Information exchange and interoperability of heterogeneous Building Automation Systems and BIM applications

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Abstract. The traditional stand-alone building industry is transforming into a digitally intelligent building system. The traditional building automation systems are limited to performing set tasks and have only basic device control capabilities; as technologies evolve, new building automation systems requires more information integration possibilities (e.g., Building Information Modeling (BIM), Internet of Things (IoT), intelligent computing). In this paper we provided a review of the different levels of data exchange in the building automation system and the methods of integrating Building Automation Systems (BAS) with multiple building phases. In the first part, we review the data exchange of BAS at three levels according to the IEEE definition of interoperability and evaluate its advantages and challenges. Subsequently, we analyze the current status of BIM-BAS integration and review the case applications of various integration methods one by one to provide a contextual overview of data exchange based on the full building lifecycle. Finally, we analyse limitations of current research which are systematically summarized. Future research directions are proposed in complex multi-service integration, real-time data linkage, and edge computing.

1. Introduction

The concept of Building Information Modelling (BIM) was first introduced in the 1980s and has rapidly evolved in recent years. From traditional workflows-based drawings to the era of 2D digital drawings to 3D model-based workflow, BIM has significantly changed the way of working in the Architecture, Engineering, Construction, Operation (AECO) fields [1]. Meanwhile, the Internet of Things (IoT) provides technical support for BIM technology with the goal of achieving seamless integration between the virtual model and the physical world, which adds sensor data, recognition technologies, networks and computing services from the physical world to the model-based model [2]. Early-stage Building Automation Systems (BAS) were introduced in the 1970s and were initially used to control the Thermal Comfort (TC) of buildings, including Heating, Ventilation, and Air Conditioning (HVAC), lighting systems, and security systems. While technologies such as the IoT and Digital Twin have inspired further developments in BAS, including sensor technologies, wireless communications, communication protocols, etc [3].

Compared with the early-stage BAS that only automate the control of electrical devices during the building operation phase, the current BAS approaches apply a comprehensive set of automated workflows throughout the full building lifecycle. Nowadays, BAS are capable of standardizing and smoothing the workflow to reduce the error rate by reducing human work. For instance, digital files from the design and construction phases can be delivered to the facility operations manager for further use to reduce duplication of effort. Interoperability in the AECO domain refers to the ability to exchange data between applications in multiple specialized domains. Application Programming Interfaces (APIs) were the very first widely used tools to achieve data interoperability [4]. With the advancement of information technologies, in addition to APIs, vendor-neutral data formats can also be considered as a way to achieve data interoperability, such as Industry Foundation Classes (IFC), City Geography Markup Language (City GML). In addition to the numerous data exchange scenarios between the participants in the planning process, vendor-neutral data format enables the digital transfer of building data to the contractor during the construction phase and the" handover" of building data to the client or building operator after completion.

Despite the attention BAS has received over the past years, there is a general lack of review studies on the subject of interoperability. Tang et al. [5] explore the current status of IoT device integration with BIM, subdividing IoT into four application domains (Construction Operation and Monitoring, Health and Safety Management, Construction Logistic and Management, and Facility Management) and detailing multiple integration approaches, but limited to IoT devices. Boje et al. [6] provide a study of how the building industry can profit from the digital twin paradigm, and data integration methods supported by semantic models. However, this study is limited to the interoperability based on the semantic web-based paradigms, still analysed from multiple application areas of BIM (e.g., Construction logistics, Clash detection, Site monitoring, etc.). O'Grady et al. [7] provide a systematic review on building automation, but the authors focus more on an overview from the application domain of BAS rather than on the interoperability of BAS, or heterogenous data exchange. In this paper, we bridge the research gap by providing a classification of interoperability into three levels for BAS, and by exploring multiple approaches for integrating BAS with BIM.

