A Survey on Reasoning on Building Information Models Based on IFC

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Abstract

Building Information Models (BIM) are computer models that act as a main source of building information and integrate several aspects of engineering and architectural design, including building utilisation. They aim at enhancing the efficiency and the effectiveness of the projects during design, construction, and maintenance. Artificial Intelligence, which is used to automate tasks that would require intelligence, has found its way into BIM by applying reasoners, among other techniques. A reasoner is a piece of software that makes the implicit and hidden knowledge as explicit by using logical inferring techniques. Reasoners are applied on BIM to help take enhanced decisions and to assess the construction projects. The importance of BIM in both construction and information technology sectors has motivated many researchers to work on surveys that attempt to provide the current state of BIM, but unfortunately, none of these surveys has focused on reasoning on BIM. In this article we survey the research proposals and toolkits that rely on using reasoning systems on BIM, and we classify them into a two-level schema based on what they are intended for. According to our survey, reasoning is mainly used for solving design problems, and is especially applied for code consistency checking, with an emphasis on the semantic web technologies. Furthermore, user-friendliness is still a gap in this field and case-based reasoning, which was often applied in the past efforts, is still hardly applied for reasoning on BIM. The survey shows that this research area is active and that the research results are progressively being integrated into commercial toolkits.

Keywords:
Building Information Models, reasoning, design assist, survey.

1. Introduction

Building design tools have evolved from paper and pencil to Computer-Aided Design (CAD) systems, to object oriented systems, and recently to the current Building Information Models (BIM) management platforms [25, 31, 85, 90]. These technologies have been adopted by many companies in both Architecture, Engineering and Construction sector (AEC), and Facility Management sector (FM). Using such Information and Communication Technology (ICT) in the AEC and FM industries has revolutionised the entire lifecycle of the construction projects [4, 13, 17].

Building Information Modelling is an intelligent model-based process for planning, designing, building, and managing buildings and infrastructures. BIM provides computer models of buildings that include rich architectural information, intelligent objects, architectural geometries, and data. These models usually store thousands of components and material information as well as geometries and details with underlying structures within it. BIM information is usually available in an integrated digital environment, which makes it accessible to all the project stakeholders, who can access and modify the design in a collaborative and consistent way. Although BIM tools are introduced as a solution to improve the construction process, they do require suitable technology to be implemented effectively and to efficiently take advantages of BIM technology [88].

Theoretically, BIM is supposed to facilitate the project information sharing during the whole life cycle of a building and between all the phases of the project. Further than concentrating all the information in a machine-friendly unique model from the project's stakeholders, the standardisation of this model through the Industry Foundation Classes (*IFC*) [45], has allowed the development of many software tools that extend the current BIM tools and that support this standard. These complementary tools are usually intended to provide assistance and assessments during all the life cycle of the building [48]. The benefits of adopting BIM have been studied extensively in the literature [8, 17, 58, 85, 93]. In particular, two complete and thorough BIM literature reviews were performed by Abanda et al. [1] and by Jung and Joo [48].

The increasing scale and complexity of construction projects has also increased the number of requirements and regulations, the number of stakeholders involved, and the

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quantity of knowledge to manage. This is the reason why the coordination between the stakeholders is more complicated, planning and cost estimations are more difficult, and the possibility of contradictions and errors is higher [79]. On the other hand, using ICT in the AEC industry has increased the possibility of taking advantages of the technologies developed in other disciplines, such as artificial intelligence, to automate and assist the design and construction tasks and to cope with the previous issues, and as a consequence to reduce time and costs.

Artificial intelligence approaches were first applied in the AEC sector in the 1980s [63, 65], and are being applied more and more in this sector since then [9, 12, 18, 21, 34, 43, 61, 62, 66, 70, 75, 86, 91, 98, 99, 102, 103]. Using artificial intelligence in ICT sector is generally intended to help stakeholders take intelligent decisions, which are based on in-depth analysis of the problem and the possible solutions using previously acquired and current knowledge. Furthermore, the decisions proposed by such tools usually allow seeing the basis and the intermediate conclusions that resulted in such decisions. Early proposals used to perform reasoning on the CAD information [5, 26, 33, 35, 53], whereas the standardisation of BIM has increased the number of proposals in the literature that allow maximising its benefits and applications. Applying Artificial intelligence in AEC is an active and extensive research field, in which a huge amount of research has been performed. In this article, we limit our focus on studying the use of reasoning in AEC, and specifically, on BIM.

Reasoning is a subfield of artificial intelligence, in which logical conclusions are derived from existing premises, aka facts; i.e., it generates new knowledge starting from a previously acquired knowledge. Reasoning techniques are now being used in many knowledge intensive fields, including AEC and FM. Recent studies have highlighted the importance of automatic reasoning in improving the capture and processing of building information models [24, 56, 76, 77, 84, 93, 97]. Unfortunately, earlier approaches applied reasoning on proprietary data models, which coupled their proposals to some tools and data objects [95]. Recent proposals leverage BIM and reasoners, which allows them to benefit from the standardisation and to export and reuse the proposed solutions with minimal effort [25].

The literature provides four surveys related to applying reasoning techniques in the AEC industry [24, 37, 92, 95]: Umeda and Tomiyama [92] surveyed the proposals that perform reasoning on devices' behaviours (aka functional reasoning). Watson and Perera [95] surveyed the proposals that use case-based reasoning in the construction field before BIM's emergence; i.e., the proposals that perform reasoning on CAD information. Recently, a survey was performed by Eastman et al. [24], in which the authors surveyed in depth a total of five building code rule-based systems that assess building designs relying on BIM, by analysing four groups of characteristics for each proposal, namely: rule interpretation, model preparation, rule execution, and results reporting. The most recent survey was performed by Greenwood et al. [37], in which the authors briefly surveyed some of the existing code checking proposals. Unfortunately, the previous surveys focused only on a small subset of the potential use of reasoners in the AEC and FM industries, and none of them focused on the proposals and toolkits that apply reasoning techniques on BIM.

In this article, we survey and compare the existing proposals in the literature on applying reasoning techniques on BIM for the building and construction sector of which we are aware, including both research proposals and existing toolkits. To the best of our knowledge, this is the first survey in the literature that surveys existing proposals for reasoning on BIM, and it identifies some applications and conclusions that shall help this sector move forward. Our survey confirms that reasoning on BIM can be used in many applications such as building code compliance, cost estimation, scheduling, energy performance assessment, and inferring missing parameters in *IFC* for interoperability, to mention a few. However, despite of the existing commercial toolkits and the promising research results, the majority of proposals that apply reasoning on BIM have not managed to shift to the industry and restrict to academic use yet. Finally, research in this area is tending towards applying the semantic web technologies to take advantage of the already existing reasoners and tools in this field.

The rest of the article is organised as follows: In Section 2 we define and explain how the surveyed approaches are classified according to categories and subcategories. These categories, subcategories, and the proposals that fall inside each one are described in Sections 3, 4, 5, and 6. Section 7 reports on some ongoing research work or related proposals for reasoning on BIM. We then compare the studied proposals in Section 8, and finally, we conclude our survey in Section 9.

