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A Review on 3D Spatial Data Analytics for Building Information Models

Yu-Wei Zhou · Zhen-Zhong Hu · Jia-Rui Lin* · Jian-Ping Zhang

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Abstract Except for various properties, accurate and intuitive 3D representations of building elements and spaces are embedded in Building Information Models (BIMs). Thus, better understanding of spatial features of building elements and spaces is possible, which brings new opportunity in code compliance checking, indoor navigation, visualization, etc. With large amount of fine-grained 3D spatial data collected quickly and continuously, there is an urgent need for new methods to overcome problems like improper spatial expression, insufficient mining and utilization of information that exist in traditional methods. This research reviews state-of-the-art of related research and provides a summary of achievements and challenges in this area. Then, a framework consists of management, analysis, and application of 3D spatial data of BIM and a detailed discussion of each part are proposed, which would give the readers an overview of relevant methods, technologies, and tools. Moreover, potential research directions and open issues for future work are also discussed. The paper enables researchers to get a comprehensive understanding of 3D spatial data analytics of BIM as well as suggestions for future work, and thus makes a solid contribution in this area.

Jia-Rui Lin (* Corresponding Author)
Department of Civil Engineering, Tsinghua University, Beijing, China 100084
E-mail: lin611@tsinghua.edu.cn
E-mail: jiarui_lin@foxmail.com

Jian-Ping Zhang · Yu-Wei Zhou
Department of Civil Engineering, Tsinghua University, Beijing, China 100084

Zhen-Zhong Hu
Graduate School at Shenzhen, Tsinghua University, Shenzhen, China 518000

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1 Introduction

Generally, human views buildings as a collection of 3D physical components and their relationships[10]. Following an object-oriented manner, computer-based modeling of buildings has been an important area of the construction informatics research community for about 20 years. With building information models (BIMs), not only the 3D representation of the physical building elements, but also their properties (or semantics) and the relationships between them are captured[13]. It is possible to serve various stakeholders like the owners, designers, engineers, contractors and enhance the collaboration between them with a seamless integration of design software and downstream applications based on BIM[12].

The current widely used BIM standard - industry foundation classes (IFC) - defines almost all the building components in the construction domain and supports various applications like evacuation simulation, building performance analysis, etc[57]. However, none of these applications needs all the data in a BIM, instead, only a partial model is needed[9]. To allow the user to extract partial models from a full BIM, a formal query language is necessary for a model server[10]. Since the structure of BIM is primarily designed from a semantic point of view, that is, building elements, their properties and relationships are modeled in an object-oriented way, geometric representations and their spatial relationships of building elements are not described explicitly[9, 11]. Though a few spatial relationships are predefined in IFC, many commercial modeling tools cannot export the BIM with appropriate spatial relationships[13]. Whats worse, other spatial relationships, like metric relationships, directional relationships, are completed ignored in IFC, which is a huge deficiency in the extraction of partial models that fulfill certain spatial constraints[10].

Meanwhile, design of buildings is a complex task involves collaboration of various designers and consideration of numerous rules[65, 66, 27]. Regarding to the compliance of building design, spatial relationships are essential when representing regulations, client demands, and technological constraints as rules, since the physical objects to be designed are of intrinsic geometric nature[8]. Only by checking alphanumeric values and spatial relationships together, it is possible to maintain the consistency of semantic and spatial nature of the design, which would reduce serious data interpretation errors and help avoid design violations[20].

As mentioned above, various simulations such as evacuation simulation, building performance simulation are necessary for the design of buildings, where geometric representation of building elements and their spatial relationships are the fundamental part of the simulation model. For example, pathfinding for evacuation simulation highly depends on the connections between spaces of a building. In addition, unresolved issues still exist in the generation of secondary space boundaries from building elements, which affects the simulation and evaluation of building performance. As 3D representation of building elements and their spatial relationships (spatial data) attract more attentions in the construction domain, efficient storage and analysis methods and tools[65, 68] are needed to enable the utilization and benefits of spatial data.

Previous researchers have conducted many valuable investigations in this area. For example, spatial operators[10, 13, 9], formal language for querying the spatial data of BIM[15, 7, 53], combination of spatial relationships and semantic reasoning[20, 23, 63], and spatial database prototype for BIM are explored[70]. However, much more work is still needed to improve the efficiency and flexibility of spatial data management and analysis, and the potential of spatial data also needs to be further explored.

Obviously, it can be found that BIM spatial data has wide and increasing demands and faces with plenty of difficulties in integration and management, as well as various challenges in data modeling and retrieval, efficient analysis and reasoning.

To provide an overview of the state-of-the-art in the analysis and management of spatial data of BIM, and to reveal possible challenges and future directions, this paper conducts a systematic review of relevant literatures in this area.

The discussion of the paper starts with the methodology and framework for 3D spatial analytics for BIM in section 2. While section 3 and 4 present the management and analysis of spatial data, on which diverse applications in Section 5 are mainly based. Finally, section 6 concludes the current research efforts and discusses directions for future study.

2 Methodology and framework

The overall methodology for the review consists of 5 steps: 1) research scope is set firstly and 2) retrieval conditions including time span, key words, etc. are determined based on research scope and all available papers are collected; then, 3) titles and abstracts of the collected papers are reviewed to further identify relevant papers and 4) all relevant papers are examined carefully; finally, 5) a framework for 3D spatial data analytics for BIM is established and the state-of-the-art and future directions are discussed in detail.

2.1 Research scope

To narrow the scope of the essay, the 3D spatial data discussed here are three folds: 1) building elements including structural ones like wall, column, beam and architectural ones like furniture, decorative board, etc.; 2) spaces that are bounded by building elements, including room, corridor, balcony, etc.; 3) topological information that describes the relationships between spaces and building elements, like connection between building elements, path from one space to another, and adjacency of spaces. Most of the mentioned data are implicitly embedded or explicitly modeled in BIMs.

