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Review

OpenBIM: An Enabling Solution for Information Interoperability

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Abstract: The expansion of scale and the increase of complexity of construction projects puts higher requirements on the level of collaboration among different stakeholders. How to realize better information interoperability among multiple disciplines and different software platforms becomes a key problem in the collaborative process. openBIM (building information model), as a common approach of information exchange, can meet the needs of information interaction among different software well and improve the efficiency and accuracy of collaboration. To the best of our knowledge, there is currently no comprehensive survey of openBIM approach in the context of the AEC (Architecture, Engineering & Construction) industry, this paper fills the gap and presents a literature review of openBIM. In this paper, the openBIM related standards, software platforms, and tools enabling information interoperability are introduced and analyzed comprehensively based on related websites and literature. Furthermore, engineering information interoperability research supported by openBIM is analyzed from the perspectives of information representation, information query, information exchange, information extension, and information integration. Finally, research gaps and future directions are presented based on the analysis of existing research. The systematic analysis of the theory and practice of openBIM in this paper can provide support for its further research and application.

Keywords: openBIM; information interoperability; standards; software

1. Introduction

The construction industry, as one of the traditional industries in the world, boosts the economic development and accelerates the realization of urbanization. However, the development of more complicated construction projects has also created a series of collaboration issues among different stakeholders and software platforms, which has placed higher requirements on the collaboration over the whole lifecycle, including design, construction, operation, and maintenance. In most cases, data in the construction field is fragmented and distributed in different sources, which is not convenient for information collection and representation. How to better solve information collaboration issues is closely related to the success of projects.

Building information model (BIM) software is widely used in design, construction, operation, and maintenance stages, providing great convenience for construction industry. However, data heterogeneity among different software leads to a series of problems, such as interoperability issues. As a universal approach for collaborative design, construction, and operation of buildings based on open standards and workflows [1], openBIM provides solutions for these problems by reducing collaborative errors, improving the interoperability between software, and ensuring accuracy of multi-party collaboration, thus improving the efficiency of the whole project.

At present, studies related to openBIM have received extensive attention, but there is still a lack of a comprehensive overview of openBIM. Therefore, openBIM related standards, software platforms and tools are summarized in this paper by analyzing openBIM related websites and literature from Scopus, Engineering Village, and so on. Furthermore, engineering information interoperability research supported by openBIM is concluded to provide a systematic review of openBIM related research and practice. Moreover, the limitations of existing research and open research challenges as well as possible suggestions are outlined to assist both the engineers and researchers in giving a guide for future research.

The whole paper is organized as follows. The research methodology of the paper is analyzed in Section 2; systematic analysis of openBIM standards, software platforms, and tools are given in Section 3; engineering information interoperability research supported by openBIM is summarized in Section 4; discussion about research gaps and future directions is given in Section 5; and the conclusion is made in Section 6.

2. Literature Search

To explore the current research status of openBIM among different countries, the paper refers to related literature from several main and authoritative databases in the world and summarizes the distribution of openBIM related publications from the perspectives of databases, standards, time, publishers, and countries, respectively.

2.1. Distribution of Publications by Databases

Papers related to openBIM were collected from five databases, namely Web of Science, Scopus, Engineering Village, Science Direct, and CNKI, which is one of the most authoritative academic databases in China. In order to comprehensively consider the development process of openBIM related research in recent years, the search period was set as from January 2000 to October 2019, giving the consideration for 20 years. The number of openBIM related papers in different databases were counted respectively by taking the combination of the abbreviation of the standard and BIM as search field, such as "IFC and BIM" when searching Industry Foundation Classes (IFC)-related papers. The statistical data according to the standards and databases are listed in Table 1. It can be seen from the table that the most widely adopted openBIM standard is IFC, while Information Delivery Manual (IDM) and Model View Definition (MVD) rank second and third respectively.

Table 1. Distribution of publications by databases.

		Scopus	Web of Science (Core Collection)	Engineering Village	CNKI	Science Direct	Total
1	IFC	738	392	620	534	147	2431
2	IDM	56	31	49	38	9	183
3	MVD	43	28	46	21	16	154
4	COBie	47	19	32	9	4	111
5	LandXML	26	15	20	13	7	81
6	ifcOWL	22	22	21	7	7	79
7	IFD	4	8	1	22	0	35
8	BCF	8	9	5	1	2	25
9	bsDD	2	3	2	0	0	7
	Total	946	527	796	645	192	3106

2.2. Distribution of Publications by Standards

It can be seen from Figure 1, the openBIM standards are widely used. As the core of openBIM, IFC, MVD, and IDM are adopted by most of the papers while IFC takes a lead with a number of 2431 which takes up around 78% of the total papers.

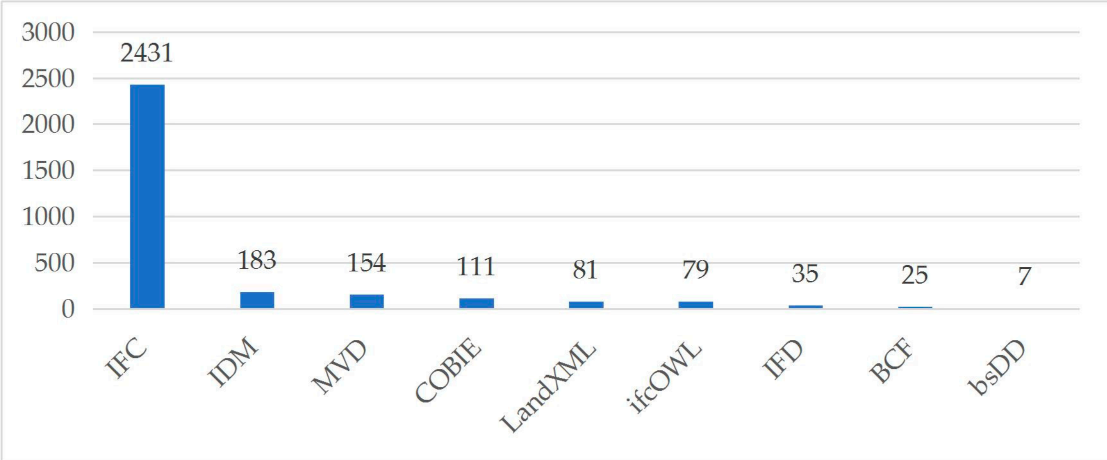

Figure 1. Distribution of publications by standards.

2.3. Distribution of Publications Over Time

It can be seen from Figure 2, the published papers related to openBIM are from 2000 to 2018, most of them are from 2011 to 2018. The number of these published papers has increased rapidly in recent years, which reflects how openBIM related research has been paid more and more attention.

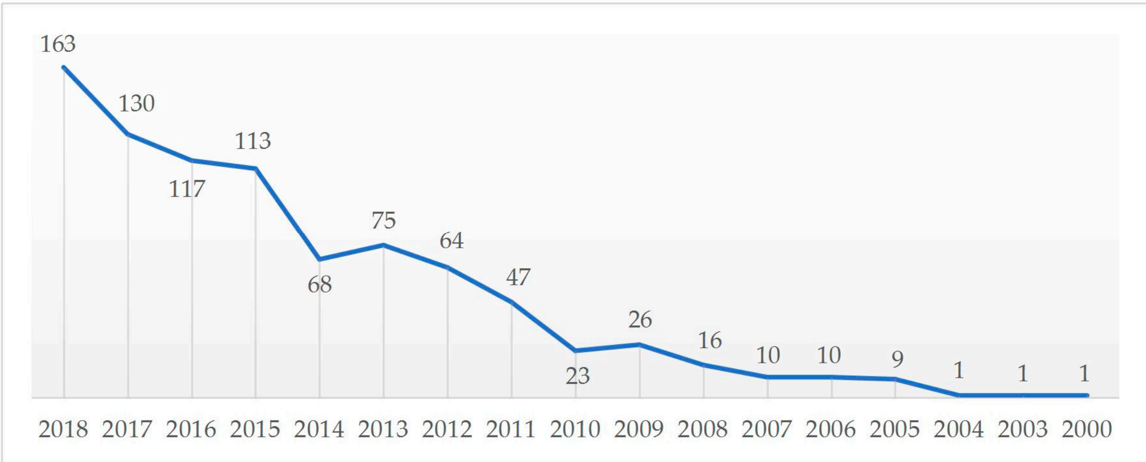

Figure 2. Distribution of publications over time.

2.4. Distribution of Publications by Publishers

It can be seen from Figure 3, most of the research related openBIM was published in journals, such as Automation in Construction, Advanced Engineering Informatics, and Journal of Computing in Civil Engineering. In particularly, papers in the journal of Automation in Construction take around 50% of the total papers.

2.5. Distribution of Publications by Countries

The statistical data of distribution of publications by countries is based on the authors of the published paper. As for papers with several different authors, the country of each author is recorded and the same country is just recorded for once. For example, if A (USA), B (Israel), C (China), and D (China) are authors for a specific paper, then the country of USA, Israel, and China is recorded once, respectively. It can be seen from Figure 4, the research related to openBIM is mainly from USA, Germany, China, and some other European countries.

