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ONTOLOGY AND INTEROPERABILITY IN PLANNING AUTOMATION WITH 4D BIM: A SISTEMATIC REVIEW[1]

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RESUMO

A necessidade de interoperabilidade de informações é uma crescente dentro da bibliografia, o que na Indústria da Construção Civil (ICC) é notadamente difícil pelo fato de as informações que circulam em projetos não estão totalmente padronizadas e digitalizadas. Com o BIM, muito se avançou neste sentido, porém, ainda não se tem uma base comum consolidada de troca de informação dos elementos da construção entre os diferentes agentes que desenvolvem e que utilizam o modelo. Visando mapear a literatura existente no assunto ontologias voltadas a modelagem da informação e sua interoperabilidade com a automação e simulação do planejamento da construção (BIM 4D) é que se propõe o presente artigo. Para tanto, foram selecionados 27 artigos, visando compreender o foco empregado na adoção de ontologias durante o desenvolvimento de modelos BIM 4D para ICC, as estratégias para atingir maior interoperabilidade entre modelo da informação e planejamento, os tipos de semânticas adotadas, as possíveis categorias e esquemas utilizados. A principal contribuição deste trabalho é a análise e exposição das ontologias no desenvolvimento do BIM 4D pela ICC. Igualmente, foram apontados caminhos em que pesquisas no tema estão evoluindo e se verificou carência de metodologia que oriente a aplicação das ferramentas nesta Indústria.

Palavras-chave: *Planejamento da Construção, Building Information Modeling, Gestão do conhecimento.*

ABSTRACT

Interoperability has been a basic requirement for modern information systems, which in the construction industry is especially difficult because information between projects is not yet fully standardized and digitalized. With BIM introduction, much progress has been made in this regard, however, there is still no consolidated common basis for the exchange of information on construction elements among the different stakeholders that develop and operate the construction model. In order to review existing literature on the subject of ontologies produced for BIM and its interoperability with the automation and simulation of construction planning (4D BIM), this article is proposed. To this end, 27 articles were selected to understand the focus used in the adoption of ontologies during the development of BIM models for the construction industry, strategies to achieve greater interoperability between BIM and planning, types of semantics adopted, possible categories, and schemes applied. The main contribution of this research is the analysis and exposure of ontologies in BIM development for the construction industry. Likewise, in what way research on this subject is advancing were pointed out and was verified a lack of methodology to guide the application in this industry.
Keywords: *Construction Planning, Building Information Modeling, Knowledge Management.*

1 INTRODUCTION

The architecture, engineering, and construction (AEC) industry is experiencing a technological revolution driven by booming digitization and automation (HUANG *et al*.,

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2021). The rapid development of information technologies has provided solutions to numerous construction management problems such as integrating design, construction activities and cost estimation. Building information model (BIM), which is an IT and is a three-dimensional (3D) framework that can digitize a great amount of building information, has attracted much attention owing to its effectiveness in data acquisition and storage in support of construction management (WANG *et al*., 2016). Hence, BIM is a paradigm shift from the traditional AEC industry practices to digital construction delivery processes and provides the capabilities of cost reduction, increase quality, enhanced productivity, and on-time delivery. Despite the numerous advantages of BIM, its adoption in AEC is vulnerable to confrontation. One significant barrier often cited to BIM adoption is data interoperability (SHEHZAD *et al*., 2021). BIM interoperability is the capability of two or more organizational units or networks to exchange information and understandably share data (SHEHZAD *et al*., 2021). In this way, Researchers have explored the integration of BIM and Semantic Web to solve the problem of interoperability, and key to the Semantic Web is an ontology of a domain (ABDULLAHI *et al*. 2019).

BIM methodology allows sharing the information about the same construction between the involved stakeholders. The same building will be affected by different AEC processes. Some n-dimensional extensions have been recently proposed in the literature. The fourth dimension of BIM (4D BIM) represents the planning of the building phases. This dimension can be used to simulate the building state at a fixed point in time, as a snapshot (DELGADO *et al*., 2015). 4D BIM in construction link 3D models with construction schedule data (CORRÊA; MARCHIORI, 2017). For Boje *et* al. (2020) the process of linking product and process models, especially at higher levels of detail makes the exploration of multiple construction management strategies prohibitive, especially when looking at the collaboration and social aspects of 4D BIM review meetings. The authors consider the use of ontologies to be better suited for representing such complex systems, paving the way toward semantic digital twins of the construction site by including concepts beyond traditional 3D model data, such as actors, sensors, management workflows, information over the web, etc.