In order to provide a comprehensive review of the BAS information exchange and interoperability, journals from the AECO field as well as journals from the environmental sciences, electrical engineers, and computer sciences were all taken into consideration. 1) Select databases: We targeted on Science Direct, American Society of Civil Engineers (ASCE) Library, Wiley Online Library, Springer library, ITcon, Electrical and Electronics Engineers (IEEE) Xplore, and Association for Computing Machinery (ACM). 2) By searching the databases, we continued to target industry journals with high impact factors and selected structured texts. 3) We searched for papers in selected databases and journals for the following keywords: Building Information Modelling, Building Automation Systems, Internet of Things, Automation and Control System, Building Performance System, Cyber Physical System, Linked Data, Semantic Web, Interoperability, Information exchange, Smart Building, approximately 1000+ papers were searched. The focus of this review is on data exchange and interoperability in Building Automation System, so the irrelevant parts were manually removed. Since 2012, a large number of papers on building automation systems have started to appear, so this paper addresses the literature from 2012 onwards. 4) The literature obtained by the search was sorted to delete duplicate and irrelevant contents. Due to space limitations in this paper, we only examine highly relevant papers, so we targeted about 40 papers for study.

2. Information Exchange and Interoperability

Building Automation systems not only involve the direct linkage of devices, but also require the integration of information from multiple domains into one building automation system, as well as the digital transmission of building system data to multiple parties in different stages. The manual-based information transfer used in the past was prone to introducing errors, in addition to many repetitive tasks. While BAS consist of multiple domains (e.g., building Information Modelling, control heating ventilation and air conditioning (HVAC) and lighting systems, etc.), the problem is that each domain has dedicated software tools and data models. Lossless data exchange requires seamless interconnection between these software tools. Therefore, the emergence of vendor-neutral data formats promises greater potential to address interoperability issues. With the concept of full lifecycle development in the AECO industry, higher requirements for data exchange have been put forward, with data being transferred from the architect to the construction contractor and then to the operations manager after the building is completed. Overall, an open, neutral, and standardized approach to data exchange is needed to achieve the paradigm of BAS data exchange and interoperability.

As for the definition of interoperability, the term has different interpretations in different cases. For example, the IEEE has four definitions for this, which are mainly based on the interoperability hierarchies, including from equipment units, different suppliers' equipment layer, to independent systems, and finally to the exchange and use of information between multiple systems (IEEE 2000). Therefore, in building automation system, interoperability can be understood primarily as facilitating, but not guaranteeing, the exchange of information and the use of information by multiple systems in a heterogeneous environment by adhering to a set of standards. In the next section, we review the BAS data exchange in terms of the hierarchical sequence of interoperability.

3. Review of interoperability in Building Automation System

Industrial and Automation Control Systems (IACS) tend to have a periodic, high volume data characteristic due to its economic interest oriented, while building automation system is mainly concerned with managing heating, ventilation, and air conditioning systems in buildings to achieve energy efficiency improvements. The building automation system is mostly composed of loosely structured data with a relatively low volume [8]. Therefore, compared to complex industrial automation, building automation has multiple levels of data exchange depending on the usage requirements. Heterogeneous domains in building automation system mainly consist of:

- Building energy and performance management
- Indoor environment monitoring
- Access and security control
- Home automation

3.1. Basic Entity Connectivity Interoperability

Some text. Due to the multidisciplinary characteristic of BAS, the most fundamental level is the interconnection between multiple device entities and multiple tasks. Through the "peer-to-peer" protocol, two devices can communicate directly without a server (see in Figure 1). For example, most commonly found in smart home systems, the temperature and humidity regulation system is connected to the room sensing system for self-adaptive adjustment according to the indoor environment. The most common instances of basic connectivity use are Bluetooth, Ethernet, WIFI, ZigBee, etc. The main advantage of these wireless communication tools is that they can be used to communicate with BAS equipment via widely used smart phones and computers. At the same time, the wireless transmission of signals can save a lot of installation costs compared to wired cables [9]. In [10], authors proposed a wired building automation control system in small scale buildings by deploying sensors, actuators and controllers in the building to collect building environment data. Basic network connectivity ensures that devices within a building can communicate effectively and to some extent meet the basic device control and management of the home, which is an economical, rapid deployment, and easy to maintain building automation solution.