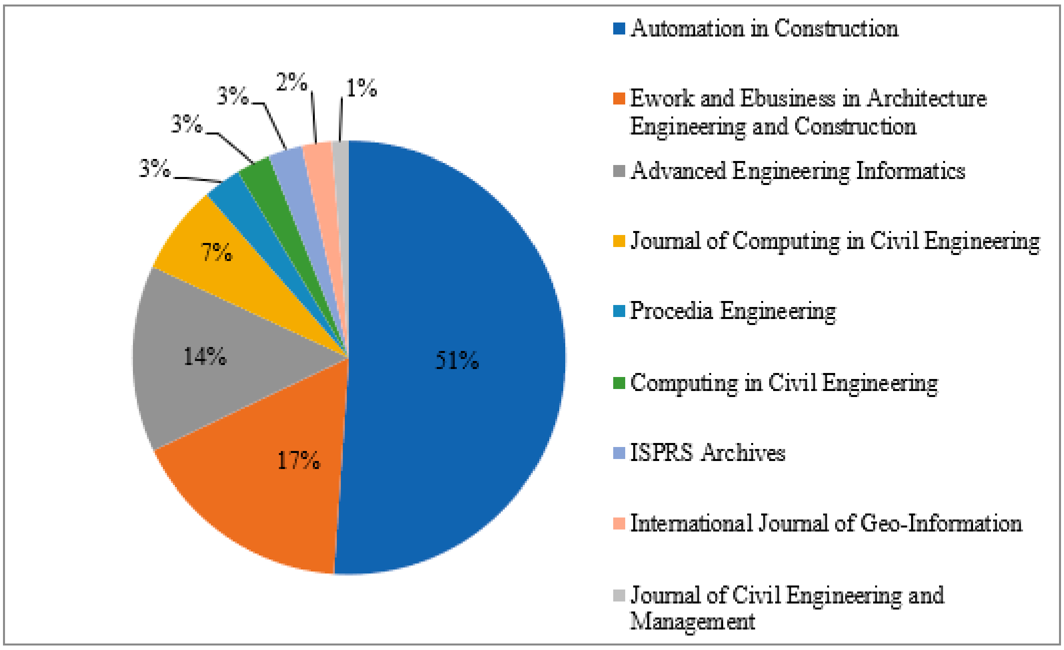

Figure 3. Distribution of publications by publishers.

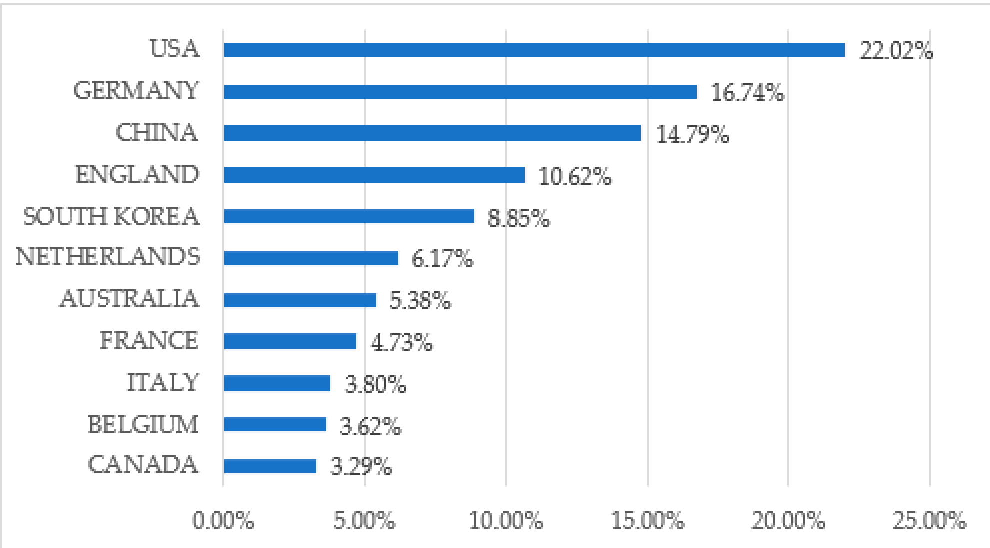

Figure 4. Distribution of publications by countries.

In conclusion, according to the above analysis result, it can be seen that: (1) among all the openBIM standards, IFC has been widely adopted by most of the fields, ranking in the top of the total application. (2) the development of openBIM varies among countries, while USA ranks first. (3) the application of openBIM standards are continuously growing over time, especially after the year of 2011.

3. Overview of OpenBIM

3.1. OpenBIM Standards

buildingSMART is an open, neutral, and international not-for-profit organization which is committed to creating and adopting open, international standards and solutions for infrastructure and buildings so as to drive the digital transformation of the built asset industry [2]. Based on the analysis of openBIM standards from the official website of buildingSMART, openBIM standards are divided into three main categories in this paper: buildingSMART standards, buildingSMART candidate standards, and buildingSMART related other standards. buildingSMART standards are the final standards that have been voted by the Standards Committee. buildingSMART candidate standards are the activities that are waiting for acquiring international consensus before being submitted to the Standards Committee for the final vote [3]. buildingSMART related other standards are formed to supplement the openBIM standards.

3.1.1. buildingSMART Standards

buildingSMART standards, as the most important part of openBIM standards, mainly includes five basic standards, the names and functions of these five basic standards are briefly summarized one by one in Table 2 [4].

Table 2. Brief summary of five basic standards.

Name	What It Does
IFC Industry Foundation Classes	Transports information or data
IDM Information Delivery Manual	Describes processes
MVD Model View Definitions	Translates processes into technical requirements
BCF BIM Collaboration Format	Change coordination
bsDD buildingSMART Data Dictionary	Defines BIM objects and their attributes

1. IFC—Data Standard

IFC is a common data schema for describing building information model data, which aims to establish a standard method of data representation and storage, so that all kinds of software can import and export building data in this format, thus promoting data sharing among different specialties and different software throughout the whole life cycle. IFC standards can be used to unify the format of information generated by different types of software so as to realize the free conversion of building information [2]. Up to now, the maturity level of each IFC version can be vividly represented in Figure 5.

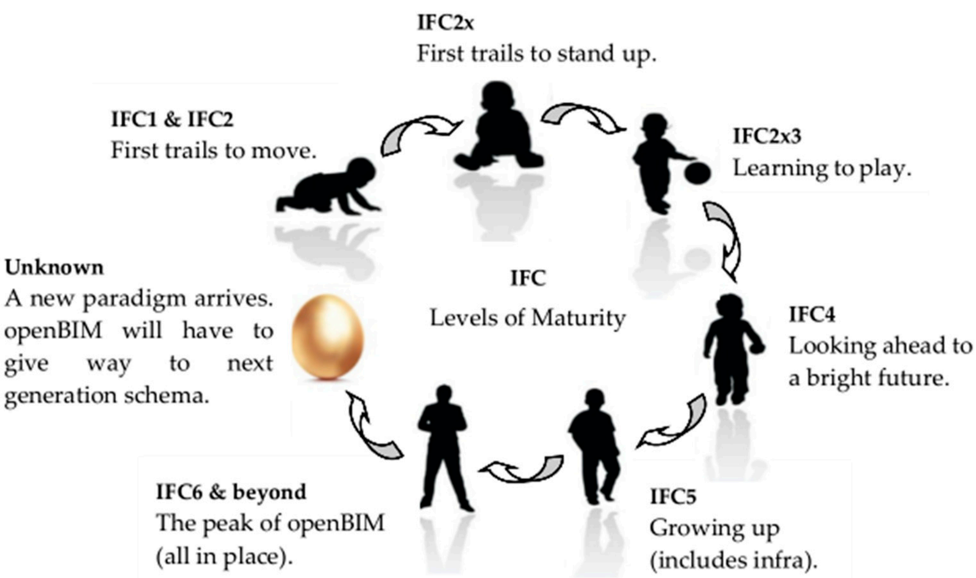

Figure 5. The maturity levels of Industry Foundation Classes (IFC).

2. IDM—Process Standard

IDM is a method for capturing and specifying the whole process and information flow during building life cycle, which aims to ensure relevant data is exchanged in a way that can be interpreted by the recipient software. The construction and maintenance of buildings involves many different participants, knowing what information needs to be communicated among them and when it is communicated is important. IDM can facilitate this information communication process by making full use of business process modelling notation (BPMN) and templates for Exchange Requirements [2].

3. MVD—Process Translation

The Model View Definition defines a subset of IFC schema that needs to meet one or more exchange requirements in the AEC industry. Together with this subset of IFC schema, a set of implementation instructions and validation rules are issued, and the method of publishing concepts and related rules is mvdXML [5]. The mvdXML is an encoding format, through which MVD can be encoded and allowable values in specific attributes of a specific data type can be defined. In practice, software applications can use mvdXML statically to support specific model views or use it dynamically to support any model view.

4. BIM Collaboration Format (BCF)—Change Coordination

The BIM collaboration format (BCF) is a simplified and open standard XML format used to encode information which enables workflow communication between different BIM software tools [3]. The development of BCF mainly includes two parts, namely a XML file format and a RESTful web service, in which the open file XML format called bcfXML can support workflow communication in BIM processes; besides, the RESTful web service called bcfAPI can enable software applications to seamlessly exchange BCF data in BIM workflows [6].

5. buildingSMART Data Dictionary (bsDD)—Standard Library

buildingSMART Data Dictionary (bsDD), as a reference library based on the IFD standard (ISO 12006-3), is one of a set of buildingSMART standards that enables collaborative work. To understand bsDD standard better, it is necessary to understand the concept of IFD standard. IFD is a terminology library-oriented or ontology-oriented standard, which ensures the accuracy of BIM information exchange and sharing by establishing the mapping relationship between IFC and information representations of different languages and vocabularies, as well as specifying the related conceptual semantics of objects [2]. Based on the IFD standard, the bsDD provides a shared system for identifying and validating the names of objects and their attributes used in building information models, which help to better understand the meaning of general terms, thereby improving the information interoperability during the construction industry [7].

In summary, each of buildingSMART's standards plays a significant role for sharing and exchanging structured building information openly during the whole life cycle, the process of using these five basic standards for collaborative work is shown in the Figure 6.

