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Review

Trends in built environment semantic Web applications: Where are we today?

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ABSTRACT

The built environment sector impacts significantly on communities. At the same time, it is the sector with the highest cost and environmental saving potentials provided effective strategies are implemented. The emerging Semantic Web promises new opportunities for efficient management of information and knowledge about various domains. While other domains, particularly bioinformatics have fully embraced the Semantic Web, knowledge about how the same has been applied to the built environment is sketchy. This study investigates the development and trend of Semantic Web applications in the built environment. Understanding the different applications of the Semantic Web is essential for evaluation, improvement and opening of new research. A review of over 120 refereed articles on built environment Semantic Web applications has been conducted. A classification of the different Semantic Web applications in relation to their year of application is presented to highlight the trend. Two major findings have emerged. Firstly, despite limited research about easy-to-use applications, progress is being made from often too-common ontological concepts to more innovative concepts such as Linked Data. Secondly, a shift from traditional construction applications to Semantic Web sustainable construction applications is gradually emerging. To conclude, research challenges, potential future development and research directions have been discussed.

1. Background

Addressing the challenges posed by the impacts of climate change is amongst the top most priorities on the agenda of most governments. A growing body of knowledge clearly depicts an interwoven complex relation between the built environment and climate change (Stern, 2006; Ürge-Vorsatz, Harvey, Mirasgedis, & Levine, 2007). Although statistics from different studies tend to vary, they often depict a general trend; that greenhouse gases (GHGs) from the built environment have significant negative impacts on communities. Furthermore, the built environment consumes a huge amount of natural resources. Buildings are responsible for 33% of worldwide energy-related GHG emissions (Robert & Kummert, 2012; Ürge-Vorsatz et al., 2007). Coincidentally, while the built environment sheer of impacts to the environment is so huge, it has been identified as a sector where huge savings can be made. For example, of the 40% of energy consumed by buildings in the European Union (EU), estimates reveal that the implementation of energy-efficiency measures could lead to cost-saving of around 28% (Ekins & Lees, 2008). Thus, the built environment is arguably a sector that can play an important role in mitigating climate change impacts, reducing energy use and natural resources (Nik, Kalagasidis, & Kjellström, 2012; Robert & Kummert, 2012). Recent advances in the development and use of Computers and Communication and Information Technology (CIT) have opened up new opportunities to acquire and share information and knowledge about various domains. The acquisition and sharing of knowledge about different aspects of the built environment and relationship with climate change impacts can potentially improve decision-making in built environment related projects and activities. The Semantic Web technology is an emerging CIT domain that can facilitate and contribute in sharing information about different domains. Its importance has widely been acknowledged and applied in many other areas including telecommunication, bioinformatics, medicine, pharmacology, etc.

However, knowledge about the trends on the applicability of the Semantic Web in managing knowledge about these afore-mentioned and related domains is limited. In fact very few studies exist about how the Semantic Web technologies are being applied. From a wider perspective, recent studies in this direction include the following:

- A study on the applicability assessment of Semantic Web technologies (Janev & Vraneš, 2011). This study surveyed and recommended an emerging World Wide Web Consortium (W3C)

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standards, presenting an overview of the state-of-the-art in the Semantic Web research in the European Union, analysed the W3C collection of case studies and use cases and discussed the extent of adoption of Semantic Web technologies;
- A review study on the ontology query expansion approaches (Bhogal, Macfarlane, & Smith, 2007);
- A study that presented the state-of-the-art of enabling wireless Web services that can be used to deliver intelligent wireless support to mobile construction (Aziz, Anumba, Ruikar, Carrillo, & Bouchlaghem, 2005);
- A review on the application of ontologies in organisational learning (Valaski, Malucelli, & Reinehr, 2012);
- A study on the applicability of Semantic Web technologies to the evolution of social network (Zhou, Ding, & Finin, 2011). In this study, social networks were extracted from within the Friend of a Friend (FOAF) documents.

While some few studies about trends of Semantic Web applications exists (Aziz et al., 2005; Bhogal et al., 2007; Janev & Vraneš, 2011; Valaski et al., 2012; Zhou et al., 2011), no such studies depicting trends exist in the built environment domain. Although the above examples are not representative, concerns by researchers with regards to evolution and maturity of the Semantic Web technology applications is now beginning to emerge. This constituted the rationale of the "Ontologies Comes of Age in the Semantic Web" (OCAS) Conference in 2011, where Semantic Web researchers gathered to explore how the Semantic Web can be used to facilitate end-users requirements vis-à-vis the application of Semantic Web to different domains (OCAS, 2011). Furthermore, the conference focussed on investigating how Semantic Web has been applied to other domains.

The aim of this study is to take a stock of the different aspect of the Semantic Web that has been applied in the management of built environment information. By exploring and exploiting Semantic Web technologies, built environment information systems can be developed that can be used to make informed decisions about energy use, greenhouse gases, water and other built environment resources. In particular, such decisions as argued in Watson and Boudreau (2011) can lead to less energy consumption. The modified Watson and Boudreau (2011) equation highlighting the impact of effective use of information on resources is presented in Eq. (1).

$$Built\ Environment + Information < \begin{cases} Energy \\ Greenhouse\ gases \\ Water \\ Poorhealth \end{cases} \tag{1}$$

The underlying idea is that better decisions about how to both use and conserve resources through the use of information can lead to effective management of the variables in the right of Eq. (1).

To facilitate understanding, four main challenges that were overcome for the study to be feasible will be discussed. Firstly, with such a wide domain as the built environment it was not so straight forward to distinguish between built environment and non-built environment aspects. It was imperative to provide a working and guiding definition of what constitutes the built environment. The built environment is such a wide complex domain that has often received various complimentary, confusing and/or contradictory definitions. It is not the goal of this paper to venture into these debates. However, within the scope of this study, the definition by Ekins and Lees (2008) suffices and will be used. It states that "the built environment consists of buildings, and a network of interlocking infrastructures for energy supply (and sometimes generation), water and sewage, telecommunications, transport and waste water management". Secondly, it was difficult to pin down which Semantic Web technology has been applied in the development of particular applications in the built environment domain. This is because in most applications, an integrated number of Semantic Web technologies are often used. However, in order to overcome this challenge, we considered the major technologies discussed in the particular peer-reviewed literature in question. Thirdly, ambiguity of terminology was another major challenge. For example, project management used in Ruiz-Bertol, Rodríguez, and Dolado (2011) does not imply building construction project management. Whereas Dong et al. (2007) specifically talk of construction project management. Thus, the former was not considered in this study while the later was considered. Fourthly, in some of the peer-reviewed literature, the particular aspect of the built environment was vague, not explicitly stated or if stated, it was generic in nature. For example, some papers referred to a Semantic Web application in construction project management domain, without specifically stating whether it was/is cost planning or any other aspect of construction project management.