2. Methodology and organisation

The references in this survey were systematically collected by considering many factors, such as the journal or conference in which an article was published and the number of citations. To ensure the quality of the survey, we followed a methodology similar to the one described by Bobadilla et al. [15]; i.e., we followed these steps: (i) most representative topics and terms related to BIM and reasoning were selected to search and identify a collection of candidate articles; (ii) the collected articles were used to identify significant terms that were extracted from their keywords; (iii) these terms were used to search for the articles in journals, conferences, and workshops, giving priority to those with high values in criteria like the importance of the paper and the number of citations. Finally, we tried to balance the number of times a paper is referenced in our survey, aiming to reference the majority of the papers selected.

Applicability	Focus	Proposal
Automatic BIM assessment	Building code and consistency checking	Yang and Xu [99] Bhatt et al. [12] Tan et al. [91] Chen and Hsieh [18] Hyunjoo and Grobler [43] Gianluigi et al. [34]
	Energy performance assessment	Pauwels et al. [75]
	Quality and risk assessment	De Vries and Steins [21] Zhang et al. [102]
Enriching BIM information	Interoperability	Beetz et al. [9]
	Querying	Mendes De Farias et al. [61] Nepal et al. [70]
	Scheduling	Weldu and Knapp [98]
	Quantity takeoff	Zhiliang and Zhenhua [103] Seul-Ki et al. [86] Liu et al. [57]
Building a knowledge base	Assist facility management Scheduling using historical data	Motawa and Almarshad [66] Mikulakova et al. [62]
Toolkits	Building code checking	Solibri Model Checker [44] Express Data Manager Model Checker [46] CORENET e-PlanCheck [49]

Table 1: Classification of the surveyed proposals.

To classify the identified proposals, we followed a bottom-up methodology; i.e., categories are identified based on the existing proposals in the literature, but without limiting them. New research proposals can fall in one of the identified categories, or in a new non-explored category in the literature. In the first case, our survey shall allow the researchers identifying the novelty of their proposals when compared to the previous approaches in the same category. On the other hand, researchers that identify new categories are actually innovating in this research field by identifying new applications of applying reasoning on BIM.

We have identified a total of twenty one proposals on reasoning on BIM, which we have classified into a two-level classification schema. The first level includes four categories of the proposals, which are based on their applicability, namely: automatic BIM assessment, enriching BIM information, building a knowledge base, and toolkits. These categories are described in Sections 3, 4, 5, and 6, respectively.

Table 1 illustrates the organisation of the proposals in our survey: inside each of the previous categories, we have classified the proposals based on their focus, which is the second level of the classification. Automatic BIM assessment category includes the proposals that allow assessing BIM, and based on our surveyed proposals, BIM assessment using reasoners can be of three types, namely: building code and consistency checking, energy performance assessment, and quality and risk assessment. Enriching BIM information is intended to make implicit information in BIM more explicit by inferring relationships, properties, and other information that shall help practitioners to work with BIM. The studied proposals in this category can be classified into four subcategories, namely: enriching for interoperability, enriching for querying, enriching with time information for scheduling (4D), and for quantity takeoff (5D). The proposals that build a knowledge based system are also classified into two subcategories based on their intention, namely: assisting facility management and scheduling based on historical data. For the toolkits category, we have identified a unique subcategory, which is building code checking.

Sections 3, 4, 5, and 6, describe each of the identified categories and subcategories, and the proposals that fall inside each subcategory. For each proposal, we report on the most up-to-date references to the literature, the hypothesis on which it relies, what it is intended for, then, we give a short description of the proposal, and its future plans, if any. Many of these proposals are still in development and the authors do not give many details on them, so we had to make an interpretation of the approach and its details based on what the authors have described in their articles. Furthermore, for the sake of completeness of our survey, we have included a section on the related research proposals (Section 7), which includes those that did not provide a specific proposal on reasoning on BIM, but describe ontologies, frameworks, and platforms for reasoning on BIM.

3. Automatic BIM assessment

The increasing number of regulations and building codes has motivated the building designers to use ICT solutions, including reasoning, to assess their designs for decision-making, especially in the early design phase. The capability of BIM to store multi-disciplinary information is usually used to access parameters necessary for each kind of assessment, infer new parameters, and assess them.

Building assessment includes the proposals that address the different performance facets over the lifespan of a building. Proposals in this category are intended to provide building assessment results starting from the current design to help decision-making, and they are classified into three subcategories, namely: compliance and consistency checking, energy performance assessment, and quality and risk assessment. In the following subsections, we describe each subcategory and the proposals that belong to it.

3.1. Building code and consistency checking

A building is subject to multiple regulatory compliance assessments throughout its life-cycle: during design, building designers shall ensure that all the aspects of their design adhere to various regulatory and user requirements; during construction, new installed building components shall be checked; the facility management requires compliance audits to ensure that the building is used and maintained as required; in the demolition phase, compliance checking is required to ensure the safety of the neighbouring buildings. The International Code Council (ICC) is intensively working in this direction and has created the SMARTcodes initiative [71].

On the other hand, the increasing number of stakeholders that participate in the design and construction, and the high number of changing requirements of building projects may increase the number of conflicts and may violate the requirements and constraints of the project. It is essential to detect inconsistencies and conflicts of the current design.

Automated compliance checking (ACC) in the construction domain started with decision tables in 1969 by the American Institute of Steel Construction (AISC), and has evolved to automatically evaluate parametrised rules for BIM. Recently, Solihin and Eastman [87] presented an approach for classifying rules in automated compliance checking systems. The idea behind ACC is to check building objects against some constraints, and output a list of objects that do not conform and the list of the non-satisfied regulations. It is important to keep the knowledge base and the rules updated according to the regulatory provisions, which usually vary according to the region and country.

IFC model, which is considered as a viable format for the exchange of data in a code-checking system, also allows to include quantitative and qualitative constraints. However, due to the complexity of the constraints for building codes and regulations, it is not unusual to define the building constraints and restrictions as rules by using a rule language, and by applying a reasoner to check them and report whether the project satisfies them or not.

We have identified six proposals in the literature that belong to this subcategory, namely: Yang and Xu [99], Bhatt et al. [12], Tan et al. [91], Chen and Hsieh [18], Hyunjoo and Grobler [43], and Gianluigi et al. [34]. These proposals are described in the following paragraphs.

Yang and Xu [99] consider that knowledge formalisation and information modeling shall help in the development of building design support systems, and that despite the existing technologies, there is still a lack of a web-enabled solution to support online building code compliance checking. Their proposal is intended to formalise the building code knowledge and to build a prototype as a proof of concept of an online automated-code checker for the national plan in Singapore [49]. Their approach reads an *IFC* file, and enriches it with property set definitions (Pset). The user-defined rules and the knowledge base are read from an *XML* file, and Jess rule engine [28] is run on the *IFC* model and on some predefined enriching rules to perform a geometric reasoning. Geometric reasoning infers the objects and relations necessary for code checking, and that are not explicit in the original *IFC* file. The code-checking rules from the chosen regulations are then run to check the model compliance. A report using HTML tables with some comments to help the users identify the building components that did not satisfy the rules is shown using a Web user-friendly interface.