Nevertheless, as the infrastructure continues to evolve and customer needs grow, BAS based on basic connectivity is unable to meet the control and management of complex autonomous home entertainment system demands.

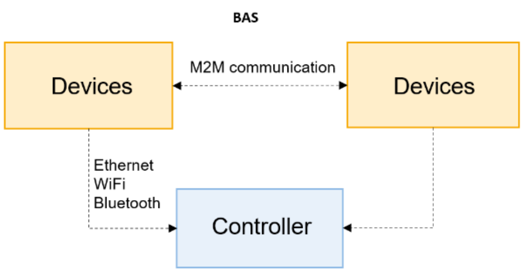

Figure 1. Basic entities connection in BAS

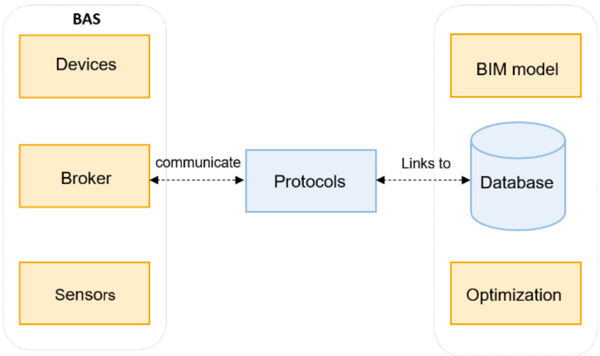

Figure 2. Gateway interoperability in BAS

3.2. Gateway Interoperability

The second level of BAS interoperability is the gateway level, where multiple heterogeneous devices exchange information by complying with communication protocols. As described in [11], a building automation system should be a low-energy network transmission system that needs to meet fault tolerance, reliability, low latency rate, and security and privacy issues. The communication protocol is international standardised protocol that defines multiple heterogeneous communication links. Examples of common data exchange protocols in building automation system are BACnet, LonWorks, EIB/KNX, MQTT, MOD-BUS, etc (see in Figure 2). BACnet was introduced by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in early 1980s, it uses the collapsed Open System Interconnection (OSI) model to break the complex system to smaller subproblems. BACnet has gradually become the dominant choice in commercial applications due to its flexibility and compatibility with other protocols. In parallel, European Installation Bus (EIB) was created in the late 1980s, which was later extended to KNX[1] and developed into a common standard worldwide, such as Chinese standard GB/Z 20965 (China Machinery Industry Federation, 2013), international standard ISO/IEC 14543-3[2], American standard ANSI / ASHRAE 135. Meanwhile, Modbus was developed by Modicon and published as an open standard protocol since 2004, it is widely used in Supervisory Control and Data Acquisition (SCADA) system. While MQTT is mainly a lightweight transmission protocol applied to IoT devices, transmitting data through publication/subscribe, which is characterized by adapting to network instability, low computing power, etc.

3.3. Basic Entity Connectivity Interoperability

The third level of interoperability is semantic or syntax level, which supports syntax information exchange, by converting individual data format to neutral data format, for example, JSON, XML, OWL, RDF etc (see in Figure 3). Operations Building information exchange protocol (COBie) [12] is a data standard that stores building model data as digital spreadsheet, to integrate digital building operation data with BIM. But this method has some restrictions and is restricted to use in the operation phase, which is difficult to achieve full life-cycle BIM integration. This method of directly linking BIM data with operational data is easy to implement, by linking the components in the building model with the relevant devices in the space through automatic creation is very effective, but there are certain limitations,

[1] https://www.knx.org/knx-en/for-professionals/index.php
[2] https://www.iso.org/standard/59865.html

for instance, it is difficult to integrate the geometric data, or need to go back to the BIM model to find the corresponding component.