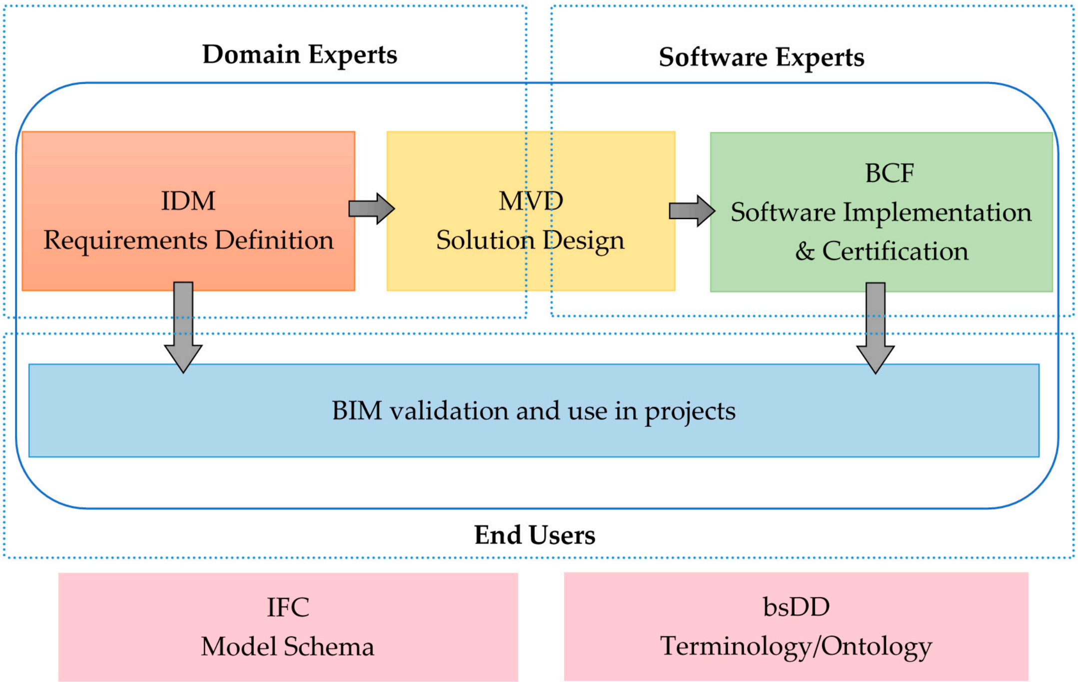

Figure 6. Process of using five basic standards for collaborative work.

3.1.2. BuildingSMART Candidate Standards

IfcOWL, as the only buildingSMART candidate standard, is used for providing a Web Ontology Language (OWL) representation for the IFC standard. To represent IFC data model as a schema, some schema modelling languages, such as EXPRESS and XML Schema Definition (XSD), are used to achieve this representation. By using OWL to provide corresponding representation of IFC schema, ifcOWL ontology is developed which has the same status as the EXPRESS and XSD schemas of IFC [8].

3.1.3. BuildingSMART Related Other Standards

1. Construction operations building information exchange (COBie)

The COBie is an information exchange specification for collecting and delivering information required by facility managers during the life cycle of the buildings. COBie can be viewed in design, construction, maintenance software, and simple spreadsheets, and this versatility enables COBie to be used in all projects regardless of project size and technical complexity [9].

2. LandXML

LandXML, as an electronic data transfer standard, was developed by the Open Geospatial Consortium in 1994. LandXML schema includes surveying, road design, and digital terrain model (DTM), which is capable of capturing, validating and displaying civil engineering and survey measurement data. Furthermore, infrastructure spatial objects based on the Geography Markup Language (GML) systems have been developed which help to realize the integration and transformation with the LandXML system [10].

3.2. *OpenBIM Software Platforms and Tools*

Based on the analysis about the existing research about openBIM, the mainly used openBIM software platforms and tools are listed as below (see Figure 7).

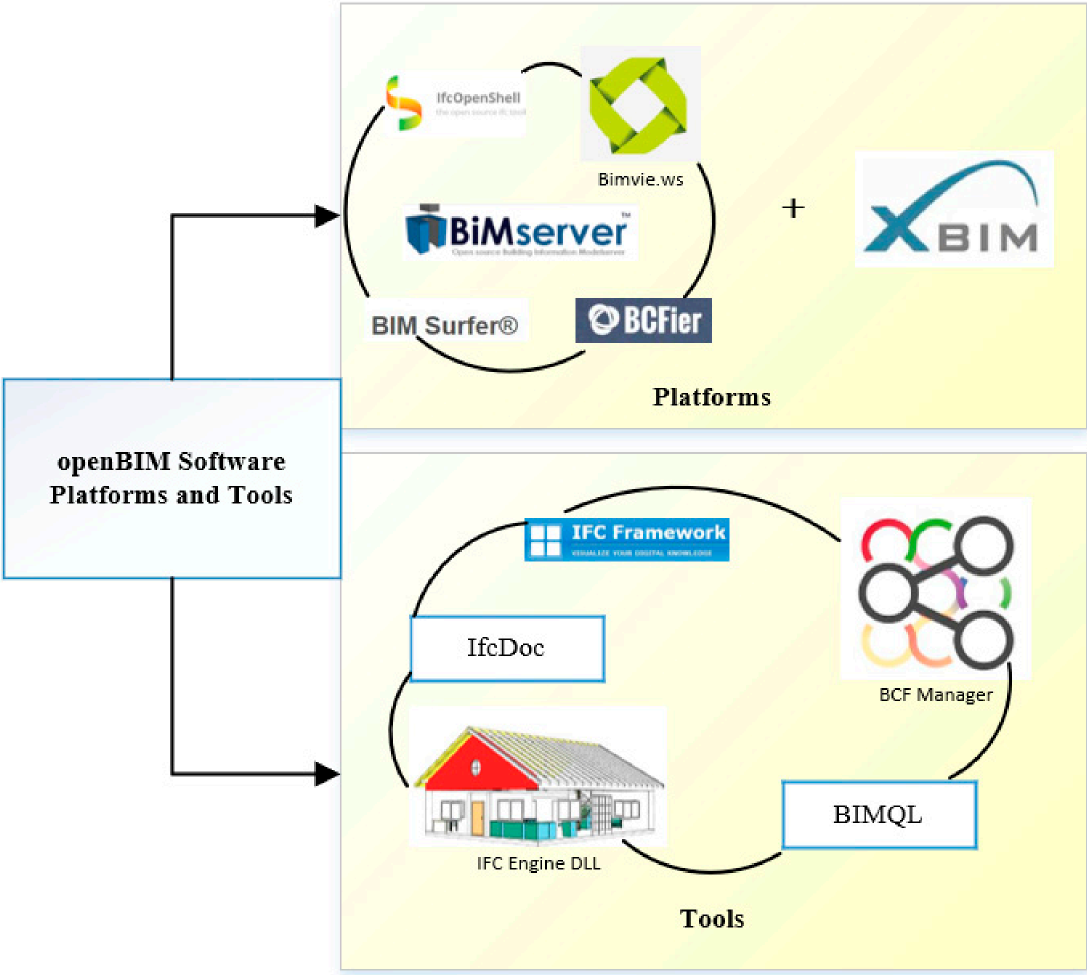

Figure 7. openBIM (building information model) software platforms and tools.

3.2.1. Platforms

Participants and stakeholders of construction projects can use different BIM software to realize the timely sharing of information [11]. At present, BIM software mainly includes Autodesk, Bentley, and Trimble series. There is a high compatibility between the same company's software, but the interoperability between different companies' software is relatively low, which leads to the difficulty of information sharing between software. Although some of the software has plugin development interface, but still cannot fully meet the construction industry's BIM software requirements about customization and modularization. This section introduces two typical open source software platforms.

1. BIMserver

BIMserver is an open and stable software, which can easily build reliable BIM software tools for supporting dynamic collaboration processes of AEC domain users. BIMserver (BIMserver.org) platform enables users to create their own "BIM operating system". The core of the software is based on the open IFC standard, so it can handle IFC data well. In BIMserver, the intelligent core interprets IFC data and stores it in the underlying database as an object. The main advantage of this method is that it can query, merge and filter BIM data. In addition to the core database functions of merging, model checking, authorization, authentication, and comparison, there are many other functions that can lower the threshold for developers [12]. BIMserver's common plugins are as follows:

- IfcOpenShell is an open source software library that helps users and software developers to parse IFC models [13].

- bimvie.ws developed an online viewing software tool of BIM built in HTML and Javascript. It is compatible with the BIM Service interface exchange (BIMSie) API interface and works with BIM on the cloud platform. BIMSie is a standard API for BIM Web Services to get BIM in the cloud. Users can use bimvie.ws with any BIMSie-compatible online BIM service [14].
- BIMsurfer is an open source IFC model viewer developed by SceneJS and WebGL to parse BIM data from IFC and glTF formats [15].
- BCFier is an application that can handle BCF files, and it can be integrated directly with BIM software as a plugin. BCFier allows users to create and open BCF files in Autodesk Revit, add multiple views and comments, and easily share them with other team members [16].

2. Extensible Building Information Modeling (xBIM)

Extensible building information modeling (xBIM) is a free open source software development platform that allows developers to create custom BIM middleware for IFC-based applications [17]. xBIM provides a rich API for IFC data standards. It allows developers to read, write and update IFC files in a few lines of codes.

xBIM has a complete geometric information engine that converts IFC geometric data objects (such as IfcSweptAreaSolid) into fully functional boundary representation (Brep) geometric models. These models support all Boolean operations, intersection, union, and calculation behaviors such as volume, area, and length. Geometric information engine not only provides optimized 3D triangulation and meshing for visualization, but also provides overall model optimization for repeated recognition and transformation to maps.

3.2.2. Tools

There are many supporting tools for openBIM standard. Among them, five kinds of common tools are introduced as follows.