2. An overview of semantic Web technologies

As of today, it is increasing apparent many different Semantic Web technologies have been developed, up to the extent that some researchers have started questioning the rationale for continuous development rather than demonstrating their applicability or improving their implementation and/or efficiency. Thus, no wonder research about trends of Semantic Web technologies has now started to emerge (Aziz et al., 2005; Bhogal et al., 2007; Janev & Vraneš, 2011; Valaski et al., 2012; Zhou et al., 2011). This study will not duplicate previous studies about the evolution of Semantic Web. However, to facilitate understanding, only core Semantic Web concepts will be reviewed.

2.1. Ontologies

Although the current Web has been successful in disseminating information to a wider public, its shortcomings have been widely acknowledged in the literature (Mika, 2007; Yu, 2007). One of the weaknesses is rooted in its Hypertext Markup Language (HTML) syntax-based information representation, only suitable for human consumption. On the other hand, key to the Semantic Web is the concept of ontology, a knowledge structure used to formally represent and share domain knowledge through the modelling and creation of a framework of relevant concepts and the semantic relationships between the concepts (Bodenreider & Stevens, 2006). Semantic Web ontology-based knowledge representation differs from the current Web in that domain knowledge is modelled in a machine-readable format which can be consumed by humans and machines. This is a major advantage as this can facilitate data annotation (Rajput & Haider, 2011), decision support (Abanda, Tah, & Duce, 2013; Jung, 2011; Tah & Abanda, 2011), data interoperability (García-Castro & Gómez-Pérez, 2010), information retrieval and natural language processing (Rajput & Haider, 2011). Thus, ontologies constitute an indispensable integral component of the Semantic Web. For ontologies to serve efficiently as a support for the Semantic Web, i.e., in enhancing data annotation and interoperability, information retrieval and natural language processing, they need to be defined using standard languages. The specification of ontologies using standard languages also contributes in minimising ambiguities in the definition of terminologies using ontologies. These languages are often called "open standard languages".

2.2. Open standards

In order to maximize consensus about the development of Semantic Web applications, set of W3C is often involved in developing and recommending a set of guidelines or specifications for data interchange on the Web. Because these specifications are often free, there are called "open standards". The main standards in the Semantic Web are resource description framework (RDF) and SPARQL Protocol and RDF Query Language (SPARQL). RDF is a standard model for data interchange on the Web. SPARQL is a W3C specification and a query language for RDF.

2.3. Ontology languages

The early languages are Extensible Markup Language (XML) syntax based such as Ontology Exchange Language (XOL), Ontology Markup Language (OML), *Simple HTML*, *Ontology Extensions* (SHOE), Ontology Inference Layer (OIL) and Darpa Agent Markup Language + OIL (DAML + OIL). The latest ontology language is the Web Ontology Language (OWL). OWL dialects are ontological languages used for the specification of classes, properties and related restrictions. OWL is designed for use by applications that need to process the content of information instead of just presenting to humans.

2.4. Semantic Web Rule Language (SWRL) and Semantic Query-Enhanced Web Rule Language (SQWRL)

SWRL is a proposal for a Semantic Web rule language, combining sublanguages of the OWL Web Ontology Language (OWL DL and Lite) with those of the Rule Markup Language (Unary/Binary Datalog) (Horrocks et al., 2004). SQWRL (pronounced squirrel) is a SWRL-based language for querying OWL ontologies. It provides SQL-like operations to retrieve knowledge from OWL.

2.5. Semantic Web services

The W3C defines a "Web service" as "a software system designed to support interoperable machine-to-machine interaction over a network". It has an interface described in a machine-processable format known as Web Services Description Language (WSDL). WSDL is an XML format for describing network services as a set of endpoints operating on messages containing either document-oriented or procedure-oriented information.

2.6. Linked data

Linked Data refers to a style of publishing and linking structured data on the Web (Berners-Lee et al., 2006). The fundamental idea that underpins Linked Data is that, value and usefulness of data are maximised when interlinked or mashed up with other datasets. Thus, unlike HTML pages for the traditional Web, data sources are required for the Semantic Web. In this regard, in 2006, the Semantic Web Education and Outreach (SWEO) Interest Group was set-up by W3C to educate the Web community, develop strategies and materials to increase awareness of the need and benefit for the Semantic Web (SWEO, 2006). Some of the best institutions currently undertaking Linked Data activities include the World Bank, the United Nations, Renewable Energy & Energy Efficiency Partnership (REEP), the New York Times, the Guardian, Open Knowledge Foundation.

Other than pure core Semantic Web technologies examined in the preceding sections, there are other technologies that have emerged and being used with the Semantic Web for mutual enhancement of domain knowledge management. These include domain dictionaries/specialised taxonomies and building information modelling (BIM).

2.7. Domain dictionaries and specialised taxonomies

In the construction industry, the challenge of managing construction information is not new. In order to address this challenge, many standard domain dictionaries and specialised taxonomies have emerged. Some include: a glossary of building and civil engineering terms (BS6100) developed by the British Standards Institution; bcXML, an XML vocabulary developed by eConstruct Information Society Technologies (IST) project for the construction industry; Industry Foundation Classess (IFC) developed by buildingSMART; OmniClass classification system; BARBi (Norwegian Building and Construction and Reference Data); UniClass and COnsistent knowledGe maNagement across prOjects and between enterpriSes in the construction domain (e-COGNOS). In the literature, diverse opinions exist as to which of these are real ontologies. While IFC and bcXML are considered implicit ontologies (Yang & Zhang, 2006), e-COGNOS is undoubtedly a construction project ontology (Lima, El-Diraby, Fiès, Zarli, & Ferneley, 2003).

3. Applications of semantic Web technologies to the built environment

Having explored Semantic Web concepts in Section 2, this section goes a step further to investigate how Semantic Web technologies have been experimented or employed in built environment domain. To facilitate understanding, we have tailored our discussions along the following categories: Semantic Web applications in traditional construction practices, Semantic Web applications in sustainability or sustainable construction, Semantic Web applications and BIM, Semantic Web applications and carbon/energy management. To gain insights and easily appreciate the applications of Semantic Web technologies in these categories, a brief summary is provided. This discussion will serve as the basis to develop a recapitulative table that will summarise all the different applications gained from the literature. The applications will be listed according to their year of publications. This categorisation reflects changes in the Semantic Web technology and the particular area of the built environment research area between the years 2000 and 2013. We chose the year 2000 as our starting point to slightly include 2001, the year the term Semantic web was first used by Sir Tim Berners-Lee (Berners-Lee, Hendler, & Lassila, 2001). In total, over 120 peer-reviewed articles were reviewed.