With the advancement of BAS, the multi-agent, complex data characteristics are increasingly reflected; therefore, researchers in AECO domains have started to introduce the Semantic Web to address interoperability problems and lossless data exchange. W3C Linked Building Data Community Group (LBD-CG)[3] was started in 2016, to address the application of linked data across the building lifecycle. Web ontology language (OWL) was first introduced by W3C [13] and has become the main tool for semantic web use in multi-domains. Industry Foundation Classes (IFC) is a comprehensive and commonly used standard format for describe building context data. Over the last decade, IFC was developed from original eXtensible Markup Language (XML) and EXPRESS schema (ISO 10303-11) to ifcOWL[4] [14], to enable semantic-based building information exchange or BIM data exchange with other domains. However, users need to import the entire agreement in different application scenarios even if a part of the information is needed, so Building Smart has introduced the Model View Definition (MVD) and MVD xml schema to intercept a subset of IFC entities for specific uses. Meanwhile, Building Topology Ontology (BOT)[5] was proposed by the LBD group, aims to describe buildings' topology through this minimal ontology [15].

Notably, ontologies associated with building automation are also proposed, e.g., Semantic Sensor Network Ontology (SSN)6 [16] Sensor, Observation, Sample, and Actuator (SOSA) are used to describe sensors and their observations in a wide range of applications (including aerospace, industry, home automation, etc.). Generic protocols are often used in specialised software such as the EST67 for KNX protocol. Meanwhile, those protocols also provide standard neutral file format for both machine-readable and human readable. Currently XML is widely used as a data interchange format, and there are languages such as XSLT and XQUERY to convert xml to other formats. BACnet has defined the Control Systems Markup Language (CSML) in the documentation Annex Y, which is an XML description of objects and properties in BACnet. Similarly, KNX has XML schema available for further use. The Brick schema [17] is a metadata schema, and it has proposed an ontology to describe physical, logical, and virtual assets in buildings. Brick describes the entities in a building by using RDF triples. Comparison to the wide range of SSN/SOSA applications, Brick schema is more concerned with the AECO domain and supports the integration with other datasets (such as BOT, SAREF and SOSA). Haystack is an open-source platform that offers standardized semantic metadata related to building systems and devices8, each entity is given a "tag" from the Haystack list, which conveys information about the building and its environment through a machine-readable set of tags. The metadata of Brick and Haystack can be queried through SPARQL and GraphQL.

With the extension of standardized semantic vocabularies and platforms, the information covered by building automation continues to expand (no longer limited to equipment such as HVAC and ventilation in the past), and BAS systems are linked with other domain knowledge.

Semantic-based interoperability can transform different types of datasets into machine-readable languages, while allowing some logical reasoning to be performed, thereby obtaining richer information [18]. The study from [19] demonstrated the use of Linked Data to integrate datasets in the building phase that can be applied to the management and evaluation of building performance. Ontology modelling also used to represent building occupancy data for building lifecycle applications [20].

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[3] https://www.w3.org/community/lbd/