- IFC Document Generator (IfcDoc) is a software tool for generating IFC documents (starting with IFC4) and developing MVD [18]. This tool is based on the mvdXML specification and can be applied to all IFC versions.
- BCF Manager enables users to create, filter, and find issues in BIM model. Users can save, load issues, or synchronize them from BIMcollab to share issues with project members who use the same or different BIM tools shown in Figure 8, thereby improving the reliability of issue management and narrowing the gap between BIM tools [19].
- Building information model query language (BIMQL) is an open domain specific query language for building information model. The query language can select and update data stored in IFC. It is currently used in BIMserver.org platform [20].
- The apstex IFC Framework is a Java-based object-oriented toolkit that provides full access to IFC-based BIM models for reading, writing, modifying, and creating IFC models. The IFC Framework provides tools for accessing and visualizing IFC-based BIM to facilitate software developers to integrate information libraries into products. End-users can also perform visual operations and model checking [21].
- IFC Engine DLL is a STEP toolbox, which can generate 3D models for the latest version of IFC. This component can load, edit, and create Step Physical Files and its framework through its own object database [22].

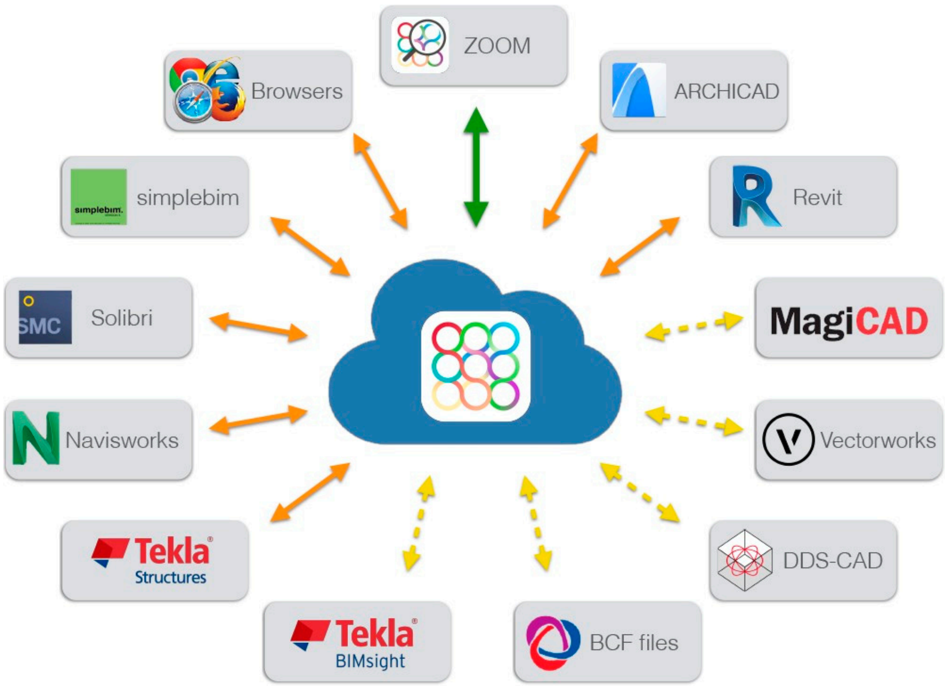

Figure 8. Building information model collaboration format (BCF) Managers are plugins for building information model (BIM) tools.

4. Engineering Information Interoperability Research Supported by OpenBIM

As a common approach of information exchange, openBIM has been applied widely in many research fields. In this paper, some related research of engineering information interoperability supported by openBIM is analyzed and summarized in five main aspects as shown in Figure 9, i.e., information representation, information query, information exchange, information extension, and information integration. The list of literatures by systematic analysis is summarized in Table 3.

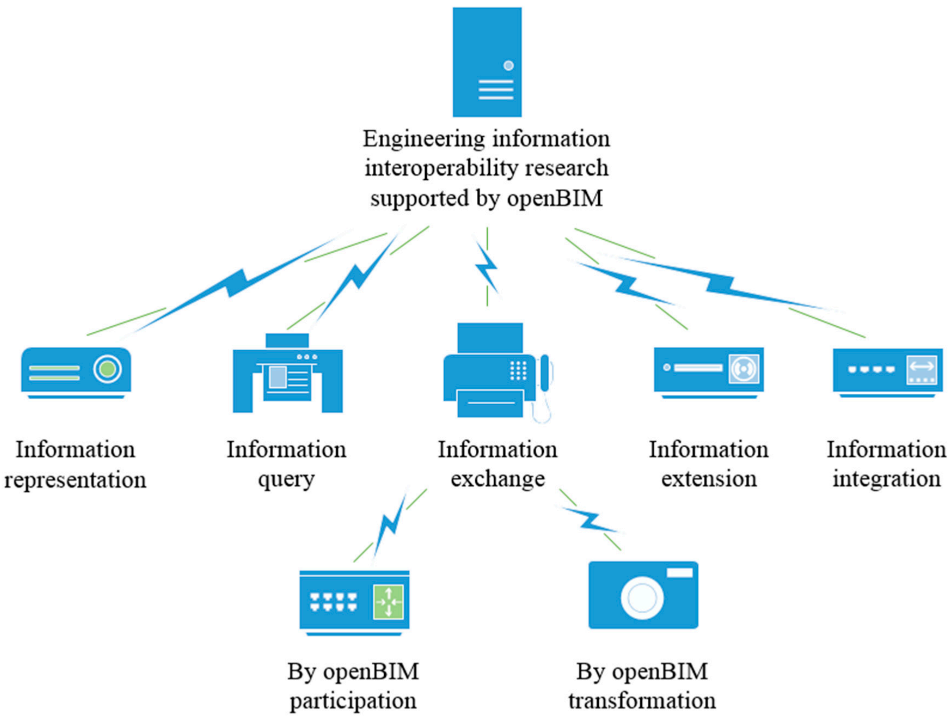

Figure 9. Engineering information interoperability research supported by openBIM.

Table 3. List of literatures summarized by systematic analysis.

Research Direction	Specific Classification	Reference
Information representation	Domain information representation	Ma et al. [23]; Sacks et al. [24]
	Semantic information representation	Sacks et al. [25]; Pauwels et al. [26]
Information query	Use openBIM only	Mazairac et al. [20]; Khalili et al. [27]; Kang [10]; Nepal et al. [28]
	Combine openBIM with other technologies	Ghang et al. [29]; Lin et al. [30]; Kuo et al. [31]
Information exchange	By openBIM participation	Hu et al. [32]; Lee et al. [33]; Solihin et al. [34]; Choi et al. [35]; Park et al. [36]; Caldas et al. [37]; Babič et al. [38]; Caffi et al. [39]; Ding et al. [40]; Lu et al. [41]; Hu et al. [42]; Edmondsona et al. [43]; Vanlande et al. [44]; Lin et al. [45]; Jeong et al. [46]; Wang et al. [47]; Venugopal et al. [48]; Lee et al. [49]; Lee et al. [50]; Lee et al. [51]; Pärn et al. [52]; Alreshidi et al. [53]; Lee et al. [54]; Du [55]; Beetz et al. [56]; Isikdag [57]; Ma et al. [58]; van Berlo et al. [59]; Solihin et al. [60]
	By openBIM transformation	Solihin et al. [61]; Oldfield et al. [62]; Terkaj et al. [63]; Le et al. [64]; Lee et al. [65]; Pauwels et al. [66]
Information extension	Domain information extension	Lee et al. [67]; Ji et al. [68]
	Attribute information extension	Patacas et al. [69]
	Semantic information extension	Venugopal et al. [70]; Belsky et al. [71]; Fahad et al. [72]
Information integration	BIM-based workflow	Andriamamonjya et al. [73]
	Integration of BIM and GIS	Laat et al. [74]; Jusuf et al. [75]; Liu et al. [76]; El-Mekawy et al. [77]; Zhu et al. [78]; Kang et al. [79]; Amirebrahimi et al. [80]; Teo et al. [81]

4.1. Information Representation

Information representation is the basis of information interoperability. openBIM standards, such as IFC and IDM, provide convenience for information representation in many domains. For example, in building domain, Ma et al. developed an BIM application with reasoning support in which BIM data was assumed to be stored in files that conformed to the Industry Foundation Classes standards (IFC files) for better extensibility and reusability [23]. In the field of bridge, Sacks et al. proposed a Semantic Enrichment Engine for Bridges (SeeBridge) system for bridge inspection, in which IDM was responsible for compiling specific information while MVD was mainly used for identifying required information based on IFC. The proposed system can meet the requirements of automatic information inspection and can also be further applied to other infrastructure [24]. Overall, the application of openBIM facilitates the process of domain information representation, thus improving information management of construction industry.

In addition to domain information representation, openBIM can also be applied to semantic information representation. For example, Sacks et al. used IDM for identifying needed domain data and related elements for topological rule processing in the proposed procedure which was targeted to improve the shortage of Semantic Enrichment Engine for BIM (SeeBIM) tool in enriching building model [25]. Furthermore, Pauwels et al. optimized geometric data in ifcOWL semantic representation and proposed four alternative representations of ifcOWL geometric aspects. They also quantified the influence of these metrics on the size of ifcOWL ontology and instance models, eventually they suggested to use the well-known text (WKT) representation as an additional component for ifcOWL ontology, which greatly reduced the scale and complexity of the ifcOWL construction model [26].

The framework of information representation using openBIM is shown in Figure 10.

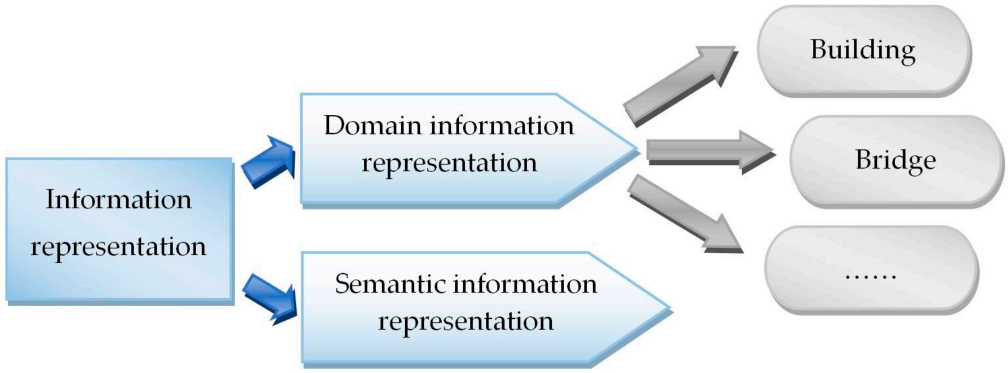

Figure 10. openBIM for information representation.