Aiming to maintain an up-to-date schedule, automation of construction planning can assist to minimize the time and resources necessaries to this purpose. Automation in construction scheduling is a challenge because it requires to generate and optimize multi-objective problems, which usually include several parameters (NATICCHIA *et al*., 2018). Automation can be exploited if a BIM repository is used as the archive of all the information required by the optimization algorithms to perform its estimations. The generation of construction schedules can retrieve data (e.g. spatial, geometric, quantity, relationships and material set of information) from what is stored in BIM models (KIM *et al*., 2013). This approach would achieve significant time reductions in scheduling, compared to the traditional manual methods (NATICCHIA *et al*., 2018).

This paper aims to review existing literature on the subject of ontologies produced for BIM and its interoperability with the automation and simulation of construction planning (4D BIM). The paper is organized as follows. Section 2 outlines the research methodology. Section 3 explains the prior work on 4D BIM, ontology and interoperability linked to the literature review. Section 4 discusses the results of the bibliometric literature analysis. Section 5 presents the conclusions and suggests future research directions.

2 RESEARCH METHODOLOGY

SSF - SystematicSearchFlow (FERENHOF; FERNANDES, 2015) was the method for systematic literature review adopted for this research, which is composed of 4 phases and 8 activities.

2.1 Phase 1 - Definition of the research protocol

The search strategy was defined employing the keywords “4D” AND “BIM” AND “interoperability” AND “ontology” in titles, abstracts and keywords, with no time limit for publications. The search took place in three databases, papers were found only in two of them: Science Direct: 73; Web of Science: 0; and Scopus: 1 paper. Following, the results were inserted in bibliographic organizer Mendeley, standardization and selection of articles initiated by reading titles, abstracts and keywords. After this initial filtering, composition of article portfolio started, by full reading them, aiming to choose does that had adherence to the theme under investigation. Subsequently the above activities, the composition of the bibliographic portfolio resulted in 27 articles.

2.2 Phase 2 - Analysis

An electronic spreadsheet was built including the following fields as titles for the columns: authors, year, title, publication vehicle, number of citations, keywords and countries involved. The results of this analysis are presented in item “4. Discussions” of this article.

2.3 Phase 3 - Synthesis

Initiated through the construction of the Knowledge Matrix (FERENHOF and FERNANDES, 2015) seeking to extract and organize the data from the analysis of the articles.

2.4 Phase 4 - Writing

Elaborated in order to consolidate the results obtained, resulting in this research work. For the list of selected publications, see “APPENDIX A[2]”.

3 ONTOLOGY AND INTEROPERABILITY IN PLANNING AUTOMATION

This section aims to present the main concepts used in the development of this research, based on construction ontology, BIM interoperability and planning automation.

3.1 Construction ontology

Development of a domain ontology in the construction industry has been another crucial step to improve knowledge management and workflow (ZHANG *et al*. 2015). Venugopal *et al*. (2012) presented a formal classification structure for IFC implementations for the domain of Precast Concrete Industry to improve the interoperability of BIM applications. Gruber (1995) described ontology as “an explicit and formal specification of a conceptualization.” Preferably, an ontology should capture a shared understanding of a domain of interest and provide a formal and machine readable model of the domain (HORROCKS, 2005). The main areas, in which ontological modeling is applied, include communication and knowledge sharing, logic inference and reasoning, and knowledge reuse (ZHANG *et al*. 2015).

Zhang *et al*. (2015) proposed a construction safety ontology to formalize the safety management knowledge, aiming to integrate safety knowledge with project planning and execution to enable early hazard identification and BIM-based visualization. It consists of three main domain ontology models, including Construction Product Model, Construction Process Model, and Construction Safety Model. Visualization and simulation (4D) of models with safety resources become available.