[4] https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL/index.html

[5] https://w3c-lbd-cg.github.io/bot/

[6] https://www.w3.org/TR/vocab-ssn/

[7] https://www.ets6.org/?lang=de

[8] https://project-haystack.org/

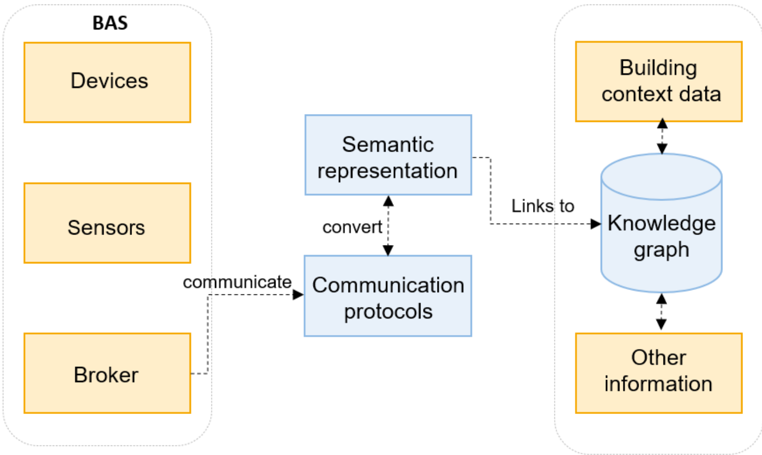

Figure 3. Semantic interoperability in BAS

4. BIM and BAS Data Exchange

Generally, BAS is involved in the operation phase of the building life cycle, because it relates to device systems and security systems inside the building, rather than being based on the full life cycle. BIM, on the other hand, as a tool throughout the design to the construction phase, mainly uses IFC to improve data exchange. In the initial stages, AutoCAD, Revit, and Rhino were the main tools used in the building design phase, while EnergyPlus was the most commonly used building simulation software in several publications, it is capable of the simulation and calculation of HVAC, lighting, and building energy systems. In the early manual interface stages, building design information was mainly connected to building automation systems using Revit or AutoCAD in combination with EnergyPlus. As the more specific energy calculation demands (e.g., daylight calculation, occupancy calculation, etc.), researchers started to use visual programming languages (VPL) such as grasshopper to personalize specific BAS scenarios for optimization [21] [22].

With the expansion of large-scale commercial buildings and the development of BAS data volume, it was difficult to link a large amount of data by manual connection, so the open standard-based data exchange method began to develop. Middleware is a bridge between BAS and BIM systems, and the development of middleware enables existing BAS to interact with BIM to exchange information, avoid duplicate modelling, and expand BAS from operation phase applications to the whole building life cycle [23]. By mixing the existing technologies and connecting them using middleware, it tends to reduce a lot of duplication of work and data redundancy. However, the research is currently scarce in the review, with only a few studies. As mentioned before, COBie (Construction Operations Building Information Exchange) was proposed as an open data format for non-geometric information exchanges.

Subsequently, COBie was further developed as COBieOWL [24], which semi-automatically maps spreadsheets to OWL classes, further enhancing the interoperability of dematerialized building data, and the authors explored the possibility of linking COBieOWL to other datasets. Tang et al. [25] developed a middleware tool called BACnet MVD using MVD and IDM to exchange IFC and BAS information via BACnet protocol and tested the application in Revit and web browser, which makes it possible to extend the use of BIM information to operation phase. Nevertheless, the data exchange based on multiple protocols still remains to be explored. Since researchers have brought the Semantic Web into the AECO field, the dominant data exchange formats used have evolved from static IFC formats to dynamic and open semantic vocabularies such as IfcOWL and BOT. Terkaj et al. [26] created an ontology called BACS to integrate information from BIM and BAS by reusing and aligning existing domain ontologies. Researchers are paying more attention to using Semantic Web technologies in BAS and integrating BAS with other datasets (e.g., geometry data, product manufacture information, and disaster and emergency management) by using link data.

As IoT technology has evolved in the last decade, BAS are no longer limited to HVAC system related home devices, but has developed into a network-based, more intelligent and highly integrated" cyber-physical-data" paradigm. BIM is mainly the digital representation of building information, while DT is the combination of physical and virtual worlds, forming a more intelligent and adaptive tool. Nevertheless, this approach is currently still a hybrid framework [27] that describes BIM contextual information using semantic vocabulary [18], and most of the data for the time series generated in the BAS system are still stored and queried using relational databases or time series databases [28].