Bhatt et al. [12] consider that Ambient Intelligence (AmI), which is involved in building smart homes, is becoming a mainstream, and that it shall be considered from the initial building design phases. According to the authors, the designers shall count on a tool that helps them to validate the functional or intelligent behaviours of their buildings. The authors consider that spatio-terminological reasoning can be a useful way to ensure that the designed building satisfies the requirements. Their proposal is intended to validate smart environments during design phase by validating structural and functional requirements. It builds on three ontologies that model the architectural elements, the spatial relationships between these elements, and the metrical and geometrical information of these elements. Once these ontologies are populated with the building information from its *IFC* file, and the describing rules for smart buildings are defined, the *RacerPro* [39] reasoner for spatio-terminological inference is applied to validate the current design.

Tan et al. [91] consider that the automatic checking of building compliance for codes and regulations is a complicated task since it covers different building functions, that existing tools still have some limitations dealing with design regulations, and that existing code compliance techniques build on some values that are not part of the BIM model. Their proposal, called ACCBEP, is intended to enrich BIM by simulation results and building codes to perform compliance checking for the building envelop design. It exports the current design model into *IfcXML*, including the materials, dimensions, and other information necessary for performing simulation. A simulation tool for transient hygrothermal analysis of building envelopes is run, and the simulation results and the building information model are now used to create a so-called Extended Building Information Model (EBIM). User-defined code checking rules for envelops are run on the model using JBoss [7] as a rule engine. It checks the compliance of the exterior walls design using a decision table, and then generates an assessment report to highlight the building walls that do not comply the regulations.

Chen and Hsieh [18] consider that automating calculation and rule-checking relieves the designers from the tedious, repetitive and error-prone manual process to check their current design code compliance. Their proposal is intended to automate the evaluation of compliance of the current design with green building standards and give real-time visual feedback to the designer using BIM, rule-based reasoning, and virtual reality technologies. Given an *IFC* model, a so-called model extractor extracts the data required for the evaluation formulas and inserts it as facts into a *NOSQL* database. Predefined rules that implement the calculation formulas for the Green Building Code and the facts are inserted into the reasoner, which infers new facts that include the results. The inferred facts are sent to a so-called model control system, which interacts with Revit for a real-time visualisation of the results.

Hyunjoo and Grobler [43] extended a first work by the same authors [51], in which they studied the development of a light-weight ontology model to support reasoning in early design phases using *OWL_DL* and *SPARQL*. The authors consider that the high number of stakeholders participating in a building project increases the number of conflicts and violations of constraints and requirements. This proposal is intended to successfully coordinate the design process by performing reasoning on BIM for consistency checking, and conflicts detection during the design phase of the building. The authors handcrafted an ontological representation using *OWL_DL* to model the restrictions and constraints. This ontology is populated by extracting the building information and constraints from the building *IFC* file and mapping them into this ontology. A reasoner is now run on the ontology and its instances to identify inconsistent components and notify about the detected conflicts; i.e., it notifies whenever a new building component, that does not satisfy the existing constraints and model requirements, is added to the model. The extraction of the constraints is performed manually in this proposal, but the authors mention that they were working on an automatic constraints extraction from the *IFC* file.

Gianluigi et al. [34] consider that building designers have to check their designs continuously due to the increasing number of stakeholders and of the changing requirements. Furthermore, the authors consider that the existing technologies, like ontological models that rely on reasoners to detect inconsistencies and conflicts, can be used to assist building design process by verifying the performance and alerting the designer in case of inconsistency. The authors mention that their proposal is intended to check the current design consistency against the design constraints and the fulfilment of client's requirements. The *IFC* model of the building under design should first be exported to a relational database. This database is used to populate an ontological model that represents the BIM knowledge. Then, the user requirements are defined by means of *SWRL* rules [41], and Jess reasoner [52] is applied on the ontology and these rules inside Protégé [72]. The inferred results and the modified instances are shown in Protégé and can be exported to a text file.

The high number of proposals in this subcategory is due to the increasing interest of organisations and governments in automated building code and consistency checking. On the other hand, the majority of the proposals in this subcategory has taken advantage of the semantic web technologies, and use existing reasoners from this research area.

3.2. Energy performance assessment

Energy performance assessment of a building can be done using dynamic or quasi-static models. Dynamic models apply physical models and real-world constraints and variables to model the time varying behaviour and they provide highly precise calculations [20, 73]. Unfortunately, they require the building model to be more complete and also require more time when compared to quasi-static models. Quasi-static models are not based on time and they estimate the energy performance of a building applying simplified rules and formulae, and using average or predefined values. The latter is usually faster but less precise [83].

Reasoning can be used to perform quasi-static and on-the-fly performance assessment for design assistance. The idea is that assessment rules, containing formulae, are fired automatically whenever the necessary building information is available. Using reasoners abstracts the designer from the level of details (LOD) concept since it is not mandatory to know the necessary LOD for each kind of performance assessment. An example within this subcategory provides the work of Pauwels et al. [75], which concludes that semantic web technologies applied on BIM shall allow selecting and converting the relevant information into the required structures easily, and without using Model View Definitions (MVD). The proposal is intended to demonstrate that relying on the power of logic techniques, the declarative approaches provided by the rule engines, and the query processors of the semantic web technology, performance assessment using static simulation models can be performed. First, the input *IFC* file of a given building is converted into the Resource Description Framework format (*RDF*) using an online tool developed by the same authors (UGent MultiMediaLab)[1]. Information in *RDF* is used to create the explicit building information (aka facts) in the knowledge base, whereas, *N3Logic* [11] is used to express the rules. The knowledge base is enriched with more explicit information by integrating existing construction information, such as acoustic and thermal characteristics, from existing relational databases. A collection of rule sets is added to the knowledge base, in which each rule set is intended to infer implicit information from the explicit *RDF* information and to study a specific domain; i.e., acoustic or thermal performance. Some of the rules inside a given rule set are intended to convert existing information into new information that is necessary for other rules to perform their calculations. Then,

[1] The online tool is not available anymore.

the *EYE* reasoner [81] is run on the entire knowledge base and generates the output, which is added to the knowledge base and is expressed in *RDF* statements also. Depending on the defined rules, the inferred statements can show the calculated values directly, or just an indicator that shows how good a result is for a given standard.

Despite the importance of assessing the energy performance of the buildings, especially during the design phase, the number of proposals in this subcategory is still low. However, the promising results achieved by Pauwels et al. [75] shall encourage other researchers to investigate this type of applications for reasoning on BIM.

3.3. Quality and risk assessment

Working conditions, comfort, and indoor environmental quality are qualitative assessments necessary to obtain approval for constructing and occupying buildings. Furthermore, meeting human preferences of comfort, safety and privacy are major factors in the success of construction projects [32]. These factors are usually evaluated manually after a building has been constructed using surveys and check lists [42, 100]. BIM has allowed to perform automatic qualitative assessments during the design phase to detect problems and safety issues early, and consequently, avoid costly building changes during construction or once constructed.