Soman et al. (2020) presents a novel method, using semantic web technologies, to model and validate complex scheduling constraints. According to Soman et al. (2020), existing

[2] https://drive.google.com/file/d/1NZJbDfYmZJb_6LrbDF4ajlIL2GP3UrhL/view?usp=sharing

ontologies are reused for the linking data across domains in the proposed approach. The authors used IfcOWL to capture the model information, LinkOnt (a custom ontology) to capture the resource information and links, and SHACL to model constraints. LinkOnt is the ontology that they propose to support dynamic constraint-checking. This ontology introduces classes that are missing from IfcOWL but are required to do constraint-checking.

With the process-centric integration of engineering and management information and the ontology support for interoperability a variety of new formalized evaluative models and respective semi-automatic analyses can be exploited (SCHERER; SCHAPKE, 2011).

3.2 BIM interoperability

Shehzad *et al*. (2021) proposed a BIM Interoperability Adoption Model (BIAM) that consists of four dimensions: technical, organizational, semantic, and legal. The technological dimension covers factors such as data integration, complexity, compatibility, and data security. Top management support, organizational readiness, financial constraints, and uncertainty are covered by organizational interoperability. Semantic interoperability comprises exchange standards, common definitions, data dictionaries, and workflow mapping. Finally, legal interoperability applies to factors such as insurance framework, regulatory support, intellectual property, and contractual environments.

Shirowzhan *et al*. (2020) argues that interoperability issues prevail as the key practical barrier to BIM implementation, interoperability needs to be considered as one of the technology adoption model measures for successful BIM implementation at the technical level.

3.3 4D BIM and planning automation

Near real-time tracking of construction operations and timely progress reporting are essential for effective management of construction projects (MOSELHI et al., 2020). Since the process of collecting data to measure construction progress is highly time-consuming and labor-intensive, some researchers have focused on using new technologies for automatically measuring or tracking the actual progress of a construction project and comparing it with the planned progress (WANG et al., 2016).

Automated Data Collection (ADC) technologies, such as Global Positioning Systems (GPS), Radio Frequency Identification (RFID), computer vision, and other sensor-based data collection methods, help to automate tracking and monitoring prerequisites for work packages. Prerequisites are the conditions necessary for a work package to be executed such as availability of resource and completion of prior tasks. (SOMAN et al., 2020).

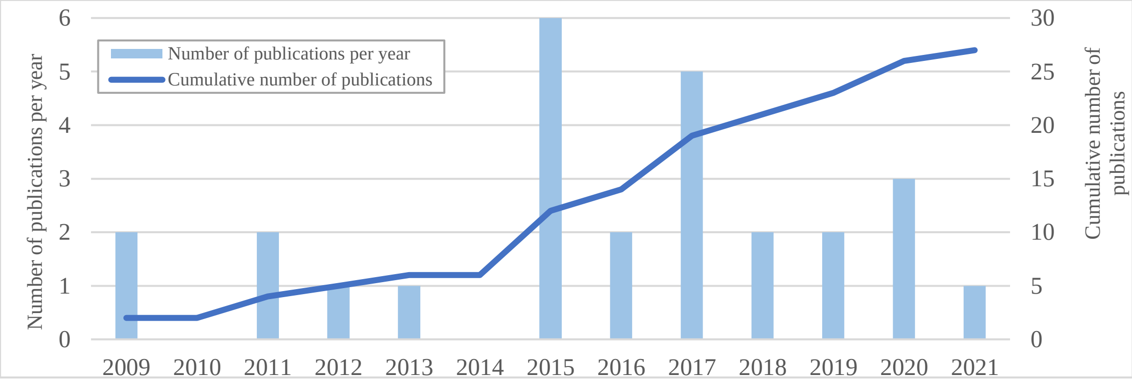
4D BIM can support tracking and monitoring of construction progress when daily construction progress is reflected in the 4D BIM model (STAUB-FRENCH; KHANZODE, 2007). The acquisition of as-built data is a fundamental step to ensure accurate progress monitoring. The identified activity states can be used as an information resource for assisted decision making, which may result in re-scheduling. The updated schedules can then be exploited for subsequent inspections. (KROPP *et al*., 2018). The concept of ontology has proven their worth for representing and sharing domain knowledge in machine-readable format. They are widely used in various approaches as an effective supporting tool for process knowledge exchange and management

(SIGALOV; KÖNIG, 2017). Therefore, ontology in scheduling domain can facilitate data acquisition integration with 4D BIM and planning automation.