4.2. Information Query

In addition to using openBIM for information representation, more operations can be performed on the subsequent processing of engineering information with openBIM. The standards, such as IFC, IFD, and BCF, can be used in querying information to realize data retrieval and analysis. For example, Mazairac et al. presented a framework based on a domain specific and open query language which can be used to select, update and delete the data stored in IFC. An outline of existing approaches, conceptual sketches were provided, and the implementation status was recorded as a prototype plugin which was developed for bimserver.org [20]. To speed up topological queries among building elements, Khalili et al. used IFC as a new topology driving method, and proposed a new schema called the Graph Data Model (GDM), through which 3D objects such as building elements could be mapped into a set of nodes, and their relationships could be converted to a set of edges by using IFC standard. In addition, a new IFC-based algorithm was used to deduce the topological relationships among building elements [27]. Due to the difficulty of obtaining civil engineering and building model objects represented by LandXML schema and IFC respectively using linkage manner based on shape information, Kang proposed an effective method of BIM-integrated object query using LandXML and IFC through an object query method based on the BIM linkage model. In addition, the object type and simple query language were defined [10]. Moreover, Nepal et al. proposed an efficient method of extracting and querying information from BIM models by combing ifcXML and spatial XML data, which can save time and reduce errors of extracting information manually [28].

In addition to use openBIM only, some other advanced technologies, such as database technology, natural language processing, and machine learning, can also be combined with openBIM to solve information query issues. For example, combining the advantage of traditional relational databases, Ghang et al. developed an innovative object–relational IFC server which can improve query performance of traditional IFC servers [29]. Lin et al. proposed an approach to realize intelligent data retrieval and representation based on natural language processing. The proposed concepts "keywords" and "constraints" can be mapped in IFC entities or properties through IFD to enable data retrieval and analysis [30]. Kuo et al. proposed machine learning steps to extract and process BCF data. A conceptual framework of queryable knowledge discovery system was introduced to integrate knowledge for future problem prediction [31].

Intelligent information query can improve the efficiency and effectiveness of traditional information query. The data standards provided by openBIM play an indispensable role in intelligent information query process. The combination of intelligent technologies such as natural language processing and machine learning with openBIM standards is a very interesting research direction of information query. The framework of information query supported by openBIM and other advanced technologies is shown in Figure 11.

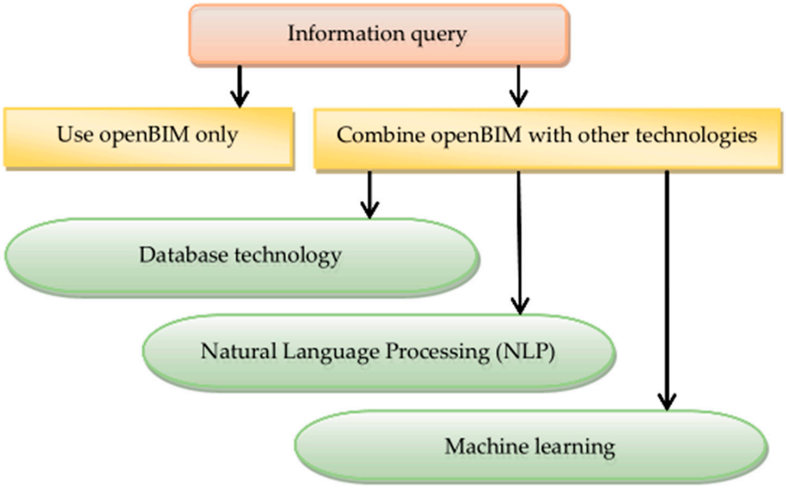

Figure 11. Information query supported by openBIM and other advanced technologies.

4.3. Information Exchange

The development of BIM software contributes to the improvement of work efficiency for different disciplines, which facilitates the process of informatization in construction industry. However, the interoperability among different BIM software becomes a key problem during the collaboration process of stakeholders and how to realize information exchange effectively matters the whole collaboration process. By taking the advantages of openBIM, information exchange can be smoother and easier. Based on the analysis and summary of the existing literature, the information exchange process supported by openBIM is divided into two ways: (1) openBIM standards or platforms participate in information exchange; (2) information exchange is realized through openBIM standard data transformation. The specific classification of these two ways is shown in Figure 12.

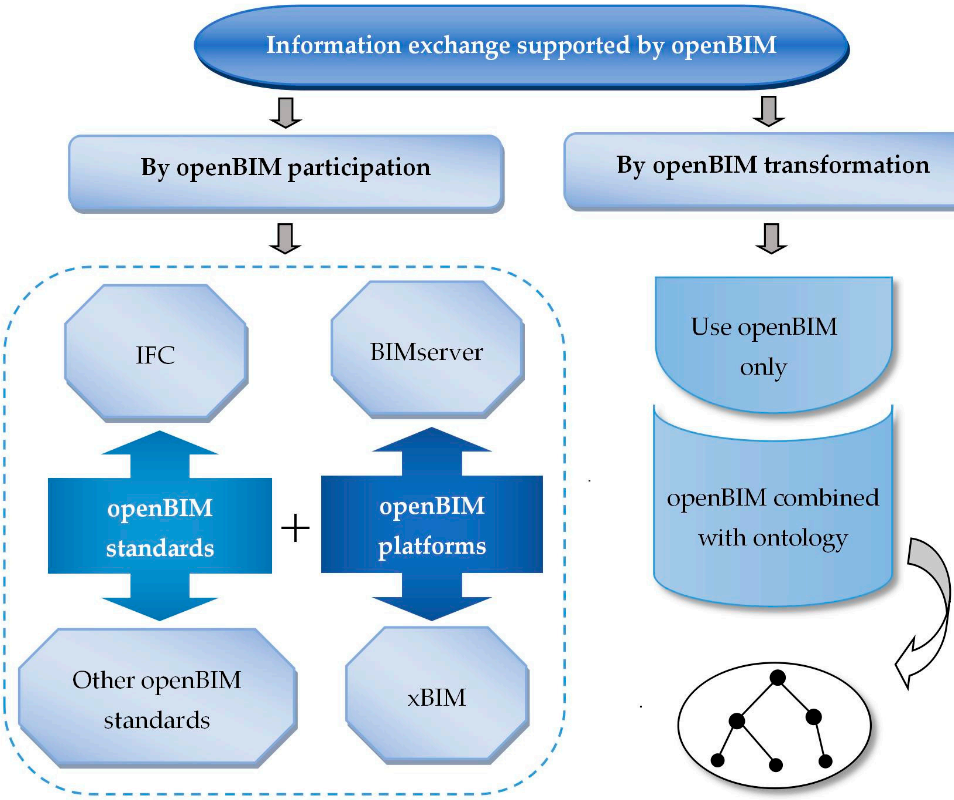

Figure 12. Information exchange supported by openBIM.

4.3.1. Information Exchange by OpenBIM Participation

1. Information exchange by openBIM standards participation

(1) Use IFC only

Some researchers applied openBIM in the process of information exchange. At present, the most widely adopted openBIM standard is IFC, which is applied in building life cycle, including design, construction, operation, and maintenance phases, as shown in Figure 13.

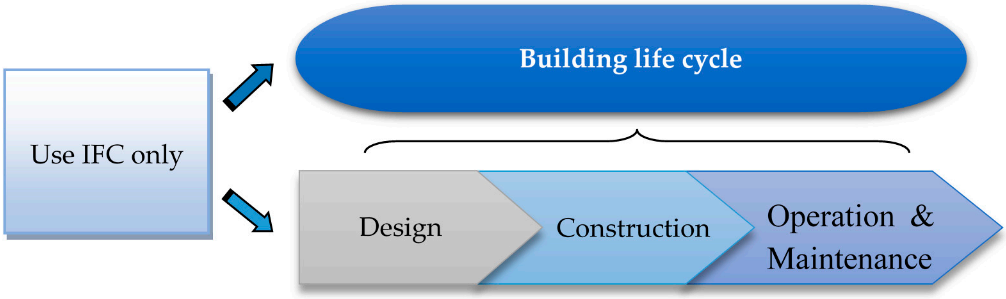

Figure 13. Information exchange by IFC participation.

- Design phase

To improve the interoperability of the design phase, Hu et al. proposed a new method of combining IFC based unified information model with various algorithms, in which IFC based unified information model was used to form the comprehensive central information layer of the model transformation. Moreover, through the proposed method, the entities, attributes, and relationships required for the conversion can be standardized to overcome the inconsistent representation of data and information in different structural analysis applications [32]. Lee et al. described the implementation process of the Building Environment Rule and Analysis (BERA) Language related to BIM, which could contribute to design rule checking and many other analysis purposes, in which IFC was used as a given building information model to transfer BIM data into the BERA Language framework [33]. Solihin et al. demonstrated multiple representations for BIM 3D geometry data using a traditional relational database model to support high-performance rule checking related queries, IFC acts an important role in this information exchange process [34]. Choi et al. proposed a Quantity Take-Off (QTO) process and QTO prototype system within the framework of openBIM to improve the low reliability of early design phase estimation. As long as the worker inputs the necessary task data, the concept of IFC model can progress throughout the entire task of the building lifecycle [35].