Reasoning can be applied during the design phase to automate the quality and risk checking of the building. We have identified a proposal in the literature, by De Vries and Steins [21], in which the authors apply reasoning on BIM to assess the working conditions of a given building, and another proposal by Zhang et al. [102] that analyses the construction risks of a construction project, based on its schedules. Both proposals are included in this subcategory and are described in the following paragraphs.

De Vries and Steins [21] affirm that some building regulations related to the working environment are often vague and ambiguous, which makes validating them using classical rule-based systems a difficult task. Their proposal is intended to formalise non-formal and open-for-discussion regulations, by using fuzzy logic and applying a reasoner on the building's *IFC* file, in order to detect possible building problems beforehand and to prevent costly changes in the building. Input *IFC* files are first read to retrieve the geometric information, which is enriched with two kinds of data necessary to check the regulations, namely: physics data such as acoustic and lightening measurements, and organisational data that provides occupational information. Since both kinds of data are obtained using external simulation tools, users have to perform some manual work to configure these tools, provide them with the inputs, and to integrate the simulation results. Later, the regulation rules shall be modelled in a fuzzy rule-based system. The reasoning results are then aggregated, defuzzyfied, and reported by adding them as an extension to the input *IFC* file, whereas building objects that do not comply with the working-condition regulations are highlighted in an *IFC* viewing tool.

Zhang et al. [102] consider that BIM design tools do not provide model checking functions themselves, and that the information available in BIM and the schedule of a construction project can be used to detect safety hazards during construction and to suggest preventive measures. Their proposal is intended to detect the safety issues and hazards that could take place during and after the construction of the project (why, where, when, and what), and to provide the guidelines to fix these issues. The proposed method is based on If-Else rules to process the safety rules. It reads *IFC* files generated by the design tool and the construction schedule provided by the user, and allows rerunning the rule engine whenever the design or the schedules are updated. Its rules, which can be customised by the project manager using a graphical user interface, detect two types of safety issues, namely: safety issues for the construction workers during the building construction phase, and safety issues that may affect the building users. Furthermore, the proposal counts on a library of safety actions used to propose corrective actions that can be taken into consideration to resolve the detected safety issues.

The proposals in this subcategory try to assess qualitative and subjective features of the buildings, and need external information to be able to perform this assessment. However, the reported results are considered as subjective, and may be considered as warnings by the building designers.

4. Enriching BIM

Although BIM provides a rich representation of the design of a building, there are still many challenges in getting construction-specific information out of BIM, which limits the usability of these models for construction and other downstream processes [70]. Furthermore, *IFC* is an open standard, in which not all the information is mandatory and missing information can be introduced by hand for interoperability reasons. For instance, some component properties like component shape and relationships, which are usually missing, shall be inferred by applying geometric and spatial reasoning on the building components.

Since introducing such information by hand is a tedious and error prone task, it is preferred to automatically infer required data wherever possible [24]. Reasoning on BIM is considered a solution for this challenge since it allows to infer the missing information and even to automatically create a richer representation of BIM.

We have classified the proposals that apply reasoning on BIM for automatically enriching the building information into four subcategories, based on their focus, namely: interoperability, querying, scheduling, and quantity take-off. In the following subsections, these subcategories are introduced, and the proposals that fall inside each subcategory are described.

4.1. Interoperability

The high costs of interoperability in AEC sector were identified by Gallaher et al. [29]. The challenge emerges when trying to merge the different models from different stakeholders, that have used heterogeneous applications and systems during the project phases [38]. BIM has been considered as one of the solutions for reducing interoperability costs but this is still an open challenge in AEC to date. Reasoning on BIM for solving interoperability problems is a possibility, since some information needed by some applications can be inferred applying reasoning on the available information in the original model. For instance, given an *IFC* model of a building exported from a BIM tool, it is necessary to add some information to the model so that it can be used by energy performance tools. This is necessary since CAD applications use geometry-centred models, whereas energy performance tools use topological space-centred models; this information can be inferred using reasoning. Beetz et al. [9] consider that existing technologies can be used to facilitate the interoperability in BIM. Their proposal is intended to enrich the input model with spatial relationships, by performing topological reasoning, so that it can be used by the energy performance tools that usually need topological models. The final goal of the ongoing work is to demonstrate that applying semantically enhanced reasoning services shall allow integrating decision support tools during the design process and solve interoperability issues; i.e., it can be used to enrich models and prepare them for further tools, such as the ESP-r performance simulation tool [89]. The developed method takes an *IFC* model as input and converts it into *IfcOWL* model, which was proposed by the same authors in [10]. Then, since the authors assume some boundary conditions, the model is checked to ensure that the spaces do not overlap and that walls are connected to each other only at their endpoints. *SPARQL*, as a query language for *OWL*, is used to retrieve the relevant entities and relationships from the *IfcOWL* model and map them into a partial model that contains all the information necessary for the next step, in which reasoning is performed by applying an implementation of the *RETE* algorithms [27]. The inferred information is reintroduced into the model for further use during reasoning. The output is a model with sufficient spatial relationships information that can be used by simulation tools.

Although interoperability is an issue in BIM, only one proposal, by Beetz et al. [9], has applied reasoning on BIM to resolve it. However, the results obtained by this proposal shall encourage the researchers to investigate this field as one of the possible solutions.

4.2. Querying

An *IFC* model usually contains a huge amount of information on a construction project. Unfortunately, it is not easy for the stakeholders to retrieve the information of their interest, and many features and properties may not be explicitly present in the model.

Proposals in this subcategory aim at enriching BIM for providing stakeholders with richer representations and with information of interest for each stakeholder, to ease the burden of model querying. Two proposals were identified for this purpose, namely: Nepal et al. [70], and Mendes De Farias et al. [61], which are described in the following paragraphs.

Nepal et al. [70] consider that despite the rich representation of a building in BIM, it is challenging and time consuming to retrieve specific information relevant to construction practitioners from it. According to the authors, BIM does not include many properties for the building components, so construction professionals spend too much time and effort in analysing and interpreting the design information manually to identify construction-specific information. Their proposal is intended to create a richer and more explicit representation by including construction-specific information, and to avoid the error-prone manual process. This is achieved by relying on ontological models, query processing, and on the previous research for creating design-specific construction knowledge. The authors use an ontology that represents a wide range of construction-specific information; i.e., features, their values, and the relationships among them. This ontology is populated using the design model in *IfcXML* format. Then, a rule-based reasoner is applied on the ontological model to infer the features, which are added to the *IfcXML* model. This model is then mapped into a construction-specific feature-based model (FBM), that is an enriched representation of BIM, tailored for construction stakeholders, and that provides formal and configurable query methods for the users interested in retrieving additional information from the model.