3.1. Semantic Web applications and traditional construction

In the construction domain, the Semantic Web has been employed in the field of construction education, supply chain, project and construction management, material storage, project design, architecture and graphic designs, etc.

In the field of construction education, repositories have been developed in managing objects as well as metadata using ontologies that offer a set of services such as storing, retrieving and searching of learning objects using Semantic Web technologies (Ahmed, Pathmeswaran, & Aouad, 2007; Argüello, El-Hasia, & Lees, 2006a, 2006b; Pathmeswaran & Ahmed, 2009). In the domain of supply chain management, great use of semantic repositories about information from different partners on common or different projects has been undertaken (Zou & Seo, 2006). In construction and project management Semantic Web repositories have been developed to enhance interoperability over computer systems to facilitate different companies'construction projects' information (Aziz, Anumba, Ruikar, Carrillo, & Bouchlaghem, 2004; Cheng, Buchheit, Garrettt, & McNeil, 2005; El-Diraby, Lima, & Feis, 2005; Owolabi, Anumba, El-Hmalawi, & Harper, 2006; Ruikar, Anumba, Duke, Carrillo, & Bouchlaghem, 2007; Shelbourn et al., 2006). In project design, information generated from the pre-planning stage can be processed and retained in the format which all the project participants can share. This has been achieved using object-oriented attributes and meta-data in BIM and implemented in OWL ontologies (Lee, Lee, Min, Kim, & Kim, 2008). Lima et al. (2003), Lima, El-Diraby, and Stephens (2005) and Wetherill, Rezgui, Lima, and Zarli (2002) have proposed a high level generic ontology (e-COGNOS project) for interoperation between the knowledge bases of construction enterprises. El-Diraby and Kashif (2005) investigated the use of distributed ontology architecture for knowledge management in highway construction. This architecture linked utility to highway geometry and served as a base for a cross-discipline knowledge exchange in the infrastructure domain. It was developed as an extension for the e-COGNOS ontology. Teller, Keita, Roussey, and Laurini (2005) have investigated how ontologies work in practice to inform the development of future ontologies and conceptual tools that will make communication between urban development disciplines easier. In Beetz, van Leeuwen, and de Vries (2009), an OWL ontology called ifcOWL was derived from the EXPRESS schema of the IFC version 2×2. The IFC data model is a neutral and open specification, an object-oriented file format with a data model developed by buildingSMART (International Alliance for Interoperability (IAI)) to facilitate interoperability in the building industry, and is a commonly used format for BIM. EXPRESS is a standard data modeling language for product data (Beetz et al., 2009). Another IFC compliant information model is CityGML (Kolbe, Gröger, & Plümer, 2005). While the IFC model describes project information such as building elements, geometry and material properties, costs, schedules, and organizations (Cerovsek, 2010; Wang, Song, Hamilton, & Curwell, 2007), CityGML defines the geometry, topologies, appearance, and semantics of urban objects including buildings for modeling and exchanging virtual 3D city models to support such applications as urban planning and simulation, facility management, and disaster management (Kolbe et al., 2005). Although IFC and CityGML both model information about buildings, they differ in the richness of their data content. While CityGML represents objects information at the scale of a city, the IFC model represents object information at the building level with great amount of detail and richness.

3.2. Semantic Web and sustainable building construction

Semantic Web applications were noted in the areas of environmental education, carbon and energy management, renewable energy, building energy efficiency, etc. Macris and Georgakellos (2006) explored the use of ontologies to help students to understand the contemporary global environmental issues, how they are linked and interrelated and to consider the different views of these issues, before reaching a decision or judgment. Edum-Fotwe and Price (2009), on the other hand, explored the use of ontologies in appraising sustainability of construction projects and development from the social component of sustainable development. It emerged that there is abundance of green/sustainability specifications/standards/ratings/metrics in the literature dealing with various aspects of sustainable constructions. Some examples of these specifications are databases that contains the different building household appliances in the UK houses arranged in a well-defined taxonomy (Firth, Lomas, Wright, & Wall, 2008; Wood & Newborough, 2007), the Green Guide to Specifications (Anderson & Shiers, 2009), the Uniclass (Smith et al., 1997) and the Leadership in Energy & Environmental Design. The Green Guide aims to provide a simple green guide to the environmental impacts of building materials which is easy-to-use and soundly based on numerical data. Uniclass is a recent classification scheme for the construction industry (Smith et al., 1997). It is intended for organising library materials and for structuring product literature and project information. It incorporates both CAWS (Common Arrangement of Work Sections for building works) and EPIC (Electronic Product Information Co-operation), a new system for structuring product data and product literature. The Green Guide is part of BREEAM (BRE Environmental Assessment Method) an accredited environmental rating scheme for buildings. LEED is an internationally recognized green building certification system developed by the United States (US) Green Building Council, providing third-party verification that a building or community was designed and built using strategies intended to improve performance in metrics such as energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts. As these specifications have been developed by different individuals or agencies they tend to overlap, and often it is difficult to establish the detailed content of a specification and the challenges they address. Of recent there have been discussions in the research community on how to find ways of harmonising these specifications through the use of software to facilitate interoperability. Currently the "Green-Sustainability Specifications Knowledge base" is developing Web-based front-end based on ontologies developed in XML, RDF, and OWL. The Green-Sustainability Specifications knowledge base will aim to contain all known regulations and standards in green and sustainability space.

There are also indication of Semantic Web technologies being applied in managing carbon and energy information. A classic example is SEMANCO (e.g., semantic tool for carbon reduction in urban planning. The purpose of SEMANCO is to provide semantic tools to different stakeholders involved in urban planning to enhance end-users ability to make informed decisions about how to reduce CO_2 in their cities (Madrazo, Sicilia, & Gamboa, 2012). To improve efficiency, accuracy and speed, emerging BIM software packages have often been used in assessing the afore-mentioned aspects of sustainable construction. In the ensuing section, the relationship between Semantic Web applications and BIM will be examined.

3.3. Semantic Web applications and BIM

Although not a Semantic Web technology, BIM has recently gained popularity in the construction industry. Perhaps, because of the common vision of facilitating interoperability of both BIM and the Semantic Web, it is not uncommon to find some studies integrating ontologies with BIMs (Langroodi & Staub-French, 2012; Lucas, Bulbul, & Thabet, 2011; Venugopal, Eastman, & Teizer, 2012; Zhang & Issa, 2011; Abanda, Zhou, Tah, & Cheung, 2013).

In the preceding sections, an overview of Semantic Web applications in the built environment has been examined. To facilitate understanding, in addition to these, others have been presented in Table 1.