- Construction phase

Park et al. proposed a visualization method supported by web and database technology to realize real-time construction progress information sharing and visualization of daily 4D BIM, in which the 3D BIM model had been previously created and followed the IFC standard. By parsing the BIM models based on the IFC file format, the information of the BIM model entity could be recorded to the 4D BIM database [36]. In order to achieve integration of AEC/facility management (FM) information which stored in text documents, Caldas et al. proposed a method to automatically integrate AEC/FM project documents in model-based IFC compatible systems, in which IFC model was used as a benchmark to classify text documents and associate project objects, thereby improving the information interoperability during the construction phase [37]. Babič et al. proposed a system architecture for the interconnection of subsystems in construction company, in which the BIM was used to link the information from an enterprise resource planning (ERP) system with the building object related information. The system architecture is based on the IFC standard, therefore the level of interoperability among project participants is improved and the process of industrialized construction is promoted [38]. Caffi et al. declared the use of INNOVance database for construction process management, and with the adoption of the IFC protocol, interoperability at the end of the project is guaranteed [39]. Ding et al. developed an Industrial Foundation Classes-based Inspection Process Model (IFC-IPM). Within the IFC-IPM schema, a physical, schedule and quality management model exist to meet the requirement of real-time quality-related information exchange during the construction process [40].

- Operation and Maintenance phase

Lu et al. developed a semiautomatic image-driven system for building the original BIM objects in IFC from the images of existing buildings at the stage of operation and maintenance. Three subsystems were developed for this purpose, in which the IFC BIM object generation subsystem used ifcengine to create BIM objects in IFC, and selected IFC2 $\times$ 3 and IFC4 as its basic schema standard, so that the subsystem can automatically convert the identified objects into IFC BIM objects [41]. Hu et al. proposed an IFC-based practical multi-scale BIM which was described in detail with the information required by the mechanical, electrical and plumbing (MEP) components for both construction management (CM) and facility management, in which IFC2 $\times$ 4 was used to represent this information and exchange them among different BIM applications. Based on the proposed multi-scale BIM, BIM-based CM system and BIM-based FM system were presented to support the collaborative management with multi-scale functions among MEP project partners at the stage of operation and maintenance [42]. Some advanced technologies, such as Internet of Things (IOT), can also be combined with openBIM to solve the information interoperability problems. For example, Edmondsona et al. designed and developed a Smart Sewer Asset Information Model (SSAIM) of existing sewerage network using IFC4, which integrated distributed intelligent sensors to realize real-time monitoring and reporting for sewer asset. In the end an approach of sensor data analysis was proposed to promote the real-time prediction of flooding [43].

- Building life cycle

Vanlande et al. used IFC as a model to define the elements and relations of the construction projects, then constructed an information system which was exclusively used in the building life cycle and developed a platform called Active3D to facilitate information sharing and exchange process in the whole life cycle of the AEC projects [44]. Lin et al. proposed a new approach to deal with 3D indoor space path planning by using IFC file as input, in which IFC was used to restore both geometric information and rich semantic information of building components to support life cycle data sharing [45]. Jeong et al. carried out a structured set of detailed benchmark tests of data exchange between BIM tools. These tests illustrated that a mutually agreed standard which defines how building elements are modeled and mapped into IFC schema is needed to achieve totally effective interoperability [46]. To achieve the efficient transformation between architectural and structural models, Wang et al. developed an IFC-based transformation software which can facilitate transformation process [47]. The relevant literature, which only uses IFC standard to participate in information exchange, is summarized in Table 4 according to the classification of building life cycle.

Table 4. Literature relating to information exchange by Industry Foundation Classes (IFC) participation.

Building Life Cycle Classification	Literature
Design	Hu et al. [32]; Lee et al. [33]; Solihin et al. [34]; Choi et al. [35]
Construction	Park et al. [36]; Caldas et al. [37]; Babič et al. [38]; Caffi et al. [39]; Ding et al. [40]
Operation and Maintenance	Lu et al. [41]; Hu et al. [42]; Edmondsona et al. [43]
Life cycle	Vanlande et al. [44]; Lin et al. [45]; Jeong et al. [46]; Wang et al. [47]

(2) Use other openBIM standards

Apart from IFC, other openBIM standards were also adopted for information exchange. For example, Venugopal et al. applied MVD for information exchange in sub-domain of building by embedding semantics into information exchange, to solve the insufficiency of IFC in defining entities, attributes, and relationships during the specific information exchange process [48]. Lee et al. proposed a method called extended process to product modeling (xPPM), which can implement the integration and seamless development of IDM and MVD. Based on this method, corresponding tools were developed to analyze the validity of xPPM by copying the existing IDM and MVD, thereby achieving efficient and seamless exchange of building data [49]. To validate the accuracy of BIM model information change, Lee et al. conducted a survey based on available software (such as IFC server ActiveX Component, the IfcDoc, and so on) on conformity to IFC, MVD, and design requirements, which was aimed to provide integrated approaches for improving interoperability [50]. Lee et al. suggested a robust MVD validation process using a modularized validation platform that evaluated an IFC instance file according to diverse types of rule sets of MVDs to address challenges existing in MVD validation process [51]. To realize the integration of BIM and facility management for promoting the process of information exchange in project operation and maintenance (O&M) phase and reducing the cost of the FM team to update and maintain the BIM, Pärn et al. iteratively developed a FinDD API plug-in which could manage the semantic FM data in BIM, in which COBie could provide relevant parameters that meet the requirements of O&M phase. The FinDD was a bespoke extension of COBie, and the data requirements and model structure of its API plug-in were mainly influenced by COBie standard [52]. Alreshidi et al. analyzed the requirements for BIM collaborative platform and pointed out that compatibility among standard-based software, such as IFC-based software, was a big setback for advance of BIM adoption and IDM can play an important role in the BIM collaborative process [53]. Lee et al. suggested a new approach for evaluating BIM data in accordance with diverse requirements of MVD, and examined their embedded checking rule types and categorized corresponding implementation scenarios [54]. Based on IFC and IDM, Du put forward an innovative cloud-based building information interaction framework based on cloud computing and open web environment [55].

2. Information exchange by openBIM platforms participation

(1) Use BIMserver

Except for openBIM standards, some researchers explored to realize information exchange and sharing progress with the aid of some software platforms related to openBIM, such as BIMserver and xBIM. As an open and stable software core, BIMserver can easily build reliable BIM software tools to support the dynamic collaboration process of AEC users. And the BIMserver.org platform enables users to create their own "BIM operating system". For example, Beetz et al. introduced the open source IFC server BIMsever.org and gave an outline of existing IFC toolkits and servers. An implement-independent model based on IFC STEP EXPRESS schema was proposed and used as a database persistency framework. The authors also introduced a model server application based on this framework which can realize interoperability about storage, maintenance, and query of BIM among different stakeholders [56]. Isikdag proposed three service-oriented architecture design modes, BIM AJAX, BIM SOAP Facade, and RESTful BIM, in which IFC model was used to promote information exchange and sharing progress. In the RESTful BIM mode, IFC object tree was used for information exchange, and the REST function of the BIMserver could further promote the collaborative use of web-based BIM [57]. In order to reduce the workload of inspectors, promote their cooperation and prevent inspection omissions in the construction quality inspection, Ma et al. proposed a comprehensive application system based on BIM technology and indoor positioning technology, in which IFC format was responsible for storing the BIM model and establishing the detection task generation algorithm, and the BIMserver.org platform was used to manage the BIM model, or was used as a IFC analyzer and a viewer [58]. Van Berlo et al. took advantages of online 3D viewer, BIMserver and the developed open source BCF server to streamline workflow, which can provide convenience for collaborative design [59].

(2) Use xBIM

As a free open source platform, xBIM allows developers to create bespoke BIM middleware for IFC-based applications. For example, Solihin et al. proposed a framework to integrate totally different models in a federated environment through the adoption of IFC schema and standardized procedures. In the validation and testing stage, a prototype implementation was developed by using a modified xBIM toolkit to parse IFC files, import and integrate IFC data [60].

4.3.2. Information Exchange by OpenBIM Transformation

1. Use openBIM only

As a common standard of information exchange, openBIM can not only participate information exchange, but also support information exchange through its standard data transformation. For example, to transform BIM data into a form which can be easily queried, Solihin et al. focused on the definition of a schema and transformation rules and proposed a methodology to transform IFC files to the BIMRL schema (an open and queryable database schema), which can realize flexible and efficient queries into the BIM data using standard SQL [61]. Oldfield et al. followed a standard BIM approach of first defining the requirements using IDM and then translating the process described in the IDM into technical requirements through the use of MVD. The modelling of an MVD or a subset of the IFC data model helped to create and exchange boundary representations of topological objects, which can be combined into a 3D legal space overview map [62].

2. openBIM combined with ontology

As an efficient way of structured information representation and the core of semantic technology, ontology has been paid much attention in recent years. It is important to realize information exchange by integrating ontology with openBIM. For example, Combining IFC with ontology, Terkaj et al. explored the conversion from IFC EXPRESS to OWL and proved the usability of ifcOWL, which provided a new idea for further application of ifcOWL ontology [63]. To realize the interconnection of life cycle data spaces and support the highway asset management, Le et al. proposed a life cycle data exchange framework based on ontology, in which LandXML was used for describing the various design data in the XML format of civil engineering, and some rules were proposed to transform LandXML design data into RDF graphs. The authors also tested the mechanism using a sample road project retrieved from Landxml.org [64]. Due to the lack of logical link in the data transformation process from IDM to MVD, redundant requirements and rules of data exchange may be caused. Under this circumstance, Lee et al. adopted ontology theories to generate IDM in the precast concrete field and link its MVD with formal information modellings to satisfy the requirement of identifying the intent of mapped MVDs and keeping track of the mapping issues. In addition, in order to integrate IDM and MVD, the authors parsed and transformed ontology-based IDM from OWL/XML to mvdXML, which automatically generated MVD documents in IfcDoc tool [65]. To improve the interoperability of construction projects, Pauwels et al. took the ifcOWL ontology as a connection between the semantic web technology and the IFC standard. By analyzing the corresponding application standards required by the key features of the recommend ifcOWL ontology, a conversion program from the EXPRESS mode to the OWL ontology of the IFC was proposed, and the transformation results of the program was used as the recommended ifcOWL ontology [66]. The literature that suggests how openBIM transformation support information exchange is summarized in Table 5.