Mendes De Farias et al. [61] consider that BIM integrates heterogeneous data and processes, which hampers data querying, retrieval, or modification on BIM, and that the semantic web technologies can be used to reduce this effort. Furthermore, they claim that it is possible to increase the data model expressiveness without compromising the interoperability of *IFC* files. Their proposal is intended to enrich *IFC* model by reasoning on an ontological model and a set of rules to create new objects, which are necessary for further stakeholders and other BIM tools. The *IFC* data model is first exported to create an ontological model similar to *IfcOWL* ontology proposed by Beetz et al. [10]. This ontology is visualised in Protégé tool, in which *SWRL* rules are also defined. The authors created rules that infer new objects necessary for facility management sector to perform the case study. Later, a parser is used to export the *IFC* data from the *IFC* file in order to populate the ontological model. The reasoner is run to infer new objects, which are added to the model that can be viewed and queried in Protégé. This model now contains more explicit information that can be queried more easily by the practitioners in the facility management sector.

The proposals in this subcategory try to make explicit what is implicit in BIM in order to help practitioners in the AEC sector to access this information more easily. Furthermore, Mendes De Farias et al. [61] consider that it is necessary to provide an extended model of BIM that contains the inferred features and characteristics.

4.3. Scheduling

An important application of BIM is the one related to scheduling the construction activities and linking them to the construction objects. It is called 4D BIM and it is intended to allow all the stakeholders in a project to visualise the tasks schedule and the progress of the current project.

Reasoning has been used to solve construction planning problems during the last decades [3, 23]. BIM has allowed applying the existing planning techniques to schedule the tasks of construction projects by taking into account the project constraints, such as temporal restrictions and structural constraints. A representative example in this regard provides the work of Weldu and Knapp [98]. They consider that creating a schedule for a construction project during early design phases is difficult and error prone; i.e., it requires visualising and performing a mental walk through the structure to be built, which can only be performed by experienced schedulers. Furthermore, the authors consider that BIM already contains the information necessary to perform a reliable cost estimation, scheduling, and visualisation of the schedule information. Their proposal presents an ongoing research that aims at generating a technologically and physically meaningful construction sequencing, associating the tasks with BIM components, and visualising them, based on a rule-based spatial reasoning. Given an *IFC* file from the design tool, this proposal applies a reasoner to infer the components, their relationships, and new information useful for deciding the logic of a sequence of tasks at the component level. Then, the project manager shall provide the rates of production and the quantities that cannot be inferred from the model. A spatial reasoner is applied to divide the scheduling process into three high level and interrelated blocks: i) the structural components, which include the critical structural blocks; ii) the internal construction; iii) the finishing works.

4.4. Quantity takeoff

Quantity takeoff is one of the most important applications for BIM [64]. Traditionally, quantity takeoff was performed manually by identifying building items and their relationships, calculating dimensions, and aggregating the quantities of the identified items. BIM has allowed to automatically perform many of these tasks accurately, and to make a cost estimation automatically and directly from the model, if the model contains enough details.

Reasoning can be applied on BIM to perform quantity takeoff by defining rules to identify the relevant components, extract the material quantities that exist among construction products, calculate the quantities such as volumes and areas, generate the item description, count the number of occurrences, and then generate the bill of construction products. Three proposals in the literature were identified in this subcategory, namely: Zhiliang and Zhenhua [103], Seul-Ki et al. [86], and Liu et al. [57].

Zhiliang and Zhenhua [103] consider that traditional construction cost estimation is error prone and time consuming, and that the current technologies, like BIM and ontologies, shall allow performing an automatic and accurate construction cost estimation. Their proposal is intended to perform automatic project cost estimation by enriching BIM with information necessary for a prior calculation process using *OWL* and an existing reasoner. The authors first define an ontology to represent the BIM knowledge in *OWL*, which is populated by mapping information from three sources, namely: i) the information from *IFC* file, which is transformed into *OWL*; ii) the information from the chosen construction cost specification; iii) historical data from previous projects that can be used to infer the costs of some unknown elements during reasoning. Then, rules of three types are defined using *SWRL* [41], namely: i) rules that infer construction information that is not included in the design model, and that is available in the historical data collected from previous projects; ii) rules that are intended to infer the cost items from the construction products; iii) rules that are necessary to infer the spatial relationships among construction products, and that are necessary for cost estimation. *JessSWRL* [52] reasoner is then applied to enrich the knowledge base with all the information necessary for construction cost estimation. Finally, the authors apply two processes: a first process that uses the previous information to perform an automatic quantity takeoff and a second process that automatically calculates the costs using the user-provided information about prices. These processes return the cost reports to the user by including them in the *IFC* file.

Seul-Ki et al. [86] consider that the information included in BIM allows to automatically infer appropriate work items in order to overcome the subjectivity of cost estimators and to automate the cost estimation task, and that ontological models shall help reasoning on the data for this purpose. Their proposal is intended to use semantic reasoning on BIM to infer work items based on work conditions, and then to perform a cost estimation. The authors define an ontology that models the so-called work conditions such as room usage, building elements, and finishing thickness, and another ontology that models the work items such as tile type, tiling material type, and joint material type. The *IfcXML* data is first read to find the working conditions. Then, retrieved components are transformed into *RDF*, which is used to populate the ontological model on work conditions. The Semantic reasoner Bossam [47] is then applied on both ontologies to infer the work items, which are used to populate the work items ontology. The results can be visualised in Protégé, queried using *SPARQL*, and exported into *XML* for their usage in cost estimating applications.

Another proposal was provided by Liu et al. [57], in which the authors considered that current BIM information lacks domain semantics to extract construction-oriented quantity take-off information, and that some important information in BIM remains implicit, which restricts information extraction from the BIM model for downstream analyses in construction. They propose a so-called ontology-enhanced BIM model, which contains BIM information for light-frame buildings, enhanced with domain terms, properties, and interrelationships, that are necessary for quantity take-off. The ontological model, which is defined in *RDF*, is populated from the *IFC* file of the building design using a so-called BIM data parser. Then, *SWRL* reasoner is applied on the ontological model to infer missing relationships, and inferred facts are reinserted into the reasoner for further reasoning. At the end, the ontology-enhanced BIM model is generated, containing the required construction-oriented quantity take-off information. The results can be visualised in Protégé and can be queried using *SPARQL*. The authors mentioned that the provided prototype in the article does not fully comply with the proposed approach due to some technological and research limitations.

The importance of quantity take-off, which is considered as the fifth dimension of BIM, can be seen in the high number of proposals in this subcategory, when compared to the other ones. All of these proposals take advantage of the semantic web technology by using its language and reasoners.

5. Building a knowledge base

It is possible to use the knowledge acquired from previous problems and their solutions to find solutions for new problems, based on the premise that similar problems have similar solutions. Case-based reasoning are usually used for this purpose: given a problem, the reasoner searches for similar cases in the case-base and adapts their solutions to create a new solution for this problem [80, 96].

Beside the knowledge representation and the need to count on rich historical data, the challenge of case-based reasoning resides in finding which attributes of the projects shall be considered for their comparison, in defining a threshold for the calculated similarities, and in finding which attributes have more influence on the overall similarity [5, 50]. Earlier proposals used to apply case-based reasoning using CAD objects [23, 36, 56, 62], whereas recent ones started using BIM objects [62, 66].