4. Discussions, conclusion and further research

In this section a discussion and an appraisal of what has been undertaken in this paper will be examined. Firstly, an appraisal from the Semantic Web applications' perspectives will be examined. In the ontology community ontologies are classified in two categories, lightweight and heavyweight ontologies. More meaning can be made from heavyweight ontologies than lightweight ontologies. From the review of Semantic Web applications, it emerged that some of the ontologies are lightweight and cannot be exploited in sophisticated reasoning. However, over the years it

Table 1
Built environment semantic Web applications.

Sources	Semantic Web technology	Built environment	Description
2000–2004			
Cheng, Trivedi, and Law (2002)	ifcXML	Scheduling	This paper addresses information exchange problem by building translators among process specification language, ifcXML and aecXML in the project scheduling domain. An ontology mapping among process specification language (PSL), ifcXML and aecXML, and their expressive power compared
Cheng, Kumar, and Law (2002)	ifcXML	Construction Project Management	In this paper, ifcXML is adopted as the knowledge representation format. Based on this format, a prototype system has been built and tested to illustrate its usefulness for project management applications
Cheng and Law (2002)	Ontology	Scheduling, resource and cost management	This paper presents a process specification language for managing construction project scheduling information, resource and cost information
Staub-French, Fischer, Kunz, Paulson, and Ishii (2002), Staub-French, Fischer, Kunz, Ishii, and Paulson (2003)	Ontology	Building cost estimation	In this paper, an ontology that represents the features of building product models. The ontology is important to estimators for understanding how the building features affect the activities, resources, and resource productivity rates in construction costs' calculations
Cheng, Law, and Kumar (2003)	Web services	Construction Project Management	Specifically, information modeling for project management applications and communication mechanisms are examined. Process Specification Language (PSL) is employed as the information modeling language
Aziz et al. (2004)	Semantic Web services	Project management Focus on project collaboration	The synergy between the Semantic Web, Web Services and agent technologies is used to provide mobile collaboration between partners on construction projects
Pan, Anumba, and Ren (2004)	Semantic Web	Construction Project Management	This paper reviews the key concepts, functions and applications of the Semantic Web, and discusses how it improves the performance of construction information management and its potential applications in design, procurement, communication, change and claim Management, and the benefits of applications
Gu, Wang, and Zhang (2004)	Ontology	Smart homes	In this paper, a formal context model based on ontology using OWL to address issues including semantic context representation, context reasoning and knowledge sharing, context classification, context dependency and quality of context in context-aware home has been proposed
2005–2008			
El-Diraby and Kashif (2005)	Ontology	Higher construction	In this paper, a proposed ontology architecture models highway concepts into six major concepts including project, process, product, actor, resources and technical topics (attributes and constraints) has been examined
Aziz et al. (2005)	Web services	Mobile construction	This paper presents a state-of-the-art review of the enabling technologies and discusses how, by exploiting the convergence and synergy between different technologies, it is possible to deliver intelligent wireless Web support to mobile construction workers
Schevers and Drogemuller (2005)	Ontology	BIM	This study exploits the deficiencies (i.e., loss of IFC data) that exist in the conversion of IFC to OWL to develop a prototype system through reengineering the building model to gain more advantages of functionality offered by OWL
El-Diraby and Briceno (2005)	Ontology	Construction infrastructure	This paper presents a taxonomy for outside plant construction. It includes a description of related processes, actors, products, resources, and technical concepts. The taxonomy was developed as an extension of the e-COGNOS taxonomy. Relevant terms from inside plant construction were also included in the taxonomy
El-Diraby et al. (2005)	Ontology	Project management	This paper proposed an ontology that classifies construction concepts into project, process, product, actor, resource and technical topics and was used to support a Web-based portal for knowledge management of the e-COGNOS project
Lima, El-Diraby, and Stephens (2005)	Ontology	Construction Knowledge management	This paper presents the e-COGNOS platform, the first comprehensive ontology-based portal for knowledge management in the construction domain
Yang and Zhang (2006)	Ontology	Project management with focus on project collaboration	This paper proposes an ontology that is employed alongside object-based CAD representations and AEC interoperability standards to enable semantic interoperability in building designs
Argüello et al. (2006a)	Ontology	Construction Knowledge Exchange	This study employs a construction domain case study to compare the performance of a traditional Web portal using a keyword-based search engine and a Semantic Web portal using an ontology-based search engine
Argüello et al. (2006b), Argüello, Lees, and Ong (2006)	Ontology	Construction Knowledge Exchange	This study developed a construction knowledge exchange Semantic Web portal that can potentially help promote innovation and best practice throughout the construction industry, with the aim of developing a strong network of organisations able to share knowledge at different levels

(*continued on next page*)

Table 1 (*continued*)