Since 3D spatial data is widely used in collaboration, model checking, simulation, and visualization in the design, construction, and maintenance of buildings, when discussing 3D spatial data analytics, data sharing or interoperability, data management, retrieval, etc. should all be considered.

2.2 Literature sources and statistics

Based on the above research scope, key words including BIM database, BIM spatial data, BIM interoperability, BIM spatial query and BIM rule checking are used when searching relevant papers, and web of science is taken as the main source of literatures. A rough search with the keyword "BIM" showed that, there are much more

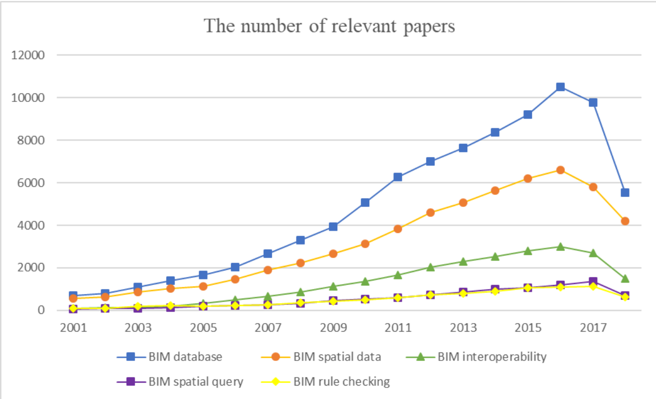

Fig. 1 Published papers related to 3D spatial data analytics for BIM

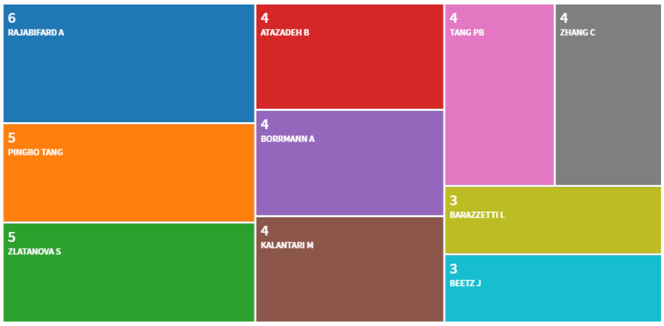

Fig. 2 top10 authors in search of "BIM spatial data"

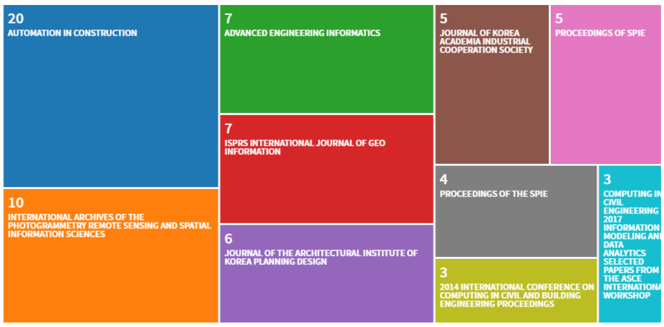

Fig. 3 top10 publishers in search of "BIM spatial data"

papers after 2000 than the period before 2000. Therefore, the data of relevant papers presented below are retrieved from 2001 to 2018. As in Fig. 1, most of the collected papers concern about BIM database and management of BIM's spatial data, while a small portion of them focus on the spaital query and checking of BIM.

Based on the search results from web of science, top 10 authors and top 10 journals related to the keyword "BIM spatial data" are extracted (Fig. 2 and Fig. 2). Then, key reasearchers like A. Borrmann and P. Tang and key journals including Automation in Construction, Advanced Engineering Informatics, etc. are identified.

2.3 Framework of 3D Spatial Analysis for BIM

With a deep reviewed of collected papers, a framework as illustrated in Fig. 4 is presented to clarify the structure of related researches. The foundation of the study is spatial data and its management. Through proper modelling, spatial data can be integrated into database for the preparation of utilizing and analysis which needs common database SQL and specific geometric algorithm. The ultimate intention is to solve present problems like inefficient use of spatial data and to adapt it for future applications like design optimization. With this framwork in mind, the following sections will discuss each part of it in detail.

3 Management of spatial data

The way to store and use spatial data is becoming wider and wider. Both GIS (Geographic Information System) which relatively mature and BIM which is discussed in the essay, have contained tremendous spatial information. More importantly, the phenomenon is not a temporary occasion but a continuous trend, because BIM are expected to involve more buildings of complicate design and large scale. It is estimated on the basis of a building companys informatization that the average data amount of every building project is around 10 TB. And there are hundreds of thousands of projects in China in one year. That means the order of magnitude of information can reach EB scale in only one year in China[45].

Currently, the expression of data in BIM is mainly derived from GIS and CG (Computer Graphics), namely Triangle Mesh and 3D Point Cloud. The Former is common in practice. Since any shape or topological surface can be represented by meshes, which doesnt need to satisfy complex inter-patch smoothness conditions, so that simple and efficient algorithm can be used to generate and handle geometric properties. The latter is developed a little bit later, but possesses its unique edges. That is to say, it does not have to store or maintain polygonal-mesh connectivity and topological consistency, thus presenting better performance and consuming less cost[31]. 3D Point Cloud has generally been applied to BIM, like mapping 3D object of rooms[62], combining BIM and GIS to realize the integration of indoor and outdoor[49], and so on. Faced with increasing spatial data in BIM, it is necessary to extract, mine and analyze the information as fully as possible in order to maximize the value of information. In that case, much cost can be saved in the stage of designing, constructing and managing. Otherwise, any amount of data obtained is meaningless and useless.