In the following subsection, we describe two subcategories that use case based reasoning on a knowledge base, namely: assisting facility management, and scheduling using historical data. Inside each subcategory, we describe the proposals that belong to it.

5.1. Assist facility management

The longest phase of a building life-cycle is the operation phase that constitutes about 60% of the total cost [2]. Facility management ensures efficient and effective functionality of a building by integrating people, place, process, and technology during operation phase of a building [19]. Current technologies focus on transferring BIM information to the facility management software to support planning maintenance activities.

According to Volk et al. [93], reasoning is essential to provide unambiguous attribute definitions and to improve the capture and processing of building information, allowing future facility management and deconstruction functionalities. Furthermore, the use of reasoning shall allow resolve future building problems based on the knowledge base built, and taking advantage of the previous experiences.

Motawa and Almarshad [66] consider that the majority of the current facility management tools focus on capturing the building maintenance information, and not on capturing the knowledge that can be used to support maintenance decisions and prevent the building deterioration. Their proposal, called KMOBM, is intended to develop an integrated knowledge-based BIM system that captures the knowledge on building maintenance and apply case-based reasoning to assist building maintenance teams trace the building history and learn from previous cases. The authors devised a taxonomy to model the maintenance tasks in order to easily capture the knowledge, and to apply the case-based reasoner. The taxonomy includes the building elements, which are part of the building *IFC* files. The case-base is populated with historical maintenance cases, which are structured according to the developed taxonomy and include for each case various attributes, such as the affected building elements, the problem and its solution, to mention a few. Whenever a new maintenance case is reported, the case-based reasoner searches for the most similar case in the case-base using the nearest-neighbor technique that applies similarity scores. It shows the similar cases and the ones related to the same building element in the case-base, and sorts the results according to their similarity. The identified solution and the results are also saved in the case-base to solve future cases.

5.2. Scheduling using historical data

In AEC, case-based reasoning is used to support designers by previous experiences [59, 60]. For instance, it is used to produce construction schedules and cost estimations of a project in order to reduce planning and cost estimation efforts in recurring situations; i.e., time and cost information from previous successful projects are used to infer a possible schedule and a possible cost of a new construction project. The idea is to apply case-based reasoning to find projects from the knowledge base similar to the current one since construction processes usually do not change much. To find similar projects, a similarity model is used, in which attribute similarity calculations are defined, weighted, and combined. Applying case-based reasoning for design tasks in architecture has been also known as case-based design (CBD). Regarding

BIM, we have identified one proposal in the literature by Mikulakova et al. [62], that belongs to this subcategory. The authors consider that hand-crafted schedules for construction projects usually suffer from errors because of the incompleteness of the available information when schedules are performed, and due to the fact that schedules are not updated when the project conditions change. Their proposal is intended to generate and evaluate different scheduling alternatives for a given construction project, to allow the project manager to choose the schedule that best fits, and to dynamically regenerate the chosen schedules in case the project is modified. Given the *IFC* file of a new project, an *IFC* tool extracts the components from it and compares them to the case-base using a similarity measure between the components. The case-base for the case-based reasoner, which contains previous successful scheduling projects, is supposed to be populated by the project manager, who decides which projects shall be added to it. Each case in the case-base contains construction parts, which consist of one or more BIM building components, and the successful schedule of this project. The result of the similarity check is obtained by weighing and adding the similarity measures of similar geometric components and similar materials. Once similar cases are identified in the case-base, the next step merges their schedules to create the best schedule alternatives, which are reported to the project manager. This process is repeated each time the project is modified. The proposal was later extended by Hartmann et al. [40] to include a hierarchical structure that stores related cases and abstract elements, which allows to cover a wide range or objects involved in the building process.

6. Toolkits

This category includes the toolkits that apply reasoning on BIM. These toolkits are usually intended to provide commercial or non-commercial software for practitioners, who are interested in assessing their current design. The existence of such toolkits is a clear example of the importance of applying reasoning on BIM not only in the research field. However, all currently available toolkits we have identified belong solely to the subcategory building code checking.

As already mentioned in Section 3.1, building code checking is an essential task to validate the design of a construction project using automated compliance checking systems. This has encouraged some companies and even governments to create toolkits for building code checking that allows validating the buildings' models.

Solibri Model Checker[2] [44], aka SMC, is a commercial, rule-based, and BIM quality-assurance platform. It is one of the most mature rule-based systems that is intended to support checking the integrity, quality and physical safety of building projects by analysing their *IFC* models and checking that the models comply with building codes and other standards. SMC reads the *IFC* file and maps it into an internal structure. It first performs some basic prechecking of the model to detect geometric clashes, such as overlapping and inconsistencies in the design. It has many built-in and configurable rules that can be activated and parametrised depending on the study case, such as accessibility and fire code checking rules. These rules are grouped into rulesets, where each ruleset can be activated and applied according to the user's selection. However, the number of rulesets already included in SMC is increasing continuously. The validation results are reported in different formats, and can also be viewed in an *IFC* viewing tool, in which clashes are highlighted. Although SMC provides an API, the rule engine and rules are vendor-specific and the API is not public, so users can only configure the parameters of the existing rules, or contact the vendor in case they are interested in adding new rules. It has been used in many real world projects such as HITOS project [55], and projects from some Australian institutions [14], to mention a few.

Express Data Manager Model Checker[3] [46], aka EDMmodelchecker, is also one of the most advanced rule-based systems and is part of the Express Data Manager Suite, developed by Jotne EPM Technology in Norway. It provides a flexible rule definition system by allowing the encoding of new rules into computer code using the EXPRESS language; i.e., rules and functions can be defined using the EXPRESS schemata, which is the same language used to define the *IFC* standard. It is intended to automate the design checking process of a given building, by analysing its *IFC* model against a given set of regulations and building codes and verifying its consistency. EDMmodelChecker reads an *IFC* file, validates it according to the *IFC* EXPRESS schema, and applies a number of predefined rules. This kind of validation allows to check *IFC* files against the EXPRESS schema to ensure that they conform to all the rules and constraints in collaborative teamwork environments. Users can also define their own rules separately and select which rules shall be checked for each project. For instance, the Australian Building Code was defined using EDMmodelChecker [14]. Once the model is validated, a report is created as a text file. Although it provides a flexible system for extending the existing rules, writing rules requires users with technical background to be able to define them. It has been used in many real-world projects as a part of the Express Data Manager Suite.