4 DISCUSSION AND BIBLIOMETRIC ANALYSIS

Research involving 4D BIM, ontology and interoperability retrieved from the literature review began in 2009 (Figure 1). In the last 6 years it had a significant increase in the number of publications per year, notably in 2015 and 2017, these two years combined are responsible for 37% of the publications investigated.

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



Source: Authors (2021)

Automation in Construction represents the core zone of the research with 70% of the articles published (Table 1). Advanced Engineering Informatics and Computers in Industry reports for 19% of the articles published and represents the relevant zone of the research.

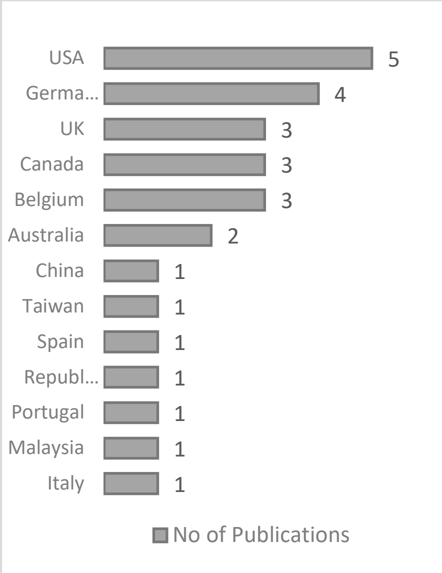
Table 1 – Number of publications per journal

Zone	Nº of Journals	Journals	Nº of Articles	%	∑(Nº)	∑(%)
CORE	1	Automation in Construction	19	70%	19	**70%**
RELEVANT	2	Advanced Engineering Informatics	3	11%	5	**19%**
		Computers in Industry	2	7%		
MARGINAL	3	Engineering Science and Technology	1	4%	3	**11%**
		Journal of Cultural Heritage	1	4%		
		Renewable and Sust. Energy Reviews	1	4%		
			TOTAL		**27**	**100%**

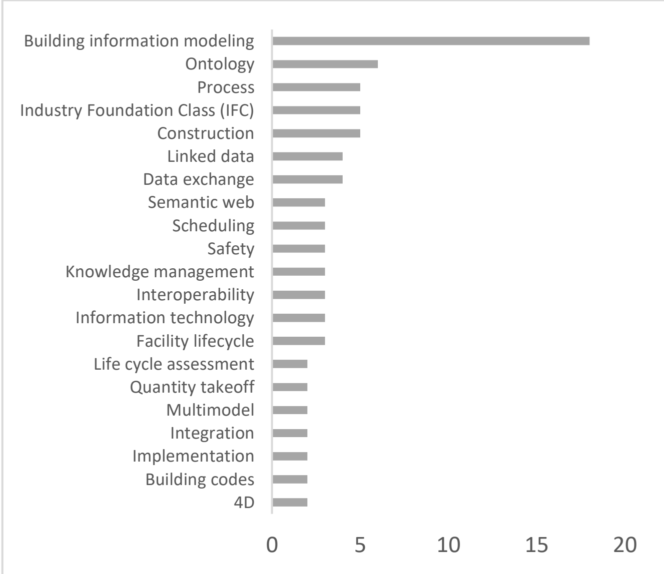
Source: Authors (2021)

When relating the number of publications to the country of the main author, there is a strong predominance of US authors, with 18% of the publications followed by German authors with 15%. Figure 2 (a) shows the countries of the main authors with the number of publications. Figure 2 (b) presents the frequency of keywords adoption by the authors. BIM, ontology, process, IFC and Construction are the most adopted. Linked data, data exchange, semantic web, scheduling, interoperability, and information technology are other keywords of research presented in the articles.

