Connecting the Dots between Building Information Modeling, Ontologies and Systems Engineering: Why and What for?

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Abstract
With the advent of BIM, the paradigm of construction projects where the whole life cycle is accounted for has emerged. Research presented in this paper points to the need to develop ontologies and to adopt systems engineering views to improve the management of the complexity in projects, including in the construction phase. The objective of this article is to present a literature review carried out to evaluate to which extent ontologies have been used in the implementation of BIM, in a framework offered by systems engineering. This review highlights relevant studies in this field in the last ten years. It results from the selection and analysis of 22 research papers published in international journals filtered out of 120 initial results. Even though BIM is relatively widely studied, BIM combined with ontologies and systems engineering appears as emerging and the main outcomes of this combination so far are summarized.

Keywords: BIM, Ontologies, Systems Engineering, Design, Construction.

1 Introduction

Building Information Modeling (BIM) is the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions" (ISO 19650-1 2018, § 3.3.14). From the viewpoint of the asset owner, BIM is a tool for managing the overall performance of its asset, whether in terms of environmental impact, integration in the built environment, quality, cost, schedule, and so on. For the construction companies, the adoption of information models is hindered by the complexity of the production process of built assets, some characteristics of which are:

- the coordination of numerous specialized companies.
- on-site delivery of a large variety of raw materials to be transformed, pieces of equipment to be installed, manufactured products to be assembled.
- heterogeneous teams where the work to be performed ranges from basic to highly-skilled and sometimes is inherited from ancient oral traditions (masonry, molding…).
- a series of hazards such as changes in the project design, delays in the supply chain, or bad weather conditions.

BIM can host the data companies create. As this benefits operations and maintenance activities as well as their own efficiency, construction companies are developing skills in information management. In the project delivery phase, there is nowadays the need for designing a meta-information-model (MIM) - that is a model of information model - to be adopted by each actor according to its specific needs. This MIM has to meet two complementary purposes. First, it must comply with international BIM standards for an efficient integration of the project sets of information in the asset information model it is encapsulated in. Second, the adoption of this MIM and hence the implementation of an information model in the project delivery phase has to happen with a level of information (granularity) that is relevant to the companies involved because significant margins of progress have been identified at the company level (WEF 2016).

The combination of ontologies and systems engineering appears as an appealing methodological framework for designing a MIM that construction companies could adopt and implement in their activities to benefit from, and contribute to, the overall BIM process in construction projects.

Research on ontologies with applications in the construction sector has been carried out and its trends have been identified and analyzed in (Zhong et al., 2019). Of particular interest here is that the authors concluded that BIM and ontology research are tightly related. An ontology provides a formal specification of concepts within a domain and the relations among them (Noy et al., 2001). The concept emerged 25 years ago from research activities in the field of Artificial Intelligence and standardized ontologies have been developed for sharing and annotating information in many disciplines and sectors. Ontologies are especially suitable for a common understanding of the structure of information aggregated from several actors, and for defining and reusing knowledge in a domain.

The need for adopting a system-of-systems approach for the development of BIM in the construction sector has been established for instance in (Cerovsek 2011). A system can be defined as "an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not" (Dori et al. 2020). Systems engineering is nowadays widely based on models that can represent the key features of a system: the components that build its structure (hardware, software, people), its functioning (organization and information flows), its behavior in its environment (regulations, contracts). Modeling is intended to architect and engineer a system so that it best serves its purposes.

In (Yang et al. 2019) the authors show how ontologies support model-based systems engineering in many knowledge areas. Among the 52 ontologies analyzed, one only was identified as falling in the scope of construction. This shows some unexpected disconnection between ontology-based systems engineering research and the construction sector: although ontologies and systems engineering can obviously support the design of a MIM to be implemented in construction companies and hence support the adoption of BIM in construction projects, the construction sector is not identified as a significant contributor to this research effort.

The purpose of this paper is to identify, analyze, and discuss research outcomes where BIM, ontologies, and systems engineering have been considered together. To this end, a review of the scientific literature concerned with each and every of these 3 keywords has been carried out. Next section is dedicated to the presentation of the methodology adopted. A bibliometric analysis is presented in Section 3. Before drawing some conclusions, the different areas covered by the selected corpus of papers and the main outcomes of the research involving BIM, ontologies, and systems engineering are identified in section 4.

2 Methodology for the literature review

The process for systematic literature review adopted in this research was the SSF - Systematic Search Flow (Ferenhof & Fernandes 2016), which is composed of 4 phases and 8 activities.