CORENET e-PlanCheck[4] [49] is a part of the Singaporean governmental project called COnstruction and Real Estate NETwork (CORENET), which was launched in 1995 by several government agencies of Singapore [49]. It is one of the earliest rule-based systems that is intended

[2]http://www.solibri.com/products/solibri-model-checker/

[3]http://www.jotneit.no/products/express-data-manager-edm

[4]https://www.corenet-ess.gov.sg/ess/

to perform automated rule checking for buildings during design phase, using cutting-edge computer aided design and drafting technologies incorporated with expert knowledge and artificial intelligence system. CORENET builds on a client-server architecture, in which clients upload their *IFC* files, CORENET e-PlanCheck reads the building *IFC* file and creates FORNAX objects, which are enriched objects that extend the *IFC* Schema by including additional inferred attributes and semantic information to enable the implementation of checking functions. CORENET e-PlanCheck contains an updated database with the regulations used to conduct audit checks. These regulations are expressed by computer-coded rules, which are of two kinds, namely: rules to check building plans, and rules to check building services. Since the FORNAX objects and attributes are created depending on the building's type, the rules are also different for each building kind. Once the system has finished its checking process, it generates a downloadable report, in which detected violations are highlighted, and inconsistencies are illustrated using the FORNAX viewer. CORENET e-PlanCheck is one of the leading rule-based applications for building code checking. It has been adopted and used by many building projects in Singapore and has promoted the development of similar solutions in several countries [24].

All the existing toolkits that rely on reasoning on BIM focus on automating the building code checking process. This clearly shows the high interest of the BIM practitioners in the automated validation of the building designs, and on the need of such tools in the market.

7. Other related research proposals

In addition to the research proposals discussed above, the literature contains several related work to reasoning on building information models. Some of them just describe an ongoing work or some future research ideas, whereas the other ones describe some frameworks that do not apply reasoning on BIM, but provide a platform to develop such approaches without starting from scratch. In the following, we briefly describe them for the sake of completeness of our survey.

Borrmann and Beetz [16] presented two possible applications of spatial reasoning on building information models (BIM). The first application is to detect contradictions between individual requirements and/or regulations. The second application is to perform a compliance checking of the devised building with a specific regulation or with the client's requirements. However, this work did not provide a specific proposal but just a description on using reasoning techniques on BIM, possible models for using directional relationships, and two possible implementation concepts.

Kruchten et al. [54] proposed an ontological model to build an architectural knowledge base, on which existing reasoners can be used to support architectural tasks and design decisions. Similarly, Zhang and Issa [101] proposed a lightweight ontological model for reasoners. Gao et al. [30] presented *BIMTag*, which provides a lightweight ontology in order to support semantic annotation of BIM product documents without using reasoning. It applies a word-level annotation algorithm and a latent semantic analysis technique to discover the relationships which are not explicitly defined in an *IFC* file.

Kim and Grobler [51] proposed a framework for reasoning on BIM, based on a lightweight ontological model. The framework allows to apply automatic reasoning techniques on the model, and the user to interact, retrieve, store, and inquire the information and the inferred results to make decisions efficiently. The framework was validated by some possible use cases for performing spatial reasoning on *IFC* models. Another framework was presented by Wang et al. [94], who proposed an ontology-based framework that allows retrieving, classifying, managing, and reasoning on construction information. Similarly, Nawari [67–69] proposed an ontology-based framework for BIM-model checking using first-order logic.

Recently, Andres et al. [6] proposed a framework to develop case-based reasoning systems based on ontological models, whereas Paul and Charlesraj [74] proposed a conceptual framework that includes a knowledge-base for reasoning on Building Information Models to make easier the facility management tasks using ontological models.

Another ongoing work was presented by Weise et al. [97], in which the authors studied linking rules with *IFC* to develop an *IFC*-based scheduling assistant, similar to that one proposed by Mikulakova et al. [62], but that allows to visualise the schedule in MS Project and to link its tasks to the *IFC* components in an *IFC* viewer.

As for the toolkits, since the appearance of CORENET, several countries have tried to build similar rule-based solutions to automate building code checking, unfortunately, not all of them have continued. SMARTcodes was introduced by the International Code Council (ICC) in 2006 to check US building codes and standards, and its first versions were performed by Digital Alchemy and AEC3 companies, in which SMC and EDM were used. SMARTcodes development stopped by 2010 [78].

Another project was DesignCheck [22], which is an object-based rule system that was founded by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia and was first named as BCAider in 1991. It started using two rule-based engines to automate building code checking during design, namely: SMC and EDMmodelchecker. Later, they decided to only use EDMmodelchecker since it allows to freely edit the rules [22]. However, the project, which was never launched commercially, is not active any more [78].

HITOS is a European project that was founded by the Nordic countries and led by the Norwegian governmental agency Statsbygg [55]. It was intended to experiment with interoperability between different BIM platforms and rule checking. It uses dRofus as a rule-based system for checking spatial requirements, whereas SMC is used as a rule-based system to check the accessibility building code.

The project is still active and, according to a recent report [78], it has received more than 60,000 submissions for validation between 2005 and 2012 through ByggSøk, which is the project's portal.

Recently, General Services Administration (GSA) has funded a code-checking system for spatial validation in US Courthouses, that is based on *IFC* and SMC as a rule checking platform [82].

8. Comparative analysis

The comparison of the studied approaches is reported in Table 2. In the following subsections, we first describe the compared features, and then we discuss the comparison table.

8.1. Compared features

We have identified a collection of six features to compare the studied approaches side-by-side in Table 2. The compared features are described as follows:

Internal model: This refers to the information model used internally in the studied proposal. Many proposals read *IFC* files, but then, they convert them into an internal model in order to perform reasoning. This feature states the internal model type used by each approach.

Reasoner and rules: This refers to the kind of reasoner and rules used in the proposal. Some proposals reuse already existing reasoners and rule languages, whereas others use ad-hoc ones. This feature states the used reasoner and rule language, if reported.

External data: This states the kind of external data needed by the proposal, such as simulation results. In some cases, it is necessary to count on more information to be able to infer more useful conclusions. This feature states what kind of information is needed, if any.

Configurable rules: This refers to whether the rules in a proposal can be configured by the user or they are predefined. Some of the existing proposals already contain a collection of specific rules, whereas others allow including user-defined rules. This feature states whether it is possible for the user to configure these rules or not.

Reporting: This refers to how each proposal reports on the inferred results after reasoning is performed. Since it is important to properly report on the inferred results, the proposals try to show the results in user-friendly reports. This feature states how these reports are shown.

Case study: This refers to whether the authors provided a case study to validate their proposal or not. The existence of such case study may allow detecting the maturity of a given proposal.

8.2. Discussion

This section reports on the results of our analysis regarding the previously addressed features. Table 2 extends Table 1 by reporting and comparing these features, in order to have a complete view on the surveyed approaches and their characteristics.

The majority of the studied proposals can be applied during the design phase of the buildings, except for that ones by Motawa and Almarshad [66] and Mendes De Farias et al. [61], which are applied during the facility management phase. This is due to the fact that reasoning on BIM is generally used for decision-support during the design phase of buildings. Furthermore, all the compared toolkits that apply reasoning on BIM focus on building code checking during the design phase.

Since our survey focuses on reasoning on BIM, all the studied approaches take *IFC* files as input. However, not all the proposals work on the *IFC* model internally; i.e., many of them read *IFC* and convert it into an internal model. Roughly half of the research approaches work on ontological models defined in *OWL* or *RDF*, including the ad-hoc ontology called Feature-based ontological Model (FBM) proposed by Nepal et al. [70]; the other half works directly on the *IFC* model, including the work by Tan et al. [91] that extends the BIM model by creating a so-called Extended BIM (EBIM). The toolkits use proprietary internal models, except for CORENET e-PlanCheck [49] that works directly on *IFC*. This shows how the research on reasoning on BIM is tending towards using the advances in the semantic web technologies.