Table 5. Literature related to information exchange by openBIM transformation.

Classification	Literature	OpenBIM Transformation
Use openBIM only	Solihin et al. [61]	IFC to BIMRL
	Oldfield et al. [62]	IDM to MVD
openBIM combined with ontology	Terkaj et al. [63]	IFC EXPRESS to OWL
	Le et al. [64]	LandXML to RDF
	Lee et al. [65]	OWL/XML to mvdXML
	Pauwels et al. [66]	IFC EXPRESS to OWL

4.4. Information Extension

OpenBIM covers a large range of industry information, such as building components information. But for some fields, such as road, bridge, and port field, openBIM is still not enough to support specific research. Therefore, it is necessary to carry out information extension to meet the requirements. For example, in road domain, based on the IFC framework, Lee et al. added the main building components of road structures to the IFC, and developed an IFC expansion model for road structures, thus extending the BIM technology of road structures [67]. In bridge domain, Ji et al. proposed a possible extension of the existing IFC-Bridge draft, in which an object-oriented data model was used to capture the geometric description of the parameters, and then it will be converted into an EXPRESS pattern and integrated with the current IFC-Bridge draft. The proposed neutral data structure lays the foundation for exchanging parameter bridge models among different software applications [68].

OpenBIM standard can also be used for attribute information extension. For example, Patacas et al. investigated whether IFC and COBie can provide facility manager with required assets data and information from a perspective of a whole life cycle by focusing on some specific use cases including asset registration and service life plan. The result showed that though IFC and COBie cannot meet all the information requirements of asset registration and service life plan by default, they permit users to add some unsupported information in the form of attribute sets by using Revit shared parameters [69].

In addition to domain information extension and attribute information extension, openBIM can also make great contributions in the field of semantic information extension. For example, the lack of semantic clarity in mapping entities, attributes, and relationships leads to multiple expressions of the same information when mapping between different federate modellings. Based on this consideration, Venugopal et al. examined IFC from a viewpoint of ontological framework to make the definition of IFC more accurate, consistent, and unambiguous. Ontology would build interoperability of BIM by providing formal and consistent classification and structure to extend IFC and define subsets as MVD [70]. To solve the problem in existing application of BIM tools, Belsky et al. proposed a new approach which can infer meaningful concepts from BIM model automatically. What is more, the proposed approach can also enrich IFC files and achieve MVD validation by checking spatial topology of elements [71]. In the aspect of achieving automatic verification, Fahad et al. extended ifcOWL ontology with bsDD vocabulary, and compared MVDXML and Semantic Web Rule Language (SWRL) technologies for conformance checking of IFC models [72].

The framework of using openBIM for information extension is shown in Figure 14.

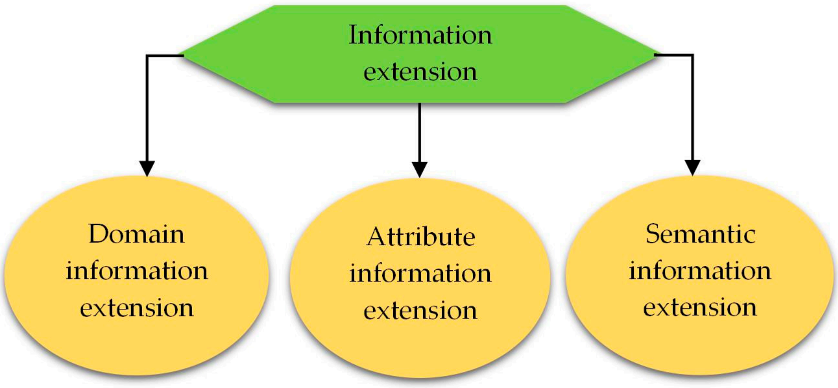

Figure 14. openBIM for information extension.

4.5. Information Integration

Information integration means that the information of the subsystems and users in the system uses unified standards, specifications and codes to realize the information sharing of the whole system, and then the interaction can be realized. openBIM provides a general standard of data exchange in this process.

- BIM-based workflow

It is evident that there is a pressing need for the standardization and uniformity of modelling. A well-defined workflow based on BIM can exploit and extend openBIM standard to improve information integration. Under this circumstance, Andriamamonjya et al. described the significant elements of an integrated BIM-based workflow, explained that openBIM comprised a standardized file format and stated what can be achieved with the help of the already available technology named IDM and MVD. Python language and open source IfcOpenShell were used in case study to illustrate the benefits of this workflow [73].

- Integration of BIM and geographic information system (GIS)

In recent years, the integrated application of BIM and GIS is gaining more and more attention. The method of realizing information interaction through simple model conversion in different fields makes only a small amount of semantic information retained, which leads to the dispersion and independence of the application. IFC and CityGML are the common data model standards of BIM and GIS respectively, and the geometric and semantic information sharing will lay the foundation for the integration of BIM and GIS.

For example, in order to import semantic IFC data into the GIS environment, Laat et al. described the development of CityGML extension called GeoBIM, which is mainly the development and the implementation of GeoBIM extension for IFC data on CityGML, thus facilitated the integration of BIM and GIS [74]. To achieve Neighborhood Scale Modelling, Jusuf et al. focused on ways of exchanging information and bringing together CityGML and IFC. The transformation system was developed using Feature Manipulation Engine (FME) by Safe Software. With the help of FME, data model (IFC) can be restructured and transformed to the destination data format (CityGML). The test results showed that CityGML format, as well as a Sketchup file, could be generated from detailed BIM models. These models can be imported to web visualization applications for urban energy modeling [75]. Liu et al. reviewed the development and difference of BIM and GIS, the existing integration methods, and discussed their potential in many applications. The author pointed out that semantic web technology provided a promising generalized integration solution and openness was the key factor to the integration of BIM and GIS [76]. El-Mekawy et al. described a new method of data integration based on the unified building model (UBM), which not only encapsulated CityGML and IFC models, but also avoided the translations between the models and information loss. The case scenario and four queries have verified that the developed UBM can integrate CityGML data and IFC data in a seamless manner [77]. Zhu et al. reviewed relevant research papers to (1) determine the most relevant data modellings used in BIM/GIS integration; (2) look for the possibility of other data modellings which can be used for data-level integration; and (3) provide guidance for future's BIM/GIS data integration [78]. In order to solve the problem of integration of BIM and GIS heterogeneous models, Kang et al. defined the integration process of BIM-GIS through the BIM-GIS conceptual mapping (B2GM) standard and proposed a mapping mechanism related to it. Based on IFC and CityGML, the schema structure of BIM and GIS were analyzed from the perspective of BIM-GIS integration. In addition, the IFC standard was also used for database integration and query process based on B2GM [79].

BIM and GIS information integration can effectively solve specific practical problems. Amirebrahimi et al. designed a new conceptual data model, which was used to integrate detailed assessment and three-dimensional visualization of flood damage of buildings. In this design process, investigation was conducted to figure out how concepts are represented in IFC format or CityGML format so that they can create a mapping between the concepts of this proposed model and IFC or CityGML [80]. Teo et al. proposed a multi-purpose geometric network model (MGNM) based on BIM and discussed the method of outdoor and indoor network connection to optimize emergency response and pedestrian route plan. To achieve these goals, the conversion between IFC and MGNM was discussed and validated by case study. The IFC-to-MGNM conversion included the following: (1) extraction of building information from IFC, (2) isolation of the MGNM information from building information, and (3) establishment of the topological relationship of MGNM to GIS geodatabase [81]. International Building Performance Simulation Association (IBPSA) Project 1 provides a BIM/GIS and Modelica framework for building and community energy system design and operation, in which Modelica is used for building and regional energy system performance modeling. It aims to create open-source software which lays the foundation for the next generation of computing tools for the design and operation of building and regional energy and control systems. All the work is open-source and based on three standards: IFC, CityGML, and Modelica [82].

In the past few years, the efforts of information integration especially the integration of BIM and GIS have been increasing from the semantic point of view. But the information loss and change are still normal in the process of data exchange. Openness and collaboration are the key to information integration. The sharing standards provided by openBIM should be fully utilized to make information integration more widely used.

The framework of using openBIM for information integration is shown in Figure 15.

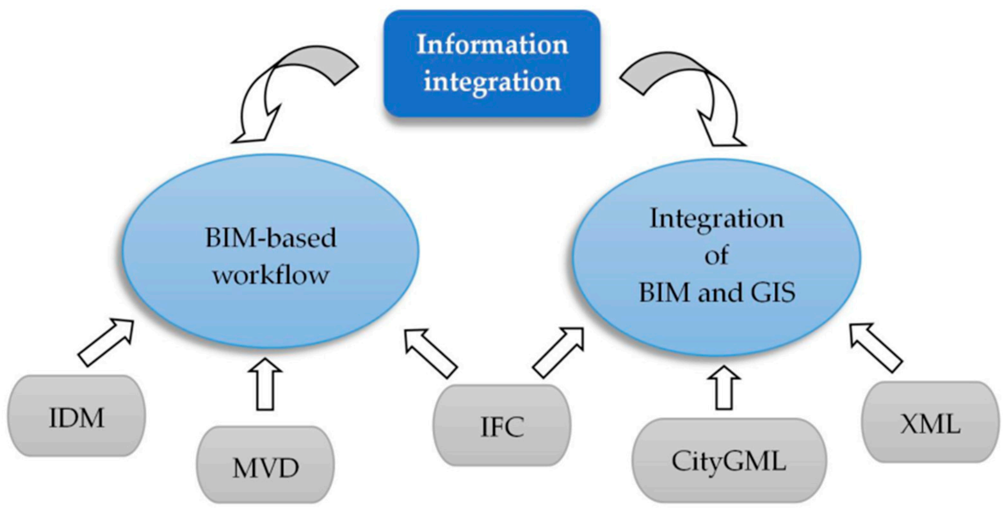

Figure 15. openBIM for information integration.

