaluation of a NoSQL database for storing and querying RDF data. Eng Appl Sci Res 41(4):537–545
88. Hoang HH, Tjoa AM (2006) The state of the art of ontology-based query systems: A comparison of existing approaches. Citeseer
89. Bizer C, Heath T, Berners-Lee T (2011) Linked data: the story so far. In: Semantic services, interoperability and web applications: emerging concepts. IGI global, pp. 205–227
90. Parundekar R, Knoblock CA, Ambite JL (2010) Linking and building ontologies of linked data. In: International semantic web conference. Springer
91. Haghighi PD, Burstein F, Zaslavsky A, Arbon P (2013) Development and evaluation of ontology for intelligent decision support in medical emergency management for mass gatherings. Decis Support Syst 54(2):1192–1204
92. Schram A, Anderson KM (2012) MySQL to NoSQL: data modeling challenges in supporting scalability. In: Proceedings of the 3rd annual conference on systems, programming, and applications: software for humanity
93. Nyulas C, O'connor M, Tu S (2007) DataMaster–a plug-in for importing schemas and data from relational databases into Protege. In 10th international Protégé conference
94. Hu M, Liu Y, Sugumaran V, Liu B, Du J (2019) Automated structural defects diagnosis in underground transportation tunnels using semantic technologies. Autom Constr 107:102929
95. Koukias A, Nadoveza D, Kiritsis D (2015) Towards ontology-based modeling of technical documentation and operation data of the engineering asset. Springer International Publishing, New York
96. Gong F, Ma Y, Gong W, Li X, Li C, Yuan X (2018) Neo4j graph database realizes efficient storage performance of oilfield ontology. PLoS ONE 13(11):e0207595
97. Vicknair C, Macias M, Zhao Z, Nan X, Chen Y, Wilkins D (2010) A comparison of a graph database and a relational database: a data provenance perspective. In: Proceedings of the 48th annual Southeast regional conference. ACM
98. Gennari JH, Musen MA, Fergerson RW, Grosso WE, Crubézy M, Eriksson H, Noy NF, Tu SW (2003) The evolution of Protégé: an environment for knowledge-based systems development. Int J Human Comput Stud 58(1):89–123
99. Das S, Srinivasan J, Perry M, Chong EI, Banerjee J (2014) A tale of two graphs: property graphs as RDF in oracle. In: EDBT
100. De Abreu D, Flores A, Palma G, Pestana V, Pinero J, Queipo J, Sánchez J, Vidal ME (2013) Choosing between graph databases and RDF engines for consuming and mining linked data. In: Cold. Citeseer
101. Bizer C (2009) The emerging web of linked data. IEEE Intell Syst 24(5):87–92
102. Carbon S, Ireland A, Mungall CJ, Shu S, Marshall B, Lewis S, Hub A, Web Presence Working Group (2009) AmiGO: online access to ontology and annotation data. Bioinformatics 25(2):288–289
103. Zaveri A, Rula A, Maurino A, Pietrobon R, Lehmann J, Auer S, Hitzler P (2013) Quality assessment methodologies for linked open data. Submitted Semant Web J 15:16
104. Lom M, Pribyl O, Svitek M (2016) Industry 4.0 as a part of smart cities. In: 2016 Smart Cities Symposium Prague (SCSP). IEEE
105. Zhang WY, Yin JW (2008) Exploring semantic web technologies for ontology-based modeling in collaborative engineering design. Int J Adv Manuf Technol 36(9–10):833–843
106. Angjeliu G, Coronelli D, Cardani G (2020) Development of the simulation model for digital twin applications in historical masonry buildings: the integration between numerical and experimental reality. Comput Struct 238:106282
107. Zhu J, Wang X, Wang P, Wu Z, Kim MJ (2019) Integration of BIM and GIS: geometry from IFC to shapefile using open-source technology. Autom Constr 102:105–119
108. Karimi S, Iordanova I (2021) Integration of BIM and GIS for construction automation, a systematic literature review (SLR) combining bibliometric and qualitative analysis. Arch Comput Methods Eng. https://doi.org/10.1007/s11831-021-09545-2
109. Niknam M, Karshenas S (2017) A shared ontology approach to semantic representation of BIM data. Autom Constr 80:22–36
110. Chi HL, Wang X, Jiao Y (2015) BIM-enabled structural design: impacts and future developments in structural modelling, analysis and optimisation processes. Arch Comput Methods Eng 22(1):135–151
111. Darejeh A, Singh D (2013) A review on user interface design principles to increase software usability for users with less computer literacy. J Comput Sci 9(11):1443

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