Regarding the reasoners and the rules used, our comparison shows that many proposals take advantage of existing reasoners and rule languages for the ontological models; i.e., Jess, RacerPRO, and EYE as reasoners, and SWRL, *OWL* constraints, and N3Logic as rule languages. Some approaches use decision tables and fuzzy tools, whereas a few do not give any details on the used reasoners and rules. As for the type of reasoning used, all of them use rule-based reasoning, except for Motawa and Almarshad [66] and Mikulakova et al. [62] that use case-based reasoning.

According to our comparison, almost half of the proposals need external data to enrich the internal model. Reasoning on the enriched model allows assessing the building performance and estimating costs and schedules. Furthermore, according to Table 2, the majority of the studied approaches allow users to configure rules, but many of them require users with technical knowledge to be able to edit the rules. For instance, in the case of both Solibri Model Checker [44] and Express Data Manager [46], the rules can be tuned and configured but with some limitations since they may require technical knowledge.

As for reporting, although the majority of the proposals provide a reporting service to present the reasoning results, only few of them provide reports in a user-friendly viewer and not using development tools such as Protégé,

Applicability	Focus	Proposal	Internal model	Reasoner and rules	Need external data	Configurable rules	Reporting	Case study
Automatic BIM assessment	Building code and consistency checking	Yang and Xu [99]	IFC	XML	No	Yes	Web-based reporting	✓
		Bhatt et al. [12]	Ontology defined in OWL-DL	OWL-DL + constraints RacerPro	No	Yes	Protégé	✓
		Tan et al. [91]	Extended BIM	Jboss Drools (Decision tables)	Simulation results, weather and material information	Yes	*IFC* viewing tool	✓
		Chen and Hsieh [18]	IFC	—	No	No	Revit	✓
		Hyunjoo and Grobler [43]	Ontology defined in OWL-DL	OWL-DL constraints	No	Yes	Protégé	✓
		Gianluigi et al. [34]	Ontology defined in OWL	Jess(SWRL)	No	Yes	Protégé	×
	Energy performance assessment	Pauwels et al. [75]	Ontology defined in RDF	EYE reasoner (N3Logic)	Thermal and acoustic material characteristics	Yes	RDF	✓
	Quality and risk assessment	De Vries and Steins [21]	IFC	Fuzzy rules	Physics and organisational data, Simulation results	Yes	*IFC* viewing tool	✓
		Zhang et al. [102]	IFC	IF-ELSE rules	The building schedule	Yes	Graphical and table-based safety reports	✓
Enriching BIM information	Interoperability	Beetz et al. [9]	IfcOWL	SWRL	No	No	—	✓
	Querying	Mendes De Farias et al. [61]	IfcOWL	Jess(SWRL)	No	No	Protégé	✓
		Nepal et al. [70]	Feature-based ontological model (FBM)	—	Geometric information from Revit	No	Protégé	✓
	Scheduling	Weldu and Knapp [98]	IFC	—	Production rates and construction costs	—	Protégé	×
	Quantity takeoff	Zhiliang and Zhenhua [103]	Ontology defined in OWL	Jess(SWRL)	Cost specification and historical construction costs	No	*IFC* viewing tool	✓
		Seul-Ki et al. [86]	RDF	Bossam (SWRL)	No	Yes	Protégé	×
		Liu et al. [57]	RDF	SWRL	No	No	Protégé	✓
Building a knowledge base	Assist facility management	Motawa and Almarshad [66]	IFC	Similarity measure case based reasoner	Historical database with successful cases	No	Web-based reporting	✓
	Scheduling using historical data	Mikulakova et al. [62]	IFC	Similarity measure case-based reasoner	Historical database with successful cases	No	Gantt decision nodes + 4D animation	✓
Toolkits	Building code checking	Solibri Model Checker [44]	Proprietary model	Rule engine	No	Yes but limited	Desktop application	✓
		Express Data Manager Model Checker [46]	Proprietary model	Rule engine	No	Yes but limited	Desktop application	✓
		CORENET e-PlanCheck [49]	IFC	Rule engine	No	No	Web application	✓

Table 2: Classification of the surveyed proposals.

which is more oriented towards end users with technical knowledge.

All the studied proposals, except for Gianluigi et al. [34], Weldu and Knapp [98], and Seul-Ki et al. [86], included a case study to validate their approaches. The three approaches introduced their ongoing research work and some future ideas, but without presenting any case study. In the case of the toolkits, since all of them are currently being used, we have supposed that they have already been validated by real world case studies.

9. Conclusions

The emergence of Building Information Modelling has introduced new practices and technologies for managing and developing construction projects. The fact that BIM includes a large set of information originated from different disciplines, has increased the number of proposals that take advantage of this information during all the phases of a construction project to reduce human workload. BIM provides potential benefits and promising impacts on the future trends associated with the advent of BIM-enabled design, construction, and operation of buildings.

Representing BIM in the standardised *IFC* model is a step forward towards advancing in the AEC sector; i.e., product models are starting to become available from commercial design software programs used in the building construction industry. The extended number of classes and relations in the *IFC* standard, and the active research and update of *IFC* by BuildingSmart, are efforts to help this sector moving in the right direction.

Applying methods and technologies from artificial intelligence has a long tradition in adding intelligence to BIM. After surveying the state of the art, we can confirm that reasoning on BIM is an active research field that has achieved promising results. The existence of commercial toolkits is a proof of the need of such tools and of their importance and applicability of reasoning in the AEC sector. Furthermore, the fact that software vendors are developing BIM tools based on reasoners is an evidence of the maturity of this field. The following conclusions can be drawn from our survey:

- Reasoning is mainly used for solving design problems; i.e., although reasoning on BIM has many applications such as code compliance checking, cost estimation, scheduling, and performance predictions, to mention a few, the majority of the research proposals focus on the design phase.

- Its most frequent application is for code and consistency checking; i.e., the majority of the approaches analysed in this survey focus on building code and consistency checking, which is quite an active research field, in which companies, researchers, and governments are getting more and more involved.

- Semantic web technologies receive increasing attention in this field, but as yet only in academic research.

- User-friendliness is currently a gap; i.e., only few proposals provide user-friendly tools.

- Case-based reasoning, while often addressed in past efforts, is still hardly applied for reasoning on BIM; i.e., the majority of the current approaches for reasoning on BIM apply rule-based reasoning.

Overall, we can conclude from our survey that the majority of research proposals are still not too developed; i.e., despite the fact that many of the existing proposals have promising applications, they have not succeeded in the industry practice and they restrict to academic use yet. However, our study of the state of the art shows the roadmap of the software toolkits that shall use reasoning, and that shall be available during the next years. Based on the survey results, we subsume that reasoning shall soon be used in many applications such as code compliance checking, cost estimation, scheduling, performance predictions, inferring missing parameters in *IFC* for interoperability, parametric design, and so on.

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