Phase 1 - Definition of the research protocol: 4 databases were interrogated using the 3 keywords “BIM” AND “systems engineering” AND “ontology” with no restriction for the publication date. References were mostly found in 2 of them: Google Scholar (82), Science Direct (37), Web of Science and Scopus (1). Then, the standardization (e.g. journal papers only) and selection of articles began by reading the titles, abstracts, and keywords. After this filtering, the references were read in full and those that did not fall in our scope of investigation (information in the design and construction phases) were discarded. The final portfolio is composed of 22 articles, all are listed in the appendix below.

Phase 2 - Analysis: A spreadsheet was prepared with the following fields: authors, year, title, journal, number of citations, countries where the research was carried out, research focus, issues considered, advantages offered by the research, type of ontology languages used, how systems engineering views were used by the authors.

Phase 3 - Synthesis: It was initiated through the construction of the knowledge matrix (Ferenhof & Fernandes 2016) seeking to extract and organize the data from the analysis of the articles. The results of these phases 2 and 3 are hereafter presented in sections 3 and 4.

Phase 4 - Writing: It was elaborated to consolidate the results obtained and resulted in the writing of this paper.

3 Bibliometric analysis

Research involving BIM, Systems Engineering and Ontology retrieved from the literature review began in 2011 (Figure 1). In 2016 and 2019 alone, 54% of the publications were produced.

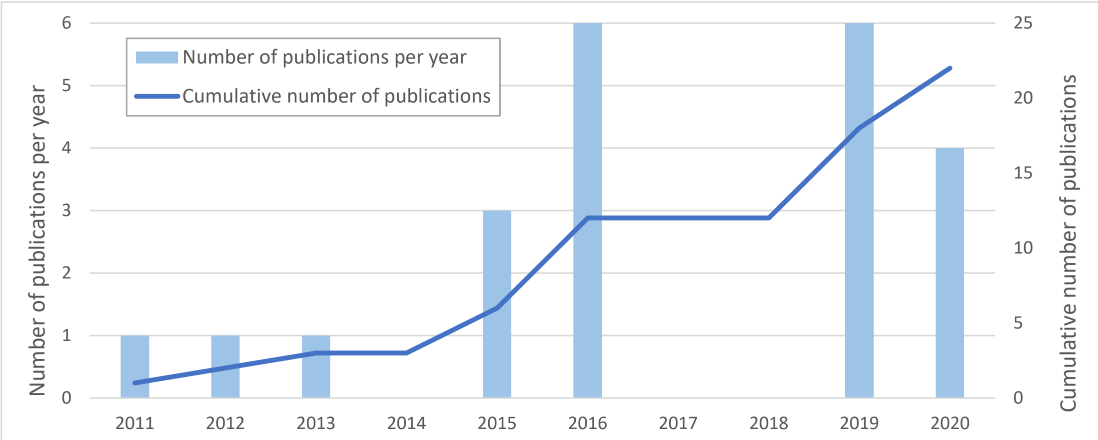

Figure 1. Number of publications per year and cumulative number of publications

Even though the sample size of articles is moderate, some indications of Bradford's law could be noticed. Bradford's law is a general rule that applies broadly to the distribution of articles among journals in a specific scientific discipline. A small number of core journals produces about a third of all the articles in that field. The second zone of journals (relevant) would also contain about a third of all the articles but with a number of journals that would be N times larger than for the core zone. The third zone of journals (marginal) would also contain a third of the articles but would be contained in a number of journals N^2 times larger than in the core. The mathematical relationship of the number of journals in the core to the second and third zones is expressed as $1:N:N^2$ (Thompson & Walker 2015). Figure 2 shows that the relationship for the sample of journals considered in this work is 1:3:6 and the number of journals produced for each zone are 27% (core), 45% (relevant) and 27% (marginal).

With the purpose of obtaining insight into the key papers and target journals, all papers in the literature review were ranked with respect to the number of citations. Figure 3 shows the fields of research explored in the most cited papers. The top 5 high-cited papers were published in *Automation in Construction*, *Advanced Engineering Informatics*, and *Engineering, Construction and Architectural Management*.