Sources	Semantic Web technology	Built environment	Description
El-Diraby and Gill (2006)	Ontology	Project risk management	The taxonomy models the concepts of privatized-infrastructure finance into six main domains: processes, products, projects, actors, resources and technical topics (technical details and basic concepts). It is an extension of e-COGNOS ontology
Beetz, van Leeuwen, and Bauke de Vries (2006)	Ontology	Urban designs	In this paper, a demonstration of how to infer spatial relations of a geometry-centred building model instance exported from standard packages. The proposed approach can be used in various scenarios where translation between different representations and mappings of other information are necessary
Yurchyshyna, Faron-Zucker, Le Thanh, Lima, and Zarli (2007)	Ontology	Construction project management	This paper proposes an overview of a formal ontological approach of conformance models for regulations in construction aiming at answering the research question: "is an IFC-represented building project compliant to a set of construction rules?" The study analyses three key subtasks: (i) transformation of the IFC of the construction project; (ii) regulations formalisation; (iii) conformance checking reasoning. While analysing the IFC model redundancy and/or insufficiency for conformance checking reasoning, an intermediate RDF-based model, semantically enriched and regulation-oriented has been suggested
Schevers, Trinidad, and Drogemuller (2006)	Ontology	Urban planning	In this study, a proof of concept implementation has been undertaken to demonstrate and validate the usefulness of machine interpretable ontologies for urban designs
Ruikar et al. (2007)	Ontology	Project information	This study explores the use of the Semantic Web to support project information management
Ahmed, Shaik, and Aouad (2006)	Ontology	Construction e-learning	This paper gives an overview of the development of e-learning in construction, highlighting the key pedagogical and technical concepts and enablers to Semantic Web technology
Schevers et al. (2007)	Ontology	Facility management	In this paper an ontology was developed and used as a proof-of-concept prototype to demonstrate the usability of IFC information to collaborate with Sydney Opera House's specific data sources
Ricquebourg et al. (2007)	Ontology/ SWRL rules	Smart homes	This study proposed to build a smart environment based on OWL ontology and inference layer on SWRL rules that takes into account the ambient context of its inhabitants, providing contextually-aware services
Aksamija and Grobler (2007)	Ontology	Building design	In this paper, an architectural ontology is proposed that can be used in software applications for automated design, where design parameters are prescribed. In that sense, information about site, physical systems, building orientation, materials and other constraints can be prescribed by the user
Cruz, Marzani, and Boochs (2007)	Ontology	Architecture	This paper presents an ontology-driven 3D architectural reconstruction approach based on the survey with a 3D scanner. This solution is powerful in the field of civil engineering projects to save time during the cost process estimation
Kim and Grobler (2007)	Ontology	Project management	This research developed a light-weight ontology knowledge representation of a building for automatic reasoning about the conceptual design process
Kaza and Hopkins (2007)	Ontology	Urban planning	This study developed an ontology of actors, decision situations and plans that make up institutional structure of a city
Lacasta et al. (2007)	Ontology	Urban planning	This paper analyzes how lexical ontologies covering different areas of knowledge can be merged to generate an enriched urban terminology
Vanlande and Nicolle (2007)	Ontology, RDF, OWL, SWRL	Facility management	In this paper framework based on Semantic Web technologies: RDF, OWL, SWRL and named graph has been developed. This framework, called C-DMF, allows facilities manager to organize all knowledge generating during building lifecycle in end-user contextual graphs
Elghamrawy and Boukamp (2008)	Ontology	Project management focus on Construction site problem management	In this paper, a construction problem framework made up of ontologies which contain semantic description of products, processes, resources and unplanned situations and their relationships is examined
Lee, Wang, and Chen (2008)	Ontology	Project planning	This study presents an ontology-based intelligent estimation agent system for managing total project cost
Lee et al. (2008)	Ontology	Project planning	The ontology knowledge-based system models space objects that can be controlled by computing in BIM-based construction project
Islam and Piasecki (2008)	Ontology	Hydrodynamic processes	In this study, the concepts necessary to design and develop a web based simulation (WBS) for the simulation of hydrodynamic processes using legacy (FORTRAN) code are introduced. A formal specification of the simulation ontology has been developed that is the underlying concept to share, retrieve, and move the simulation data between the different components of the WBS
Anumba, Issa, Pan, and Mutis (2008a)	Ontology	Construction project management	The purpose of this paper is to explore the role of ontologies in the construction project delivery process, particularly with respect to information and knowledge management
Anumba et al. (2008b)	Ontology	Construction project management	This paper explores trends in collaborative design and construction, and presents an ontology-based approach to project information management in a Semantic Web environment

Table 1 (*continued*)

Sources	Semantic Web technology	Built environment	Description
Vanlande, Cruz, and Nicolle (2008)	Ontology	AEC/Facility management	In this paper an ontology-based collaborative platform called Active3D has been developed. This platform can be used to support data exchange and data repository in the AEC sector
Yurchyshyna et al. (2008a, 2008b)	Ontology	Construction code compliance	This article presents a semi-automatic ontology model for building codes compliance checking of construction projects
Mauher and Smokvina (2008)	Ontology	Property management	This study presents an ontology-based integrated municipal asset and property management for the Web collaborative environment that serves as a framework for transition from decentralized to distributional municipal asset and property management
Trausan-Matu and Neacsu (2008)	Ontology	Urban and civil engineering	The paper presents a prototype of an intelligent ontology-based information system for urban and civil engineering
Meshkova, Riihijärvi, Mähönen, and Kavadias (2008)	Ontology	Smart home	In this paper, an ontology-enabled knowledge-base for home networks, that provides the ability to depict complex relations between devices and services working in a home environment is examined
Lepczyk, Lortie, and Anderson (2008)	Ontology	Landscape	In this paper, an ontology, has been used to define landscape. This ontology can serve as both a checklist for landscape studies and a blueprint for additional ecological ontologies
2009–2013			
Pathmeswaran and Ahmed (2009)	Ontology	Construction education	This study discusses SWmLOR ontology system, integrated within the online learning object repository to facilitate the discovery of learning construction objects by various search engines and applications
Lannon and Linovski (2009)	Ontology	Urban design	This paper examines the opportunities for integrating ontological systems into the research process for urban designers and researchers. Using the case study of urban energy efficiency modeling, the possible benefits and limitations are discussed.
Kumazawa, Saito, Kozaki, Matsui, and Mizoguchi (2009)	Ontology	Sustainability science	This paper addresses the key challenges associated with knowledge structuring in sustainability science, identifies the requirements for the structuring of knowledge, proposes a reference model, and develops an ontology-based mapping tool as a solution to one layer of the reference model
Edum-Fotwe and Price (2009)	Ontology	Sustainability appraisal	This paper proposes an ontology that can be combined with environmental and economic aspects of construction projects to assist developers and other stakeholders gain a more comprehensive view of sustainable issues in construction and urban developments
Belhadef and Kholladi (2009)	Ontology	Urban planning	This study presents an urban ontology for a publicity panel's management system implanted along roads and public ways
Tserng et al. (2009)	Ontology	Construction project risk management	In this paper, an ontology-based risk management framework that can enhance risk management performance of construction projects through the improvement of risk management workflow and knowledge re-use has been proposed
Elghamrawy, Boukamp, and Kim (2009)	Ontology	Project management	This paper presents a semi-automatic framework prototype for storing and retrieving on-site construction problem information using context information. Created problem records are indexed with context concepts taken from developed OWL
Yurchyshyna and Zarli (2009)	Ontology	Conformance checking in construction	This paper presents an ontology model that automates the checking whether a construction project satisfies a set of conformance constraints and thus deduces its conformance to building codes
Gursel, Sariyildiz, Akin, and Stouffs (2009)	Ontology	Building performance	This study develops an integral reference ontology-based model, CLIP (Computational support for Lifecycle Integral Performance assessment), that aims to improve the efficiency and quality of existing performance assessment practices of building life cycles
Xu et al. (2009)	Ontology	Building energy efficiency	This study examines an ontology-based framework to facilitate the automatic composition of appropriate applications
Kim and Grobler (2009)	Ontology and BIM	Construction project management	This paper reports on research of utilizing ontological consistency checking in the design process for identifying potential conflicts and improving coordination and communication
Métral, Falquet, and Cutting-Decelle (2009)	Ontology	Urban models	In this paper, the description and role of ontology-based approaches, considered as a powerful tool to improve the interoperability of the different types of urban models have been examined
Katranuschkov, Rybenko, and Scherer (2009)	Ontology	Building defect management	This paper presents a domain-specific level ontology that can be used in the area of defect management which, due to the thousands of defects that have to be handled in parallel and the large number of unpredictable situations, have to be dealt with in a project
Li, Rezgui, Miles, and Wilson (2010)	Ontology	Greenhouse gases	The paper describes a methodology used to develop ontology for low carbon domain, taking into account the wealth of existing semantic resources in the construction sector
Rizzolia et al. (2010)	Ontology/ Web services	Environment	This study presents TaToo, a project which aims at providing a collaborative platform for the semantic enrichment of environmental resources on the Web