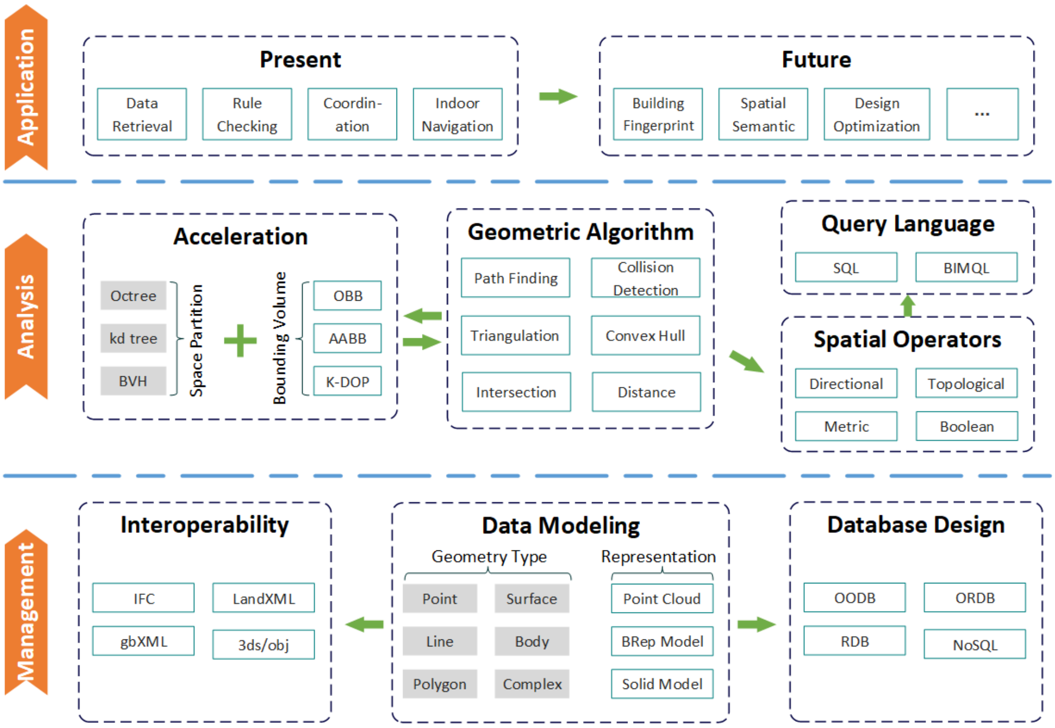

Fig. 4 Framework for 3D spatial data analytics for BIM

3.1 3D spatial data representation and modeling

In BIM database, geometric data is represented by simple ployhedra, bounding box approximation, octree decomposition, topological surface boundary representation and so on. Various 3D representations are intended to improve the performance of spatial query[69], which is somehow lacking in IFC format. Borrmann et al.[13]have built a model of high-rise buildings and made a complete definition for all entities and properties. However, after exporting in IFC format, its entity set becomes incomplete, at least lacking IfcRelContainedInSpatialStructure relationship set, so it is impossible to derive heating equipment in the room[13]. Therefore, the study of 3D representation is of great significance, which can ensure the integrity of spatial data and improve the efficiency of query and search. The relevant and detailed knowledge can be obtained from the field of computer graphics. There are three widely modeling methods of 3D spatial data (Fig. 5), whose definitions and underlying theories (Table 1) as well as applications in 3D spatial data analytics for BIM (Table 2) are discussed in detail as follows.

3.1.1 Solid model

A solid model represents information of both inner and outer surface of a object to ensure completeness, accuracy and unambiguity of elements for sake of analysis automation and integration (Fig. 5). It is mostly suitable for simple solid objects, called primitives, and their combinations. The solid primitives include cube, cylinder, cone, torus, sphere and so on, handled by Boolean operations, like union, intersection and difference so that they and their inner space can be represented correctly and efficiently (Table 1). It features handling the weakness of wireframe and surface modelling, namely ambiguity and incompleteness in the geometric description, lack of topological information and complexity. Some most popular schemes include constructive solid geometry and sweeping[36]. To achieve high-performance spatial queries of 3D BIM, ultiple representation including solid model, BRep model are utilized[69].

3.1.2 BRep model and surface model

A boundary representation (BRep) model features its topological and geometrical predicates, manipulating triangulated meshes directly, which is different from

Table 1 Elements and operations of different modeling methods

Modeling method	Elements	Operations
Solid model	Primitives	Boolean Operation
BRep model	Surface elements	Euler Operation Set
Point cloud	Points	Preprocess and Rendering

Table 2 Representation and modeling methods of 3D spatial data used for BIM

Author	Contribution	BRep model	Solid model	Point cloud
Solihin et al.[69]	Multiple representation of 3D objects; Efficient query of octree composition	√	√	
Daum et al.[19]	Direct boundary operation and R-tree query with topological and directional predicates	√		
Daum et al.[22]	Topological operators of QL4BIM; 9-intersection model; BRep-based evaluation of topological predicates	√		
Kana[36]	A detailed introduction of Solid Modeling		√	
Levoy et al.[43]	Proposition of discrete points as a display primitive			√

previous representation methods (Fig. 5). Due to its special data structure, there is a flexible and complete operation set, Euler Operation Set, helping realize complex operations like extrusion, chamfering, blending and so on (Table 1). Furthermore, combined with R-trees indexing, it reduces the execution time and prevent the exponential-level computational complexity[19]. That is to say, it handles complicated situation effectively where construction elements are of huge numbers and of refined geometry, and supplements previous representation methods well. After publishing the paper regarding this method, Daum and Borrmann have compared the performance between BRep-based and octree-based implementation approaches, and concluded that the former worked better[22]. Some papers even evaluate it as the best spatial representation way[69].

3.1.3 Point cloud

A point cloud model is built through two algorithms, the first converting geometry into points and the second rendering these points[43] (Table 1). Generally, data of a point collected includes its coordinates, normal vector, radius and color. With discrete points, the model can display shapes directly and measure objects side length (Fig. 5). PCL website provides clear division of point cloud data, including the low level of filters and segmentation, the middle level of features, and the high level of registration and recognition. In the other words, point clouds have more edges on segmentation than image processing, which makes a solid base for identification[61]. Because of its simplicity and great representation capability, it is used widely and famous for its high performance and low overhead, though there are some flaws like inability to represent topological relationships.