Zone	Journals	No of Articles	%
CORE	Advanced Engineering Informatics	6	27%
RELEVANT	Automation in Construction	4	45%
	Computers in Industry	3	
	Engineering, Construction and Architectural Management	3	
MARGINAL	Buildings	1	27%
	International Journal of 3-D Information Modeling	1	
	Journal of Computing in Civil Engineering	1	
	Journal of Information Technology in Construction	1	
	Journal of Manufacturing Systems	1	
	Smart and Sustainable Built Environment	1	

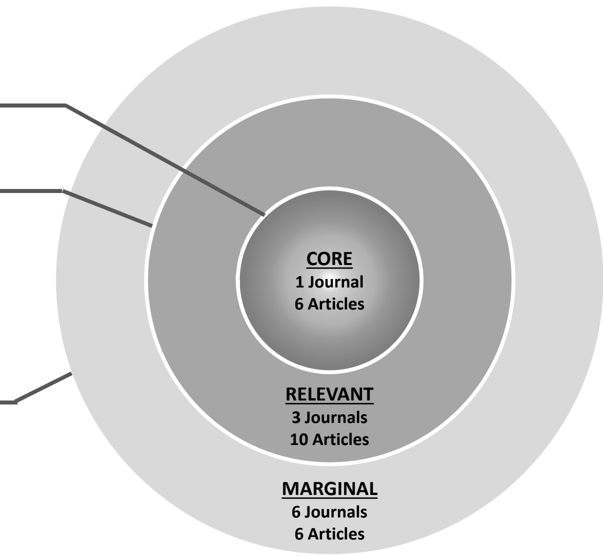

Figure 2. Core, relevant, and marginal journals for the 22 papers selected in this review of the literature

No of Citations	Authors	Year	Title	Published In	Country	Field of Research
145	Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X.	2019	**A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends.**	Automation in Construction	USA	Literature Review: BIM; Internet of Things (IoT) Device; Sensors; Smart building; Smart City; Smart built environment; Integration;
68	Lee, Y. C., Eastman, C. M., & Solihin, W.	2016	**An ontology-based approach for developing data exchange requirements and model views of building information modeling**	Advanced Engineering Informatics	USA	BIM data exchange
65	Geyer, P.	2012	**Systems modelling for sustainable building design.**	Advanced Engineering Informatics	Germany	Sustainable building design
45	Dibley, M. J., Li, H., Miles, J. C., & Rezgui, Y.	2011	**Towards intelligent agent based software for building related decision support.**	Advanced Engineering Informatics	UK	Multi Agent System ; Facility Management ; BDI (Belief, Desire, Intention) model
29	Hoeber, H., & Alsem, D.	2016	**Life-cycle information management using open-standard BIM**	Engineering, Construction and Architectural Management	Netherlands	Building life-cycle information

Figure 3. Most cited articles selected in this work based on Google Scholar

When relating the number of publications to the country of the main author, there is a predominance of US, UK, and Chinese authors with 14% of the publications each. Figure 4 shows the countries of the main authors with the number of publications.

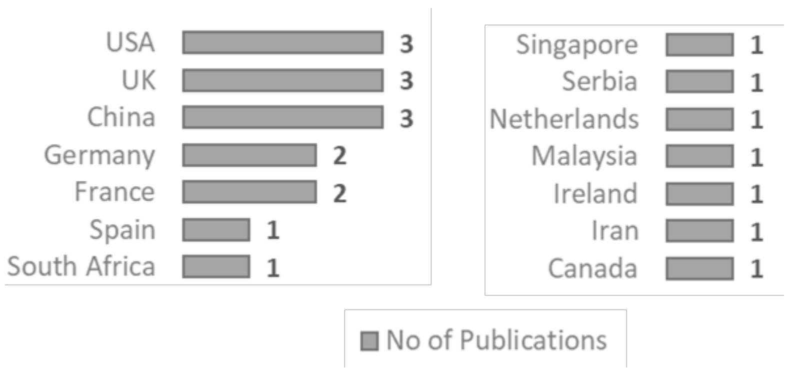

Figure 4. Country of origin of the main authors

Figure 5 shows a cartography and the number of occurrences of the main technological concepts related to BIM, ontology, and Systems Engineering that can be found in the 22 articles analyzed in this work.