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Table 1 (*continued*)

Sources	Semantic Web technology	Built environment	Description
Kumar, Tomic, Pellegrini, Fensel, and Mayrhofer (2010)	Ontology	Building energy efficiency	In this study, user-created policies have been applied to develop an ontology-based system that supports a user in gaining awareness about energy consumption habits and saving potentials
Tomic, Fensel, and Pellegrini (2010)	Ontology	Building energy efficiency	In this paper, the project Sesame has been examined. It uses semantic modelling and reasoning to support home owners and building managers in saving energy and in optimizing their energy costs while maintaining their preferred quality of living
Zhang, Di, and Liang (2010)	Ontology	Structural engineering	In this paper, a structural engineering knowledge management system which consists of a concept model structural engineering domain ontology and rule base structural engineering rule base, and provide the uniform experiment information representation in the structural engineering field has been examined
Wicaksono, Rogalski, and Kusnady (2010)	Ontology and SWRL rules	Building energy efficiency	This study presents an intelligent ontology system that can help occupants to monitor and control their energy consumption and also to notice their energy saving potentials
Valiente-Rocha and Lozano-Tello (2010)	Ontology and SWRL rules	Smart homes	The study presents an ontology-based expert system learning model called InelliDemo that can be used to control a home automation system and to learn user's behaviour
Pauwels, De Meyer, and Van Campenhout (2010)	Ontology	AEC	This paper examines architecture; engineering and construction description framework based on Semantic Web technology and compared to the BIM approach, issues which might solve interoperability are discussed
Daouadji, Nguyen, Lemay, and Cheriet (2010)	Ontology	Low carbon energy management in grid networks	In this study, an ontology-based resource description framework was developed for ICT energy management purpose where focus is on energy-related semantic of resources and their properties
García (2010)	Ontolgy	Building designs	This study proposed OWL as CAD data exchange format, giving the possibility for the addition of more descriptive information of products and processes in one self-content and self-descriptive file
Métral, Billen, Cutting-Decelle, and van Ruymbeke (2010)	Ontology	Urban planning	This study employs case studies to demonstrate how ontologies can overstep the semantic limitation of 3D city models and how ontology-based approaches can be used to interconnect urban models in order to improve their interoperability
Finat et al. (2010)	Ontology	Urban planning	This study presents an ontology-based tool for extracting dominant planes from dense 3D range information which is applied for the automatic identification of structural elements (façades, ground and roofs) and their automatic labelling in terms of data of dominant planes
El-Gohary and El-Diraby (2010)	Ontology	Construction and infrastructure development	This paper presents a domain ontology for supporting knowledge-enabled process management and coordination across various stakeholders, disciplines, and projects
Yurchyshyna, Faron-Zucker, Le Thanh, and Zarli (2010)	Ontology	Conformance checking in construction projects	This paper presents an ontological method aimed at the capitalisation and organisation of conformance-related knowledge for semi-automatic checking model of the conformance of construction projects against a set of conformance requirements
El-Mekawy and Östman (2010)	Ontology	Building and urban planning	This paper proposes a more expressive reference ontology between IFC, CityGML semantic models and an intermediate unified building modelled (UBM). Through the reference ontology, a bidirectional formal mapping between IFC and CityGML ontologies that allows bidirectional conversion between them can be done
Abdulrazak, Chikhaoui, Gouin-Vallerand, and Fraikin (2010)	Ontology	Smart home	This paper presents a universal ontology for smart environments aiming to overcome the limitations of the existing ontologies
Dibley, Li, Miles, and Rezgui (2011)	Ontology	Facility management	This study proposes an ontology knowledge-based system that can be used to support facility management decisions such as the optimisation of the energy consumption/environmental comfort demand trade-off in buildings
Rosselló-Busquet, Brewka, Soler, and Dittmann L. (2011)	Ontology/ SWRL rules	Building energy efficiency	This study examines a Semantic Web-based system that can allow an end-user to control the devices in the home network through an interface and apply energy management strategies to reduce and optimize their consumption.
Reinisch, Kofler, Iglesias, and Kastner (2011)	Ontology/ SWRL rules	Smart homes/Building energy efficiency	This study presents a novel approach to realize a smart, minimum energy, green building through the introduction of semantic context and artificial intelligence knowledge-based system which provides transparent access to data, users, building systems, and other miscellaneous services
Abanda, Tah, Manjia, and Pettang (2011a)	Ontology	Construction labour costing	This study developed an ontology that can facilitate the estimation construction labour cost for building projects
Abanda, Ng'ombe, Tah, and Keivani (2011b)	Ontology	Land economy	This study developed an ontology that can facilitate the acquisition of certificates of title in both the customary and state land in Zambia
Tah and Abanda (2011)	Ontology	Sustainable building technology	The ontology presents a conceptual model for representing information about photovoltaic system, a major type of sustainable building technologies
McGibbney and Kumar (2011)	Ontology	Sustainable design and construction	This study presents an intelligent domain-specific Web-based information search and retrieval application which employs domain specific ontology to identify (in particular) relevant energy performance building regulation

Table 1 (*continued*)