3.2 Interoperability of 3D spatial data

As is mentioned before, core BIM software saves spatial data in custom formats, resulting in difficult access and utilization. The problems have long been recognized and many scholars have done plenty of work in this area[70]. Most of their ideas are 1) utilizing a neutral file formats like Standard for the Exchange of Product Model Data (STEP), IFC, etc., 2) importing data into a central database for BIM, 2) directly using an interface or internet protocol to realize quick access (Table 3).

STEP and IFC, both international standards, possess their unique data structure. For example, in IFC4 version, there are 766 entities and 391 classes. If importing data directly, users have to deal with too many entities. Actually, most model servers were used to this one-for-one conversion in the past, but its heavy burden made scholars try to establish specific BIM spatial data structure.

In 1998, Loffredo studied database implementation of EXPRESS information models. He proposed the SDAI (standard data access interface) for EXPRESS-defined data in database to replace costly direct bindings[50]. In 2002, Adachi developed IFC model server with SQL Server, providing data access through basic API, ActiveX and network server protocol[1]. In 2003, Katranuschkov et al. studied the rationale, principle design and technical structure of IFC ontology framework based on XML schema so that users and none IFC applications can access product data simply[41]. In 2004, You S.-J et al. focused on GTCIS2SQL, which is a relational database schema based on STEP models, in order to support data exchange of P-21 files[78]. In 2010, Beetz et al. introduced BIMserver. org, a kind of open source IFC model server. It enabled to store, maintain and query IFC data according to IFC, STEP and EXPRESS formats in aid of the cooperation among various stakeholders in a buildings lifecycle[4]. He also developed BIMQL similar to SQL with Mazairac as the query language of IFC model servers[53]. These two works are of great significance and set a great example for the later researchers to convert and utilize the IFC format. In 2017, Solihin put emphasis on easy effective access to data and users concentration on logical view, estab-

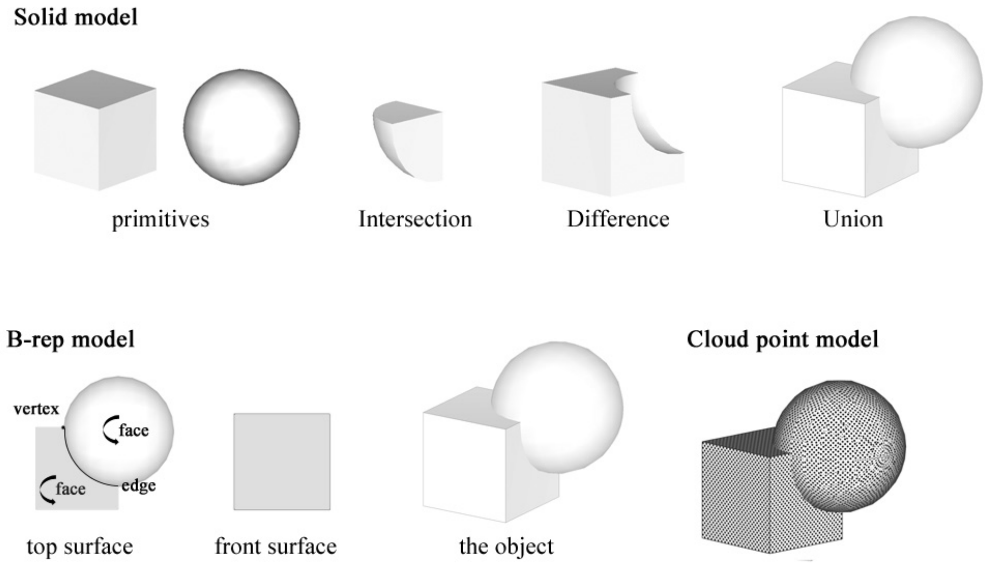

Fig. 5 Representation and modeling methods for 3D data

Table 3 Proposed methods for spatial data interoperability

Author	Contribution
Loffredo and David[50]	Standard data access interface to replace direct bindings
Adachi[1]	Data access through basic API, network protocol and so on
Katranuschkov et al.[41]	An ontology framework based on the XML schema specification without IFC
You S.-J et al.[78]	GTCIS2SQL, based on STEP supporting data exchange of P-21 files
Beetz et al.[4]	BIMserver.org, simplifying cooperation based on IFC, STEP and EXPRESS formats
Mazairac and Beetz[53]	An open source BIM query language, called BIMQL
Solihin[70]	A warehouse-like, star-like schema, called BIMRL, for relational database

lishing warehouse-like schema for BIM named BIMRL so as to map IFC entities to BIMRL based on specific conversion rules[70]. Furthermore, he also realized other approaches to access data based on RDF (Resource Description Framework), MVD (Model View Definition) and so on.

Up to now, there have been some tools for reading IFC directly, able to accomplish the import process of spatial data to the database, such as software like XBIM[70], open source script like IFCSchemaReader[51] and so on (Table 4). Through the reading of data format and the mapping of data structure, spatial data originally constrained in BIM applications can be put into a database that is easy to access and query. Some of the IFC tools are listed in the table below, whose function are mainly related to the data conversion.

In addition to IFC and STEP, there are other common 3D model formats like OBJ, 3DS, STL and so on, which are mainly applied in two fields, DCC (Digital Content Creation) and CAD (Computer Aided Design). As general formats of 3D data, OBJ and FBX are prevalent in DCC, while LandXML, gbXML, STP, IGES and STL in CAD, which all contain rich information of meshes or surfaces. However, unlike IFC, they lack sematic information, which is indispensable in spatial queries, thereby impossible to serve as formats in spatial database.

3.3 Design of 3D spatial database

According to its logical models, database can be divided as relational ones, object-oriented ones and so on. Models should be built to organize data properly in order to facilitate querying, calling and managing data conveniently, satisfying users needs as efficiently as possible. It is worth noticing that 3D data is a little special for its properties and international standard formats like IFC, STEP, so the design of BIM database needs to take these into account.