5. Research Gaps and Future Directions

This paper outlines the achievements of openBIM in various aspects of engineering information interoperability in recent years, such as information representation, query, exchange, extension, and integration. Although the application of openBIM provides favorable environment for the management and exchange of information and data, and to some extent overcomes the obstacles of cross professional cooperation in the project, more basic and applied research work are still needed. At present, the research gaps and future directions are mentioned below:

1. Rule checking

With the increase of project complexity and the number of project participants, unified BIM data exchange standards and robust validation frameworks are needed to ensure the seamless sharing and consistent maintenance of BIM data. At present, researchers have developed rule checking function based on MVD by using IfcDoc tool, and discussed the identified knowledge of BIM data validation using MVD, involving procedures, scope and complexity [83].

However, there are still some challenges in MVD-based rule checking: (1) although several versions of IFC schema provide the schematic basis of BIM data exchange standards, current rule checking cannot cover numerous types of modeling, representation, and interpretations scenarios that the IFC schema supports, thus sets back the process of validation of BIM data using MVD, which will lead to syntax problems, semantic errors, and unintended geometric transformations. (2) each field has different data and exchange processes which should be included in an MVD. However, domain experts and software vendors refer to multiple interpretations and different ways when defining their domain knowledge, which results in a broad scope of model view definitions and makes the formal rule checking process very complex and difficult.

In order to solve the limitations of current research, it is necessary to consistently examine various methods to identify an explicit link between conceptual rules and formal information models. In addition, to ensure the reliable validation of BIM data exchange and the consistent definitions of model view specifications, the existing MVDs and the related rules should be further investigated. In the future, industries, academia, and governments need to cooperate to develop formal processes for MVD development, and jointly establish generalized libraries containing knowledge in various domains and IFC schema to ensure data interoperability and quality.

2. Ontology development

Due to the lack of semantic clarity of IFC in mapping entities and relationships, it is too generic to use IFC exchange schema when exchanging information between BIM tools, which results in the inability to capture full semantic meaning required for the direct use of different construction project stakeholders' BIM tools. As a representation of concepts, relations, and rules in a specific domain, domain ontology can store, query, and share information in the domain. Therefore, checking IFC from the perspective of ontology framework can make the definition of IFC more formal, consistent, and clear. Applying ontology to engineering can support the following aspects of information interoperability: (1) realizing knowledge sharing among multiple human or software agents; (2) dealing with semantic interoperability between computer-based systems and data sources; and (3) using formal axioms accessible to machines to capitalize experts' knowledge [84].

At present, the research of data interoperability based on ontology has made some progress in some fields, such as construction, energy, and infrastructure. However, there are still technological and methodological gaps between academic researches and industrial practices. In order to take full advantage of the potential of ontology, further development and utilization of ontology should be carried out from the following aspects: (1) the development and (re-)use of inter-connected ontologies including upper- and domain-level ontologies; (2) a library of modelling alternatives to satisfy different representational needs; and (3) more effective software environments which can support different phases in the ontology-based software lifecycle.

3. Integration of BIM and GIS

Based on the developed IFC and CityGML semantic models, users can flexibly choose the corresponding BIM-GIS integration methods according to the specific problems, including extracting data from one system to another, merging data using semantic models or integrating data of both models by a third-party platform [85].

However, the above integration technologies still have the following defects: (1) when converting IFC to CityGML, the model information mismatch between BIM and GIS will lead to geometric information mismatch. Because the huge and complex IFC data stored in BIM models has various attributes and geometric expressions, most of the information representing the attributes and associations between features in IFC may disturb the geometric mapping process between IFC and CityGML. (2) when transforming data between IFC and CityGML, semantic loss of features may occur. For instance, the outer and inner walls of a real building become the same object after conversion.

Therefore, the future research should focus on improving the accuracy of BIM-GIS data integration, and can be carried out from the following directions: (1) interoperability, transformation process and detailed information processing of these two kinds of data should be focused. First, the upgrade of IFC and CityGML semantic models is needed to improve the accuracy and matching degree of semantic information; second, in addition to consider one-way information transformation from IFC to CityGML, future work will focus on the two-way transformation of model information. (2) when using the third-party platform for data integration, it is necessary to ensure the consistency of these two semantic models and the accuracy of data mapping. Data can be classified based on data hierarchy, and the integrated data from both models using a third-party platform can be developed in the direction of customer-orientation, information sharing, and simplified operations. Besides, an open multi-party data sharing platform can be developed for future use. (3) in order to obtain optimal solutions and planning decisions using BIM and GIS data, it is necessary to ensure the accuracy and diversity of the original data. The process of data measurement, collection and statistical analysis should be comprehensive and careful, not only the macro geographic information, but also the detailed information of the internal space of the building is needed.

4. Combination with IT technologies

In order to fully utilize the value of BIM and promote intelligent decision based on BIM data, it is necessary to combine openBIM with IT technologies such as cloud computing and big data. For example, the distributed architecture of cloud computing technology can solve the problem of limited capacity of a single server and facilitate information exchange; Big data technology can deeply analyze and mine massive data, discover hidden regularities in data, so as to realize intelligent decision and management; IOT technology can expand information source of projects, and realize dynamic and real-time management of projects.

The combination of cloud technology and BIM is only for storage and retrieval in the early stage, but the great advantage of cloud technology is providing BIM analysis with massive heterogeneous data spanning the whole life cycle of construction projects. The shorter the processing from original data to information representation, the less information loss will be. Therefore, the development of BIM combined with cloud technology should focus more on data-driven information exploration.

At present, some researches have discussed how to use big data analysis to extract effective information from the original BIM data that was previously considered unavailable or ignored. However, many of these researches are in the embryonic stage of concept. The possibility of using big data should be further discussed, especially the joint analysis of cloud technology and big data on the whole life cycle of the building. Accurate analysis can be made in many fields such as energy and structure by exploring the potential connection of data.

The summary of this study's findings is presented in Figure 16.

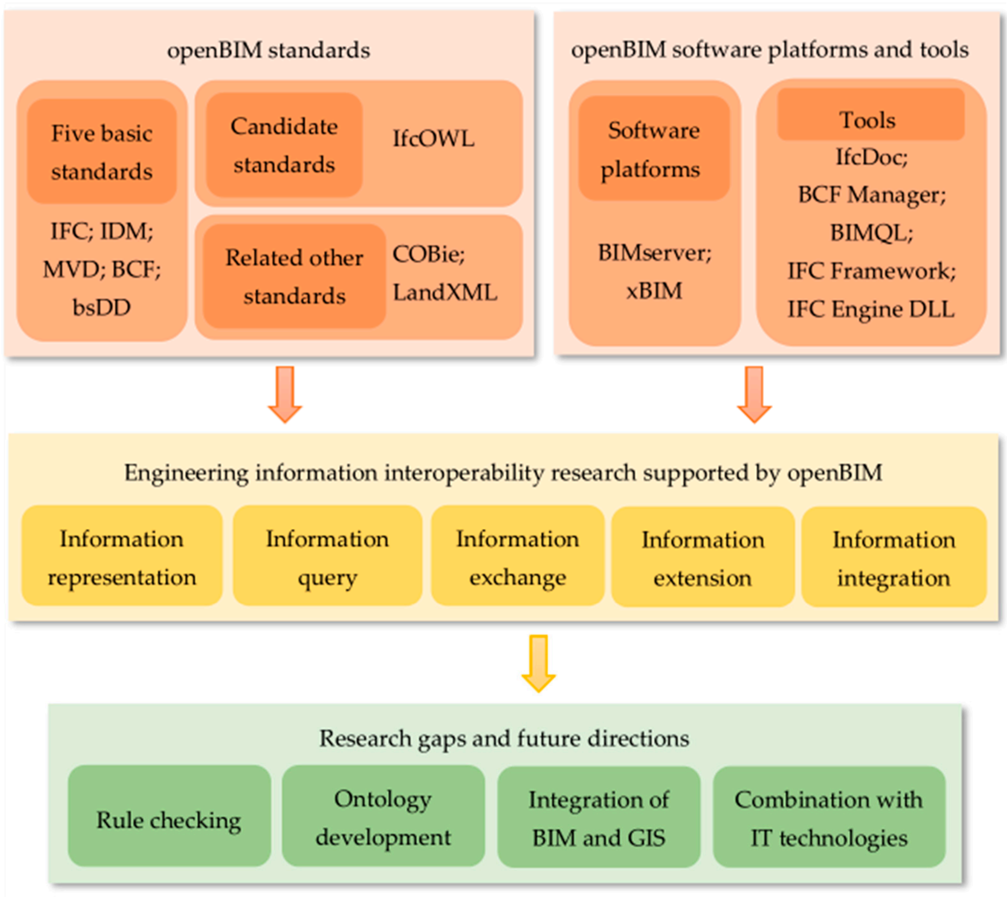

Figure 16. Summary of the findings.

6. Conclusions

The occurrence of openBIM lays a foundation for collaboration among users of the BIM platform and participants of the projects, and provides convenience for the management and exchange of information. In this paper, firstly, based on the literature from main databases like Scopus, the authors analyze the research status of openBIM in the world. And on the premise of elaborating the definitions, standards, and software of openBIM, the paper summarizes engineering information interoperability research supported by openBIM from five perspectives: Information representation, information query, information exchange, information extension, and information integration. This review provides an in-depth understanding of existing openBIM research. Moreover, the study makes a discussion of research gaps and future directions, which can provide valuable insights for academia and industry.

In conclusion, as an effective solution to the interoperability and sharing problem, openBIM has played a great role in the construction field and facilitated the collaboration process of projects. So with the continuous development of openBIM, it will provide more comprehensive solutions to the problems existing in the construction field.

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