Figure 2 – (a) Indication of the country of origin of the main authors in relation to the total number of articles published. (b) Frequency of keywords



(a)



(b)

Source: Authors (2021)

With the purpose of obtain insight into the papers and key target journals, all papers of the literature in review were ranked against their citations. Table 2 shows different fields of applications of the topic for the papers that received more citations over time or per year. The top 5 high-cited papers were published in Automation in Construction.

Table 2 - Selected high-cited articles in the literature in review based on Google Scholar data set in 2021

No of Citations	Authors	Year	Title	Published In	Country
1607	Succar, B.	2009	**Building information modelling framework: A research and delivery foundation for industry stakeholders**	Automation in Construction	Australia
608	Eastman, C. *et al.*	2009	**Automatic rule-based checking of building designs**	Automation in Construction	USA
256	Pauwels, P., & Terkaj, W.	2016	**EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology**	Automation in Construction	Belgium
234	Zhang, S., *et al.*	2015	**Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)**	Automation in Construction	USA
186	Peterson, F. *et al.*	2011	**Teaching construction project management with BIM support: Experience and lessons learned**	Automation in Construction	USA

Source: Authors (2021)

Table 3 presents a description of strategies, semantics, and schemes for applying 4D BIM, interoperability and ontology for the selected articles in the list that effectively integrated these three approaches. BIM multi-models, IFC and custom ontologies are some of the main practices observed for greater BIM interoperability and to enable construction planning automation.

Table 3 - Strategies, semantics, and schemes for applying 4D BIM, interoperability and ontology

Author	Description of the strategies, semantics, and schemes used by the researchers

Abanda et al. (2017)	Development of an ontology based on New Rules of Measurement (NRM) for cost estimation with 4D BIM software for testing
Kassem et al. (2015)	Industry Foundation Class (IFC) compliant 4D tool for workspace management
Liu et al. (2015)	BIM-based integrated scheduling for automatic generation of activity-level construction schedules under resource constraints, integration of BIM product models with work package information, process simulations, and optimization algorithms
Scherer; Schapke (2011)	Planning, production and analysis tasks with Multi-models, ontology framework and Management Information System,
Soman et al. (2020)	Linked-Data based Constraint-Checking: a semantic web technology, to model and validate complex scheduling constraints. Appling IfcOWL to capture the model information, LinkOnt (a custom ontology) to capture the resource information and links, and SHACL to model constraints
Venugopal et al. (2012)	IFC implementations for the domain of Precast Concrete Industry to improve the interoperability of BIM applications
Zhang et al. (2015)	Construction safety ontology to formalize the safety management knowledge, integrate safety knowledge with project planning and execution to enable early hazard identification and 4D BIM-based visualization

Source: Authors (2021)

5 CONCLUSIONS

This paper aimed to identify and analyze articles associated to 4D BIM, ontology and interoperability as a component of construction planning automation over time and in various contexts. This database showed a significant gap in BIM interoperability for semantic dimension. A total number of 74 articles were analyzed to explore trends over time and specifically 27 articles were select. A few main practices observed to achieve greater BIM interoperability and to enable construction planning automation are BIM multi-models, IFC and custom ontologies.

The research presented in this paper contributes to the emerging research trajectory on using automated methods for construction scheduling with ontological basis and BIM interoperability. The present article suggests that future studies should examine ontologies across the fields of automated data collection for construction tracking and BIM libraries with semantic-rich objects for construction scheduling. Alternatively, some of main trends and crucial topics in the literature are BIM interoperability, development of construction ontologies for different domains, IFC and data exchange.

REFERENCES

ABDULLAHI, A.M.; IBRAHIM, Y. M.; KOLO, B. A.; ABANDA, F. H. An Ontology for Detailed Measurement of Building Works Using Semantic Web Technology. **International Journal of Digital Innovation in the Built Environment (IJDIBE)**, v. 8, n. 1, p. 42-63, 2019.

BOJE, C.; KUBICKI, S.; GUERRIERO, A. A 4D BIM System Architecture for the Semantic Web. In: **International Conference on Computing in Civil and Building Engineering**. Springer, Cham, p. 561-573, 2020.