Besides, it is also important in choosing the type of database. Previous studies argued that object-oriented database worked better than relation one, which is not

Table 4 Available IFC tools

IFC tools	Features	Development language	Free	Open source
XBIM[70]	IfcParser and OpenCascade IFC extension, parser and handle	C# and C++	yes	yes
BIMserver.org[4]	Upload IFC data, browse BIM, Interoperation	Java	yes	yes
IFCSchemaReader[51]	Reading IFC2x3 and IFC4 formats	python	yes	yes
IfcOpenShell[51]	Help use IFC file formats	python	yes	yes
EDMdeveloperSeat Basic	Transparent access to IFC and BIM	C++, Java and ṅet	no	no
IFC Classic Toolbox	Middleware of accessing/writing IFC in P21 files	C++ and ṅet	no	no
ST-Developer v10	Read, write, create and modify IFC defined by EXPRESS	SDAI C and C++	no	no
IFC Engine DLL	Simplify practice of IFC and 3D		yes	yes
EDMmodelServer for IFC	IFC data warehouse		no	no

recognized by You et al[78]. Thats why they chose relational database SQL Server 2000 as their developing tools. As a matter of fact, both two have their own edges, so both have been applied during the process of designing BIM database. In 2008, Thailand scholars Malaikrisanachalee studied 3D object-oriented models based on Java[64] and in 2010, he integrated it to BIM database with PostgreSQL[52]. In 2014, Lee et al. compared the performance of IFC servers between relational database and object-oriented one, developed object-relational database, thereby improving stability and efficiency and supporting object-oriented query[39]. In 2017, Solihin et al. developed simplified relational database based on Oracle Spatial and established BIMRL schema (Fig. 6) to satisfy users actual needs and realize the ultimate goals of rule checking[70]. In the same year, Logothetis hoped to develop BIM open source platform based on PostgreSQL and free the whole process from data calling to data managing[35]. In addition, studies in China are of great numbers as well. In 2013, Yu and Zhang et al. proposed semi-structured BIM database based on NoSQL and managed to share data through cloud computing platform[79]. In the same time, Li and Deng developed BIM data of simple structure based on IFC formats. They stored data with only four tables, efficient but lacking spatial data[44]. And there are also some databases faced with specific construction elements like steel[73] or electrical equipment[18]. A brief summary of relevant articles is listed in Table 5.

It can be found out that the academy has long recognized the importance of BIM database. Scholars have tried different types of database, designed tables and attributes and tested their efficiency of querying and management to make full use of spatial data.

4 Analysis and retrieval of 3D spatial data

4.1 3D data processing and acceleration

There are diverse ways to improve the performance of 3D data processing. Among them, quadtree and octree decomposition are common ones in the process of space partition. This recursive algorithm is aimed to realize global access by dividing space, calculating upper and lower bounds of all eight-part regions on a level, excluding all irrelevant pairs and then recursing continuously to refine calculation precision. An obvious advantage of the way is in that the time complexity of the algorithm has its upper bound for a certain precision, regardless of the distribution of subdivision process[14]. The other well-known space-partition structure is k-dimensional tree (kd-tree), a recursively defined balanced binary tree in any dimension. The root of the tree represents the whole space, to which child nodes, namely the divided subdomain, is attached. This data structure and algorithm is suitable for high dimensional data index. Another widely accept method is bounding volume approximation, including bounding sphere, axis-aligned bounding box (AABB), oriented bounding box (OBB) (Fig. 7) as well as discrete orientation polytopes (k-DOP), space-time bounding box (STBB) and so on, all of which are put into flexible practice in the field of collision detections (CD) because they can approximate irregular objects with simple polyhegra[6]. Since adapted to dynamic detections well, bounding box method is apparently more competent to represent static construction elements.

Based on the data structure mentioned above, there are various geometric algorithms applied in practice effectively and therefore, contributing to spatial operation and query. Among these algorithms, the construction of convex hull is a relatively primary one, relying on incremental strategy[3]. Other algorithms in-

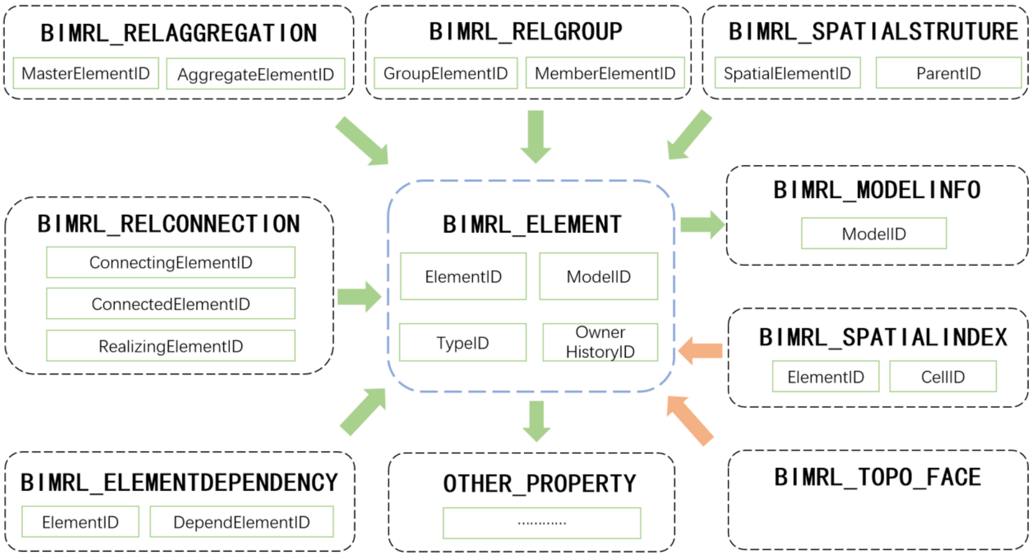

Fig. 6 the concept of BIMRL schema (created based on[70])