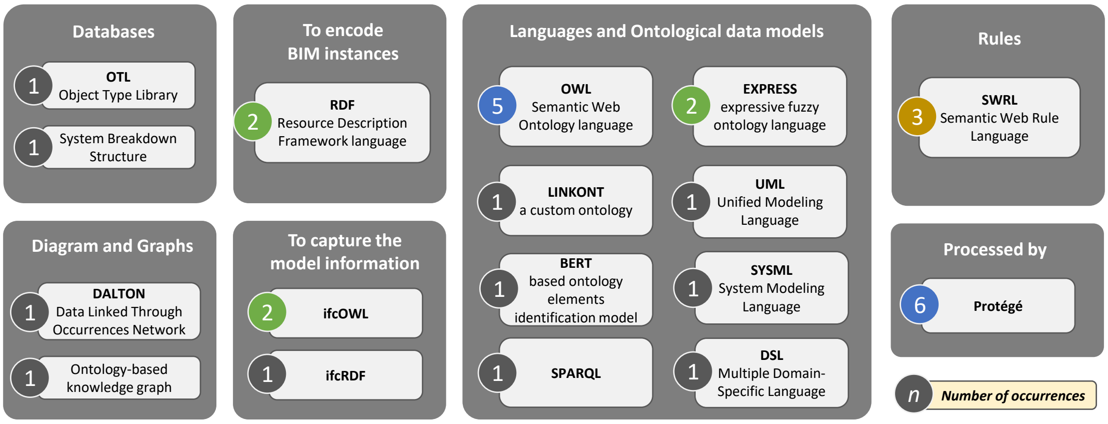

Figure 5. Map and occurrences of the main technological concepts found in the 22 articles analyzed in this work

4 BIM, ontologies, and systems engineering outcomes

A wide variety of research areas in which BIM, ontologies, and systems engineering are combined have been identified. We classified them in the 4 macro-areas introduced hereafter.

4.1 Critical factors for BIM adoption

In (Sinoh et al. 2020), the authors state that non-technical factors (such as management, leadership, and coordination) are more relevant in the success of BIM implementation in AEC firms than technical factors (such as software or hardware). The authors conclude that future research should explore the intra and inter-firm coordination, because it is likely to create a suitable environment for BIM implementation.

Another critical factor pointed out in (Lee et al. 2016) is that when no robust standard for defining construction semantics and data exchange requirements has been agreed on, the information embedded in specific domain definitions is generated separately and remains vague in scope, resulting in a lack of consistency. The authors propose ontological principles to generate an Information Delivery Manual (IDM) for the precast concrete domain and to link its Model View Definition (MVD) with formal information models. They concluded that the proposed ontology-based framework could more accurately recognize domain knowledge and appropriate requirements for developing reusable concept modules.

To improve the efficiency in knowledge management in the AEC industry, "knowledge management through experience feedback processes" were developed in (Kamsu-Foguem & Abanda 2015). The authors employed ontologies and graph-based reasoning operations for eliciting and visualizing knowledge concepts in the AEC domain. With a case study in a French AEC company, they show that an ontology graph-based editor to model knowledge along with encoded reasoning in the knowledge base can be very useful to gain information for collaborating with others and for continuously improving information sharing and re-use.

In (Gómez-Romero et al. 2015), it is stated that although open standards such as the Industry Foundation Classes (IFC) have contributed to BIM adoption, they offer limited capabilities for cross-domain information integration and query. To address these challenges, the authors use ontologies and semantic Web technologies towards more formal and interoperable BIMs. They present a fuzzy logic-based extension of such semantic BIMs that provides support for imprecise knowledge representation and retrieval. They point that resulting fuzzy semantic BIM enables new functionalities in the project design and analysis stages, such as soft integration of cross-domain knowledge, flexible BIM query, and imprecise parametric modeling.

4.2 Design and pre-construction phase

Regarding the design development and preparation for the construction phase, the proposed ontologies cover various topics such as simulation, constructability, and cost estimation. Software tools that support the Architectural Design, Urban Planning, and Construction Engineering domains are investigated in (Perisic et al. 2016). Throughout urban blocks daylight illumination simulation, the authors show the importance of a common ontology and of the development of an efficient orchestration environment that hides the inherent complexity of individual domain methods and tools while enabling cooperative design.

The need for construction inputs among different project participants at early design stages has also been identified in (Jiang & Leicht 2016) where an ontology was developed to support automated constructability review through the employment of BIM in the case of the design and construction of reinforced concrete structural elements. Such an ontology underpinned the understanding of the constructability concepts towards integrated design and delivery.

In (Geyer 2012) systems modelling is introduced as an addition to parametric geometric CAD/BIM modeling. The system model provides a tool for including non-geometric information (physical, environmental, economic) in the design to improve the sustainability of the building.

The development of a framework based on the semantic Web ontology and a forward chain algorithm is presented in (Xu et al. 2016) for automatic cost estimation in the construction industry. This work also demonstrates that decoupling the professional practice into three key components of syntax (information type), semantics (definition of the pricing domain), and pragmatics (implementation of the standards / context) can provide tangible benefits.

4.3 Construction phase

BIM, ontologies, and systems engineering have also been jointly used for supporting information exchange in the construction phase as well. Ontologies are used in (Soman et al. 2020) to support look-ahead planning in construction. They show that their model mitigates the difficulty to track and monitor the prerequisites and validate constraints in complex construction projects through data-driven constraint-checking. They also show how their model offers the opportunity to capture construction knowledge created during look-ahead meetings.