CORRÊA; L.A; MARCHIORI, F.F. 4D BIM na construção civil e sua relação com lean construction: revisão sistemática da literatura, In: **1º Simpósio Brasileiro de Tecnologia da Informação e Comunicação na Construção** (2017), Fortaleza, Ceará, Brazil, 2017.

DELGADO, F. et al. Towards a client-oriented integration of construction processes and building GIS systems. **Computers in Industry**, v. 73, p. 51-68, 2015.

FERENHOF, H.A.; FERNANDES, R. F. (2015). **Passo-a-passo para construção da Revisão Sistemática e Bibliometria**.

GRUBER, T.R. Toward principles for the design of ontologies used for knowledge sharing? **International journal of human-computer studies**, v. 43, n. 5-6, p. 907-928, 1995.

HUANG, M.Q.; NINIĆ, J.; ZHANG, Q.B. BIM, machine learning and computer vision techniques in underground construction: Current status and future perspectives. **Tunnelling and Underground Space Technology**, v. 108, p. 103677, 2021.

HORROCKS, I. Description logic reasoning. In: **13th International Conference on Conceptual Structures**, 2005.

KIM, H.; ANDERSON, K.; LEE, S.; HILDRETH, J. Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. **Automation in Construction**, v. 35, p. 285-295, 2013.

KROPP, C.; KOCH, C.; KÖNIG, M. Interior construction state recognition with 4D BIM registered image sequences. **Automation in construction**, v. 86, p. 11-32, 2018.

MOSELHI, O.; BARDAREH, H.; ZHU, Z. Automated data acquisition in construction with remote sensing technologies. **Applied Sciences**, v. 10, n. 8, p. 2846, 2020.

NATICCHIA, B.; CARBONARI, A.; VACCARINI, M. A simulation-based approach for optimal construction planning and scheduling. In: **Creative Construction Conference 2018**. Budapest University of Technology and Economics, 2018. p. 739-746, 2018.

SCHERER, R.J.; SCHAPKE, S.E. A distributed multi-model-based management information system for simulation and decision-making on construction projects. **Advanced Engineering Informatics**, v. 25, n. 4, p. 582-599, 2011.

SHEHZAD, H.M.F.; IBRAHIM, R.B.; YUSOF, A. F.; KHAIDZIR, K.A.M.; IQBAL, M.; RAZZAQ, S. The role of interoperability dimensions in building information modelling. **Computers in Industry**, v. 129, p. 103444, 2021.

SHIROWZHAN, S.; SEPASGOZAR, S.M.; EDWARDS, D.J.; LI, H.; WANG, C. BIM compatibility and its differentiation with interoperability challenges as an innovation factor. **Automation in Construction**, v. 112, p. 103086, 2020.

SIGALOV, K.; KÖNIG, M. Recognition of process patterns for BIM-based construction schedules. **Advanced Engineering Informatics**, v. 33, p. 456-472, 2017.

SOMAN, R.K.; MOLINA-SOLANA, M.; WHYTE, J.K. Linked-Data based Constraint-Checking (LDCC) to support look-ahead planning in construction. **Automation in Construction**, v. 120, p. 103369, 2020.

STAUB-FRENCH, S.; KHANZODE, A. 3D and 4D modeling for design and construction coordination: issues and lessons learned. **Journal of information technology in construction (ITcon),** v. 12, n. 26, p. 381-407, 2007.

VENUGOPAL, M.; EASTMAN, C. M.; SACKS, R.; TEIZER, J. Semantics of model views for information exchanges using the industry foundation class schema. **Advanced engineering informatics**, v. 26, n. 2, p. 411-428, 2012.

ZHANG, S.; BOUKAMP, F.; TEIZER, J. Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). **Automation in Construction**, v. 52, p. 29-41, 2015.

WANG, K.C.; WANG, W.C.; WANG, H.H.; HSU, P.Y.; WU, W.H.; KUNG, C.J. Applying building information modeling to integrate schedule and cost for establishing construction progress curves. **Automation in construction**, v. 72, p. 397-410, 2016.