Table 5 Database design for 3D spatial data of BIM

Author	Contribution	OODB	RDB	ORDB	NoSQL
You et al.[78]	A relational database implementation of CIS/2, called GTCIS2SQL		√		
Sangkaew et al.[64]	Java-based three-dimensional object-oriented model	√			
Malaikrisanachalee et al.[52]	The principle of integration of Java and spatial database			√	
Lee et al.[39]	The comparison of performance of IFC model server using OODB and RDB; ORDB development			√	
Solihin et al.[70]	A warehouse-like, star-like schema, called BIMRL, is proposed for simplified data access		√		
Logothetis et al.[51]	An open source BIM database platform			√	
Yu et al.[79]	BIM NoSQL database				√
Li and Deng[44]	Simplified BIM database with four tables		√		
Tian et al.[73]	BIM database for steel structure		√		
Chen et al.[18]	BIM database for electrical equipment		√		

clude geometric intersection, based on plane sweep algorithm[5], triangulation, aimed to complex polygon and point cloud, based on Delaunay graph[32,55,72], path finding[16], distance measure and collision detection[54]. These algorithms take good advantage of spatial representation and provide elementary access to location relationship among spatial objects.

Actually, the choice of data processing and acceleration impacts efficiency of data utilization. The reasonable and optimal approaches of spatial representation to address certain situations remains to be measured. But they are worth discussing and improving as an essential part of spatial operation.

4.2 Spatial operators and spatial query language

The important base of spatial query language is 3D representation, which originates from the formal definition of semantics of available data and the operators effect it. Borrmann[15] discusses in detail on the type of spatial data and the definition of analysis operators in his series of papers. He divides data type into the simple and the complex. The simple includes point, line, surface and body in replace of previous concepts like 3D point, 3D line, etc., and the complex is the composite of simple ones. For every simple type, there are various topological relationships, such as boundary, interior, exterior and closure. After strict definition, he lists and categorizes spatial operators, which are used to manipulate spatial data type and handle spatial semantics (Table 7).

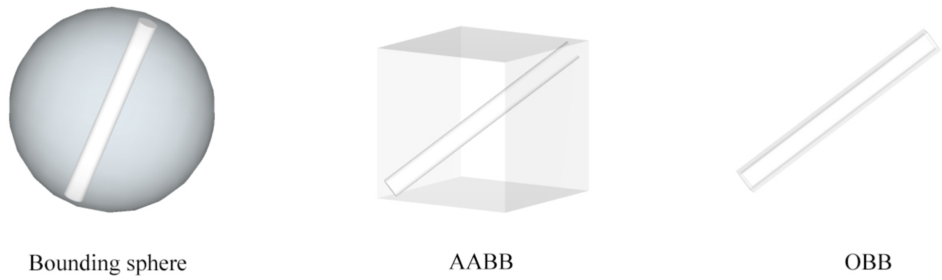

Fig. 7 Bounding volumes used for BIM

Table 6 Acceleration algorithms used for BIM

Author	Contribution	Quadtree or octree	Bounding box
Borrmann et al.[14]	Distance computation and octree code	√	
Bergen et al.[6]	Collision detection using AABB trees		√

Directional operators describe directional relationship between two spatial objects, represented by Boolean value, including *above, below, northOf, southOf* and so on. Based on point-set theory notation, the halfspace-based models can be built with axis-aligned bounding box and the projection-based models can be built with slot-tree, a newly developed space-partitioning data structure[10]. Topological operations describe topological relationships, including *within, contain, touch, overlap, disjoint* and *equal*. Based on 9-intersection model and breath-first traversal of operands octree representation, topological calculations can be conducted according to users needs and required accuracy[11]. Metric operators describe the shortest distance between any of the points belonging to the closure of spatial objects, including distance operators only and reflecting distance relationship, such as *mindist, maxdist, isCloser* and *isFurther*. Still based on point-set theory notation, the implementation methods can be realized through discrete representation of the operands geometry by means of the hierarchical, space-partitioning data structure octree, and precise distance measurements by means of the exact boundary representation[13]. Boolean operators describe Boolean relationships, including *union, intersection* and *difference*. As important logical deduction methods, it is a necessary part of spatial query language.

In a certain query of spatial BIM database, there are three possible situations, respectively a query exclusively about spatial properties, a query combining spatial and non-spatial properties or a query about non-spatial properties. For the first two, spatial operators may explicitly appear in query language. For example,[28] to select the part of a road named Grove Street in a town Orone, the SQL can be input

SELECT road.geometry
FROM road, town
WHERE town.name = Oroneand
road.name = Grove Streetand
road.geometry INSIDE town.geometry

When users input *INSIDE* or *DISTANCE()*, they dont need to take any algorithms into consideration but only apply the operators easily. Another example is to check space isolated without a means to access it[70].

SELECT a.elementid, a.longname,
b.parentid, c.longname
FROM bimrl_elementa, bimrl_spatialstructureb,
bimrl_elementc
WHERE c.elementid = b.parentid
Andb.spatialelementid = a.elementid
Anda.elementtype = IFCSPACE
Andb.levelremoved = 1anda.elementid not in
(select spaceelementid from
Bimrl_spaceboundaryv
Where boundaryElementType in
(IFCDOOR, IFCOPENING, IFCSPACE))

It seems a little bit complicated, but it is based on SQL and spatial operators as well.

It is meaningful to research the specific query language targeted at BIM database based on spatial representation, spatial operators and mature SQL language. After all, the efficiency of algorithm still has great potential because of the complication of spatial data. BIMRL[70],

Table 7 3D spatial operators

Operators	Theoretical basis	Relationships
directional operators[10]	Point-set theory notation	*northOf, southOf, westOf, eastOf, above, below*
topological operators[11]	9-intersection model	*within, contain, touch, overlap, disjoint, equal*
metric operators[13]	Point-set theory notation	*mindist, maxdist, isCloser, isFarther*
Boolean operators		*union, intersection, difference*

BIMQL[53], etc., which are mentioned above, are all the works relying on the efforts of the scholars, who expect to realize simple, efficient and systemic query.