An Internet of Things-enabled BIM platform for the modular integrated construction project is developed in (Zhai et al 2019). Rules are written in Semantic Web Rule Language (SWRL) and processed by an ontology editing environment. The main result obtained was a rule-based process control service that automatically reports emergencies to end users in a given order and quickly provides ideal guidelines for managers.

In (Moshtaghian et al 2020), a framework for the dynamic identification of project risks is created. The proposed platform reduces rework time and cost control, and it changes management as a consequence of risk identification at the right time.

A framework that integrates the construction supply chain to resolve data heterogeneity and data sharing problems is proposed in (Das et al 2015). The authors present examples of two ontologies for expressing construction supply chain information: an ontology for material and another for purchase order. They show that ontology can be used to support heterogeneous data transfer and integration through Web services and, furthermore, that distributed data storage facilitates data sharing and improves data control.

In terms of structure monitoring, (Hong Lim et al. 2020) developed a generic digital twin architecture reference model to enable context-aware product family design optimization process in a cost-effective manner. The authors show context-aware digital twin keeps products compatible with their dynamic environment throughout their lifecycle. The approach is based on semantic-driven models (knowledge graphs) using ontologies and real-time data acquisition. The system ontology, when coupled with real-time data input, extracts relevant details and infers new relations between entities. A tower crane is considered as a case-study.

4.4 Post-construction phase

The management of operating post-construction information is the foundation for the sustainability of buildings and yields databases that can be used for research works. In (Dibley et al 2010) the combination of several technologies is exploited to automatically deliver enhanced knowledge relating to building use for facility management. The system developed is supported by a range of ontologies describing the semantics of the domain as well as agents models. The agents use a distributed network of readily available wired and wireless sensors and associated data storage providing access to near real-time and historical data. Building geometry and construction is described by an Industry Foundation Classes (IFC) model. These developments support decisions for facility management such as the optimization of the energy consumption and environmental comfort demand trade-off.

Adaptive reuse projects require distinct stages, definition of interfaces, decision gates, and planning methods to secure the success of the building project. To this purpose, an ontology is developed in (Eray et al. 2019) to support a reference framework for implementing interface management in an adaptive reuse project.

In (Fitz et al 2019), the capabilities of cyber-physical systems for structural health monitoring and structural control are analyzed using metamodeling. The approach is tested on a BIM-based example, physically implemented in the laboratory. The authors found that useful information is stored, documented, and exchanged using the formal basis of IFC, facilitating design, optimization, and documentation of cyber-physical systems.

The research carried out it (Hoeber & Alsem 2016) was the one that presented the closest vision of what we were seeking in the literature: an information structure model that spreads throughout the entire life cycle of a construction project. The authors of this research intended to describe the use of Building Information Modeling (BIM) for the purpose of life-cycle information management. BIM is used in this case to store object-based information according to the semantics derived from systems engineering methodology and forming the whole ontology of information. Several benefits of the suggested approach to information management throughout the life cycle were recognized, such as an object-based structure in all construction information based on the system engineering breakdowns; semantically rich information with harmonized libraries and a fully linked data approach; all information is linked in the frame of systems engineering providing an ontology; a complete integrated information model is delivered instead of large volumes of documents; different projects, actors, and phases use the asset manager's object type library allocated to a supertype library containing standardized items; standardization of formal information transactions between the actors, meeting the information needs of the stakeholders throughout the life cycle; the delivery of the BIM containing all the information of the building in its ontology and in an editable format overcomes misinterpretations and a lot of rework such enabling interoperability.

5 Conclusions

This paper presents a review of the literature on Building Information Modeling developed with Ontologies from the perspective of Systems Engineering. Altogether, 22 papers from 11 AEC, Computing and Manufacturing Systems related journals over the last ten years were reviewed. Bibliometric information has been extracted and the main outcomes of research carried out combining BIM, ontologies, and systems engineering have been summarized. Outcomes have been found in the design, construction, and operation and maintenance phases with improved interoperability, enhanced capacities for capturing knowledge, automation of various tasks.

Despite the importance of having a systemic view of the construction projects to tackle the complexity involved throughout the life cycle of built assets, and despite the fact that ontology engineering and systems engineering have been identified as efficient for meeting this goal, research combining BIM, ontologies, and systems engineering is still emerging.

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Appendix

List of the 22 papers selected for the literature review (all are not cited in the body of the paper):

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