Sources	Semantic Web technology	Built environment	Description
Pauwels et al. (2011a)	Ontology, Semantic Web rules	Buildings	This paper documents an investigation of the nature of this 3-D information conversion problem and how it may be encompassed using Semantic Web technology
Pauwels et al. (2011b)	Ontology	Buildings	This paper presents an ontology knowledge-based system that contains information required by a rule checking environment to conduct acoustic building performance checking
El-Diraby and Osman (2011)	Ontology	Urban civil infrastructure	The paper presents an ontology that contains functions, roles and semantic attributes of infrastructure products that can facilitate the human representation of their construction knowledge
Métral and Cutting-Decelle (2011)	Ontology	Urban modelling	The study examines three ontology-based approaches in relation to urban modelling. The interconnection of urban models through ontologies has been described
Hu et al. (2011)	Ontology	Smart homes	This study examines a Semantic Web-based policy interaction detection method with rules to model smart home services and policies with the aids of ontological analysis in the smart home domain, so as to construct a semantic context for inferring the interaction of policies
Han, Jeong, and Lee (2011)	Ontology	Building energy efficiency	This paper proposes a building energy management system based on ontology, inference rules, and simulation
Kofler, Reinisch, and Kastner (2011)	Ontology	Building energy efficiency	This paper presents an ontology knowledge base which contains information for efficient management of energy in smart homes
Zhang and Issa (2011)	IFC-based ontology	Code-checking	This study presents an ontology that can be used for information retrieval and code-checking of a building model against the building code
Bellotti, Berta, Cardona, and DeGloria (2011)	Ontology	Buildings	This study presents an ontology that classifies architectonic components of buildings according to classic principles of architecture. Furthermore, the ontology is used in an algorithm – for procedural generation of buildings in an urban area, based on the concept of "architectonic likelihood
Shah, Chao, Zlamaniec, and Matei (2011)	Ontology	Building energy efficiency	This study presents an ontology knowledge-based system for home energy management. It provides a comprehensive comparison of home appliances based on their energy consumption performance and also to provide a comparative analysis of energy consumption of these appliances
Shen and Chua (2011)	Ontology	AEC	This paper presents three emerging internet-based technologies, namely, semantic search, cloud computing and mobile computing, and discusses their benefits and potentials in promoting BIM implementation and adoption to a much wider user base
Ramaprasad, Prakash, and Rammurthy (2011)	Ontology	Construction project management	This paper presents on ontological framework to envision a construction project management system. The framework has five dimensions: outcomes, stages, resources, processes and management techniques
Garrido and Requena (2011)	Ontology	Environmental impact assessment (EIA)	This paper describes a proposal of ontology for EIA to establish a conceptual framework and the building process. In addition, a friendly Web interface has been developed to provide easy access to the knowledge and the possibility to suggest changes in the ontology to environmental experts
El-Gohary and El-Diraby (2011)	Ontology	AEC	This paper presents an ontology integrator (Onto-Integrator) for facilitating ontology interoperability within the architectural, engineering, and construction domain
Mignard, Gesquière, and Nicolle (2011)	Ontology	Building and urban infrastructure	This paper presents a new architecture dedicated to the management of buildings and urban objects through a 3D digital mock-up
Scherer and Schapke (2011)	Ontology	Construction project management	The paper discusses: (1) the main components of the system for interlinking and sharing models and information, (2) the ontology-based multi-model framework and the basics for the hierarchical structuring of the models, and (3) the generation of integrated process models
Fidan, Dikmen, Tanyer, and Birgonul (2011)	Ontology	Risk and cost estimation	The paper proposes an ontology used to develop a database system for managing risk event histories of international construction projects and estimation of cost overrun
Kofler, Reinisch, and Kastner (2012)	Ontology	Building energy performance	In this study ontology for the weather forecasting domain has been developed. The weather ontology is applicable to the area of smart grids and smart cities that benefit from the additional information to increase efficiency of distributed power generation and consumption. The ontology knowledge representation system can be utilized in a dedicated system operating in a residential home optimizing home energy efficiency
Montenegro, Gomes, Urbano, and Duarte (2012)	ontology	Land use planning	The paper provides semantic and computer-readable land use descriptions of geo-referenced spatial data. This will help to make programming strategies available to those involved in the urban development process

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Table 1 (*continued*)

Sources	Semantic Web technology	Built environment	Description
Madrazo et al. (2012)	Ontology	Urban planning, CO_2 reduction	In this paper an ontology-based energy information system that can help stakeholders involved in urban planning to make informed decisions about how to reduce CO_2 emissions in cities
Kohli, Sliuzas, Kerle, and Stein (2012)	Ontology	Slum environments	This study proposes a generic slum ontology that provides a framework which includes relevant indicators that can be used for image-based slum identification
Venugopal et al. (2012)	IFC-based ontology	Fabrication of Precast/Pre-stressed Concrete	The outcome of this research provides the mechanism for applications such as modular Model View Definitions (MVDs), smart and complex querying of building models, making data sharing across applications simpler with limited rework
Curry, Jentzsch, and Cyganiak (2012) and Curry, O'Donnell, and Corry (2012)	Linked Data-Ontology-BIM	Building and facility management	In this study, Linked Data has been employed to overcome interoperability challenges so as to enable data from multiple sources to be merged into a holistic scenario models for different stakeholders of buildings
Curry et al. (2012)	Linked Data-Ontology-BIM	Building energy efficiency	In this paper, the use of Linked Data as an enabling technology for cloud-based building data services has been examined. The objective of linking building data in the cloud is to create an integrated well-connected graph of relevant information for managing a building
Nemirovski, Sicilia, Galán, and Massetti (2012)	Ontology	Building energy efficiency	This paper presents an ontology-based information system to capture the energy-related data throughout the whole building life cycle
Dibley, Li, Rezgui, and Miles (2012)	Ontology	Building monitoring	This paper focuses on the ontology development process to deliver an intelligent multi-agent software framework (OntoFM) supporting real time building monitoring
Pauwels and Deursen (2012)	RDF/Linked Data	Interoperability in AEC	The study demonstrates how IFC models can be made available as RDF graphs in the Semantic Web and how there can be linked to other information
Madrazo and Costa (2012)	Ontology/ Linked Open Data/BIM	AEC	This study provides an overview of alternatives to interlink data generated around different BIM solutions using ontologies and Semantic Web technologies following the Linked Open Data initiative
Zhong, Ding, Luo, Zhou, and Hu (2012)	Ontology/ SWRL rules	Construction quality compliance checking	In this paper, an ontology for construction quality inspection and evaluation is proposed. Based on the ontology, the regulation constraints are modeled into OWL axioms and SWRL rules
Törmä, Oraskari, and Hoang (2012)	Linked Data	AEC	This study proposed an approach based on Linked Data paradigm where interrelated partial building models are converted into Linked Datasets (utilising URIs, RDF and OWL) and published on the Web (allowing browsing and querying with SPARQL)
Si and Wang (2012)	Ontology	AEC	This paper first introduced the IFC standard and the concept of ontology. Then put forward the construction method of the architectural engineering domain ontology based on IFC. And finally build up the concepts, properties and the relationship between the concepts of the ontology
Cotterell et al. (2012)	Ontology	Energy efficiency	In this paper, an overview of Ontology for Energy Investigations (OEI), an ontology that extends a subset of the well-conceived and heavily-researched Ontology for Biomedical Investigations, is provided as well as a motivating example demonstrating how the use of a formal ontology for the EI domain can facilitate correct and consistent knowledge sharing and the multi-level analysis of its data and scientific investigations
Benevolenskiy, Roos, Katranuschkov, and Scherer (2012)	Ontology	Construction project management, process scheduling	This paper presents a new approach that combines the ontology-based process modeling with the rule-based process configuration. The proposed system supports the generation of process schedules for construction projects that could be later used in discrete-event simulation software or workflow programs
Scherer, Katranuschkov, Kadolsky, and Laine (2012)	Ontology	AEC/FM	This study proposes an interoperability method based on description logic ontology whose core is provided by a link model containing rules and constraints not only to connect dynamically any kind of models but also to allow sound quality control of the links by supporting knowledge-based management methods and protecting end-users from possible errors by the exponentially growing possible links with the increase level of detail
Yang (2013a)	Web services	Building energy efficiency	This study designed and developed a novel cloud information agent system with Web service techniques aimed at building related information agent mechanisms to support energy-saving information processing and decision-making in order to focus on a system design of succinctness, cooperation, modularizing, and easy maintenance, with emphasis on computing power with many Web service techniques
Yang (2013b)	Web services and ontology	Building energy efficiency/ energy saving	In this paper, Web service and ontology techniques are presented. The Web service and ontology supports an energy-saving and case-based reasoning information agent. The proposed system is the first energy-saving and case-based reasoning information agent with Web service and ontology techniques in a cloud environment; the proposed architecture is also the first multi-agent structure of an energy-saving information system in a practical environment