5 Applications of spatial analysis technologies

5.1 Spatial visualization

BIM provides macro- and micro- visual spatial data at all phases of a building's lifecycle, including design, construction, operation and maintenance. But users' demands are beyond this. They are more willing to find the objects they are interested in and acquire their properties, types, geometry, space or other relationships[70]. For instance, they may wonder what space a room is connected to, how large the space is, and how it interacts with surrounding objects. In addition, there are a large number of visualization requirements in the filtering and subdivision of information models, as they often serve as input to numerical simulation and analysis tools, playing a key role in the design process[15]. As the building and its inner service systems are complex and the BIM is large, it is necessary to effectively processing and visualize the spatial data.

5.2 Data retrieval

As mentioned above, design process of a building is complex and involves various numeric simulations to check whether the project is reasonable and perfect, and to help identify potential optimizations. In this situation, only part of the whole BIM is needed, and data retrieval or sub-model extraction[80] is utilized to get the required data. For example, in the face of a BIM model, equipment engineers may need to query the location of gas or electrical pipes buried in the wall to ensure that any work on the wall will not damage them. While for a medical building, a designer may wish lines of sight from a nurse station to a ward not to be hindered[?]. This type of process is not completely automatic most of the time. On the contrary, it requires both humans command and computers assistance. In that case, the spatial database which stores integrated data will play an important role in fast access to and interpretation of different types of geospatial information. Instead of manual index and statistic, database provides efficient approaches to query heterogeneous data across disparate systems and designs. Actually, there has been information systems based on discovery and retrieval of spatial data from spatial database[56]. Meanwhile, an intelligent data retrieval and visualization approach based on natural language is also proposed to help non-experts to get the BIM data easily[46]. As this application is beneficial for cooperation in construction industry, it is more than likely to have a promising future.

Except for retrieval of spatial data, semantic information and geometric processing are also considered in some scenarios. In terms of building performance simulation, semantic information like building materials, thermal environment, meteorological data, modeling integrity are necessary. More importantly, it requires the completeness and accuracy of spatial data, especially the generated space boundaries[58] and their heat transfer coefficients. Similarly, if designers wonder the situation of a building in a fire, they can rely on the 3D information in BIM, using computers for calculations and simulations[59]. And the information such as the escaping route and the topological structure of fire fighting systems can be derived from the spatial data of BIM. Together with sematic information like fire resistance time of furniture in combustion, the fireproof property of load-bearing structures, engineers can optimize the fire design to avoid specific deficiencies.

5.3 Spatial relationship enhanced rule checking

As a composition of various systems, buildings are complex. To fulfill the building codes and clients requirements and to avoid possible mistakes made during the design of the building, code compliance checking or rule checking is necessary[27]. In most building delivery processes, manually compliance checking will take a lot of time and money, which makes the rule reasoning system not only a labor- or time-saving approach but also a money-saving one[27]. Rule checking could date back to 1966 when Fenves logically normalized the decision table for architecture design[30]. Then, a new paradigm transforming from 3D drawings to 3D BIMs occurred, and automated building design review systems were proposed[40]. Recently, Azhar et al. assessed sustainable design of buildings with BIM models, simplifying LEED (Leadership in Energy and Environmental Design) rating analysis[2]. Eastman et al. standardized the delivering process of precast concrete industry and improved the seamless operation of production models[42]. Zhang et al. applied automatic rule checking to building safety, warning safety hazards and suggesting precautions to users to prevent the risk of falling during construction[81].

Reasoning and rule checking are vital applications combined with spatial data. In the past, most works focused on automatic checking of code and access standard[67]. With rich semantic information and spatial data embedded in BIM, it is possible not only to do alphanumeric checking of building components but also to validate their spatial relationships[20]. To automatically identify design errors or mistakes, formal definition of rules is required and an expert is usually needed to input them manually[67]. And possible spatial operators are also proposed[10] to help define rules related to spatial relationships. Therefore, spatial constraints can be checked to better support engineers and architects in the design process[8]. Moreover, possible inconsistency between geometric and semantic information of BIM can be detected earlier, which may avoid serious data interpretation errors[20]. There are also diverse practices based on rule checking to solve other problems, like air circulation paths, constructability requirements, ergonomic requirements, warrantee approvals, etc. Obviously, these rule inferences are important automation tools in BIM modeling, and their ultimate goal, as Solihin concludes[67], is to free the designers from the trivial and focus on critical parts of buildings, such as safety, sustainability and green building environment. Thereby, they are capable of innovating and designing without sacrificing the quality of any aspect. However, the reasoning process is still too limited to error checking of code and architectural standards at the stage of designing and delivering. As stated in [66] and [26] , efficient spatial data processing and integration with simulation still need further investigation.

5.4 Indoor navigation and path finding

Indoor navigation is another typical scenario that highly depends on the spatial and semantic information of BIM. And there is a trend that uses BIM and automatic path extraction instead of 2D-based geometries and predefined routes for indoor navigation, which is more efficient. Since indoor paths are not explicit represented in BIM, most of the current researches primarily focus on the generation of indoor paths. Relevant researches can be grouped into two categories. One is based on the space-door relationship explicitly modeled in BIM, and then the connections or paths between different spaces can be inferred[77], similar approach is also used for space accessibility checking[27], indoor emergency navigation[60]. Another kind of methods just use the geometric information in BIM, for example, Lin et al.[48] discretize the indoor spaces and mapping their semantic information into a planar grid, then proposed a fast matching method for finding the shortest path. Except for that, BIM oriented indoor data model (BO-IDM) is proposed by Isikdag et al. [35] for highly detailed semantic information of indoor navigation. However, it is also reported that to make great use of semantic information of spatial data, the transformation from BIM to BO-IDM is not necessarily the best way but a referential one so that indoor navigation can more flexibility cope with different occasion like disasters and evacuation [35].

5.5 Building operation and maintenance

Spatial data is also widely used in building operation and maintenance (O&M), and fluent information delivery technology is required[34]. Except for the previous mentioned application of indoor navigation in O&M phase, extraction and analysis of logic chain or connections of mechanical, electrical and plumbing systems is also important for O&M[69]. Meanwhile, to reduce possible occupational injuries and illness during facility management, an approach integrates safety related semantic information, spatial data and specific rules is proposed to enable fluent data retrieval and vivid data visualization[76].

6 Conclusion and future directions

The essay summarizes the state-of-the-art of 3D spatial analysis of BIM, and a framework consists of spatial data modeling, database design and development, data integration, spatial data processing, spatial query, and possible applications is established. It can be found that most of the research efforts focus on: 1) the definition and development of spatial operators and query language; 2) incorporating spatial relationships in rule checking; 3) adopting available geometric algorithms to accelerate spatial data processing. Although the application of spatial analysis of BIM is not completely mature and commercialized, it shows great advantages and is essential for quite a few scenarios. Moreover, spatial operations on traditional relational databases have been implemented and extended to enable more efficient rule checking and design optimization. However, the field is still far from mature, and quite a few challenges and limitations need further investigation and exploration:

6.1 Data interoperability

Interoperability is essential for efficiency of data usage and collaboration. However, most BIM software available saves data in their specific and custom formats, even IFC is widely used for data sharing, different BIM software do not export IFC in a consistent manner, thereby blocking free flow of information. This means customized data converters and plugins are necessary for specific demands, where the users will find their drowned in plenty of developing work. Whats more, as new technologies like 3D scanning being adopted, new data formats like point cloud are introduced, and research efforts including extending the current IFC schema[38], developing object extraction methods[74] are always needed. Meanwhile, when describing location or geographic properties of buildings, GIS data is also required, which calls for the integration of BIM and GIS[7]. Since 20th century, GIS-based 2D spatial data has taken up an important role in various fields, let alone 21st century, the era of big data, when 2D spatial technology develops rapidly, applied widely in the area of national defense, living health, climate change, geological survey and so on[75]. And it is no doubt that BIM-based 3D spatial technology will bring a new paradigm for finding potential patterns and new knowledge. Due to the semantic gaps and different coordinate systems[25] between BIM and GIS, the strengths of both BIM and GIS have not been fully integrated and utilized[71]. In addition to looking at interoperability from a data format perspective, interoperability between different stakeholders is important too when considering data ownership and privacy[80]. That is, it should be possible for a specific organization to easily define which part of a BIM model and what level of detail they want to share. This involves complex partial model extraction, consistency checking and model integration, and still needs plenty of work for real world application[80].

6.2 Implementation of 3D spatial database

2D spatial query language has long been applied in GIS oriented spatial databases, while the analysis algorithms and query language involving 3D models starts later[15]. In addition, 3D objects spatial properties are particularly complicated, including entities like point, line, surface and body, and operators like direction, topology, metric and boolean, all of which need their respective operational approaches, otherwise it will be difficult for users to have a clear idea of a spatial element. Egenhofer, an authoritative scholar of spatial analysis, argues that the principle demand of Spatial SQL is to provide a higher abstraction of spatial data by incorporating concepts closer to our perception of space[29]. However, to accomplish the target ideally still needs more efforts and the progress is slow in integrating 3D supports in spatial database management systems[69]. In the background of increasing amount of data and large numbers of users, cloud distributed processing technology may be a new research direction. For instance, NoSQL[17] is able to extend across multiple servers, easy to copy, distribute data and support numerous read and write operations. Thanks to its property of supporting multi-participation of projects, many papers list it as one of future development directions.

6.3 Efficient analysis of 3D spatial data

To accelerate the performance for 3D spatial data analysis, various conservative boundary representations are utilized. As summarized by Solihin[69], bounding sphere, axis aligned bounding box (AABB), and oriented bounding box (OBB) are used and they usually function distinctly in confrontation with different objects. For example, if the object is not axis-aligned in geometry, OBB will have more advantages, though generally AABB is easier to compute and compare. Therefore, in complex spatial models with tremendous data, efficient algorithm that can dynamically choose proper conservative bounding would save considerable cost in time and space. This question is there and remains unresolved. Besides, as mentioned above, the ability of spatial database to support spatial index and query is not adequate at present, even for Oracle Spatial and other kinds of popular database software. Performance evaluation of spatial database management systems[37] showed that most one-to-many interactions of 3D spatial data are so slow that new retrieval algorithms need to be created. Moreover, current methods are only tested on a small data set. For example, Borrmann et al. tested their Octree and BRep based implementation of metric operators with a 5-story model, which only has 216 elements[13], and they also reported that 39,600 facets will take 3.67s to query the distance. However, a typical project usually contains thousands of elements[70, 47], the amount of facets may exceed a million, and the data size is always dozens of gigabytes[46], where validation and practical application of spatial analysis are not conducted. Similar results are also reported by Solihin et al. [70], even with a carefully defined simplified database schema, certain spatial queries may takes more than 50s, which would annoy the users sometimes. In addition, there still lacks integrated analysis of temporal data, 3D spatial data, and semantic data in BIM, which is important to explode the value of BIM.

6.4 Spatio-temporal-semantic analysis

Given that the building is modelled both from the semantic and the spatial aspects, the combined-analysis of spatial relationships and semantic information could also help to detect potential duplicate elements and enhance the differencing and merging of BIM data[24]. Except for semantic information and spatial relationships, temporal data is another important part of BIM when considering the construction schedule[21] and the sensing data. And combination of spatial and temporal information will help the engineer or the manager to validate the construction schedule and avoid possible errors[21]. As mentioned above, combined analysis of semantic information, spatial relationships and temporal data of BIM is essential for model validation, compliance checking and data retrieval. New methods on spatio-temporal-semantic analysis would contribute to the consistency and integrity checking of BIM, enlarge coverage of automated compliance checking, and enable more flexible data retrieval and knowledge reuse[33]. Nevertheless, few attentions were paid in this area until now, and it is worth it to further explore the spatio-temporal-semantic analysis of BIM.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conﬁct of interest.

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