Table 1 (*continued*)

Sources	Semantic Web technology	Built environment	Description
Abanda et al. (2013)	Ontology, SWRL	Renewable energy in buildings	This article investigates how the emerging Semantic Web enabling technologies can be used to both represent information and knowledge about renewable energy technologies, and facilitate system decision-making in recommending appropriate choices for use in different situations. Based on a review of literature, a prototype Semantic Web system known as the photovoltaic technology ontology system (PV-TONS) for managing knowledge about PV-systems is developed to demonstrate some Semantic Web capabilities. PV-TONS includes Semantic Web Rule Language (SWRL) that provides a reasoning mechanism to facilitate system decision support
Reegle (2013) and Bauer et al. (2011)	LOD	Renewable energy	In this project, an information gateway data.reegle.info has been developed. The gateway consumes and publishes energy related data in a machine-readable format so as to allow the flexible sharing and re-use of information in new and innovative ways
O'Donnell et al. (2013)	Linked Data	Building energy efficiency	This paper describes how Linked Data and Complex Event Processing can form the basis of an inter-operability approach that would help to overcome technical and conceptual barriers to cross-domain scenario modeling. In doing so, the paper illustrates the cross-domain potential of scenario modelling to leverage data from different information silos within organizations and demonstrates how to optimize the role of a building manager in the context of his or her organization

appears there has been a shift in practices with more matured ontologies being developed. While a lot has been done towards the exploration of the development of Semantic Web applications, most of the applications are yet to be implemented beyond academic laboratories. Most are prototypes at best still to be fully implemented. Partly, this may be due to the emerging nature of the Semantic Web technology domain. Nonetheless, finding systems that contain matured ontologies are now becoming apparent. For example, Reegle contains renewable RDF ontologies (Bauer, Recheis, & Kaltenbök, 2011; Reegle, 2013). Secondly, an appraisal from a built environment domain applications' perspectives will be examined. From the review, it is fair to say that although a significant sheer of Semantic Web applications have been developed in the built environment, very limited work has been done with respect to the domain of sustainable building, where users with little Semantic Web background can meaningfully exploit. This outcome is by no means a surprise as the Semantic Web is still at its embryonic stage and most research institutes are preoccupied with developing high level frameworks for major domains (El-Diraby & Gill, 2006; El-Diraby et al., 2005; Lima et al., 2003) with little focus on specific areas. However, it emerged from the literature that there are thousands of basic categorization or very low level lightweight ontologies or taxonomies of information about technologies needed to foster sustainable building design. A notable example is the GreenBookLive developed by BRE (GBL, 2013). GreenBookLive is a free to use online database designed to help specifiers and end users identify products and services that can help to reduce their impact on the environment. Having discussed general appraisal of this study, the major findings will now be examined in the ensuing paragraphs.

Based on Table 1, it can be construed that over time, more built environment Semantic Web applications have been developed. Also, while in the early years, most applications were on project management-related issues, a shift towards building energy efficiency, carbon management and building sustainability applications can be noted. There has also been a shift to using more innovative Semantic Web technologies. In the early years simple ontologies were developed while the later years have actually experienced the development of advanced Semantic Web technologies such as Linked Data. Also, the later years have witnessed the merging of some Semantic Web technologies with BIM to enhance reasoning capabilities of BIM. It can be noted that cloud computing, sensor networks, stateless Web services and Semantic Web can be facilitators for BIM (Underwood & Isikdag, 2011). In particular, concepts have been merged between:

- Ontologies and BIM: Since the avocation of BIM to be used to solve some old aged problems in the construction industry, the issue of interoperability between BIM systems have always been a barrier to the uptake of BIM. To deal with interoperability challenges, ontology-based information standards have emerged and are currently being used. IFC is one the most popular construction industry standards, which many construction BIM models can be converted to and exported to other systems for use in various applications. Therefore, IFC have been central in developing construction information management systems (e.g., Cheng, Kumar, & Law, 2002; Cheng, Trivedi, & Law, 2002; Schevers & Drogemuller, 2005).
- Ontologies and Linked Data: RDF-based ontologies constitute a required recipe for developing Linked Data systems that can be exposed, explored, share and re-used. Thus, in the built environment domain, IFC models are being made available as RDF graphs and being used to link to other building information (Pauwels & Deursen, 2012).
- Ontologies, BIM and Linked Data: As earlier discussed, ontologies can be used to enhance interoperability of Linked Data. Also, because BIM is a powerful technology for digitising buildings, it provides a rich information base that can be related to other external building data to perform some building decision analysis such as energy performance and environmental assessments. Curry et al. (Curry, Jentzsch, & Cyganiak, 2012a; Curry, O'Donnell, & Corry, 2012b; Curry et al., 2012) have explored these three technologies to conduct building energy performance assessments.

Although there has been significant progress in the development of built environment Semantic Web applications, there are still many technical challenges that need to be addressed for

Semantic Web potential to be fully realised in the built environment domain. The need to overcome these challenges has already been noted in Anumba, Pan, Issa, and Mutis (2008b). Furthermore, perhaps related to the emerging nature of Semantic Web, real reusable, easy and freely available Semantic Web applications are limited especially in the built environment domain. Reegle, one of the fewest and very useful Semantic Web-based renewable energy repositories with an easy user-interface is a classic example which should be emulated. More of such easy to use interfaces are required to potentially make a change in the way built environment information is managed.

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