Table 1. Methods of integrating BIM and BAS

Methods	Tools	Challenges
Manual interface, APIs	Revit DB link, Revit API VPL, Energy Plus	Vendor neutral data format
Open standard based-middleware	COBie/MVD BACnet MVD	Building full life-cycle application
Semantic level exchange	Brick schema BACS SSN/SOSA COBieOWL SAREF	Real time data representation and storage Interoperability, querying and reasoning capabilities

5. Conclusion

This paper first introduces the definitions of interoperability and data exchange in the BAS domain, and then moves from the most basic linking methods between devices, to network-based data exchange, and then to semantic-level data exchange based on the IEEE definition of interoperability. This paper presents key research hotspots for building automation heterogeneous data exchange, as well as limitations in existing research, and suggests several directions for future research. In contrast to previous reviews of building automation systems, this study examines a mix of literature from the fields of architecture, civil engineering, and computer science to address the issue of building automation interoperability, thus providing a more comprehensive review of current research developments. By investigating the existing literature in BAS interoperability there is a strong slant towards semantic-based solutions. Such a progression is not difficult to predict, as BAS is no longer limited to the control of switches, but will move towards standard labels, robust ontology systems, and scalable systems to evolve. One of the promises of the Semantic Web for building and automation applications is the seamless integration of heterogeneous data. This means that future BAS will use structured ontology vocabularies to describe systems in a machine-readable format. Semantic-based formats such as RDF, OWL are becoming popular data formats today, thanks to powerful tools such as SPARQL and SHACL that allow querying, reasoning, and qualifying operations on RDF data. As opposed to the tree structure of XML, RDF uses unordered triples to describe the data, which together form the RDF graph, thus allowing reasoning on the web to achieve data set enrichment. Therefore, heterogeneous data exchange in BAS inevitably embarked on a shift towards semantic interoperability. By lifting XML, UML, JSON based data to RDF format data, it enables modelling, interconnection and merging with other datasets. The current application of the Semantic Web to the integration of heterogeneous data has been evolving several major development directions:1) The BAS domain has accumulated a large amount of knowledge based on natural language text, such as standards, protocols, and data models, so the task at the current stage is how to organize the existing knowledge into a linked data format. 2) The fusion of multi-domains data in the knowledge graph provides a broad prospect for future applications, but the query and modification for the knowledge graph is at the cost of a deep understanding of the data structure, which requires a high development level for developer and users [29]. 3) For BAS data, continuous time series-based data is required to support, so BAS systems need to build dynamic graph data to support e.g., risk prediction, dynamic management.

6. Future research directions

In this work, we reviewed the interoperability of BAS in several dimensions, as well as the integration between BAS and BIM. Focusing on the existing issues detected during the review process, this section presents some potential issues and research directions related to BAS equipment and BIM integration as follows:

1). Integration of heterogeneous and multi-domain knowledges. The AECO field is starting to move towards a multi-agent cooperation paradigm, where BIM contextual data will be expanded with more information (e.g., prefabricated production information, additional point clouds, etc.) and BAS data will be further integrated with IoT and AI computing. Therefore, an important future research direction will be the process of combining new technology applications with existing technologies, in which a large amount of heterogeneous data will be formed, from different sources of data formats, and existing research has proven that an internet-based interconnection is a promising approach. Currently, data from different domains are exchanged through open exchange protocols, thus multi-protocol strategies will remain to be explored in the future. The Service-Oriented-Architecture (SOA) as a framework is able to integrate multi-agent services in BAS, which has the potential to achieve real-time query, state feedback, model iteration, etc.

2). Real-time Linked Data space. BIM can provide rich geometric information for BAS and enable integration with the architectural design phase, but BAS systems generate a large amount of state information (e.g., equipment state, indoor environment state), which is time-series data. At present, it is difficult to connect the time series data with the BIM model to achieve updated feedback. The time series data generated by BAS devices can be divided into historical data and real-time data. Most of the current research has focused on historical data, such as converting historical data into machine-readable semantic data to integrate with BIM data. In the future, a large number of IoT devices will be connected to the BAS framework, so the link between the static information of BIM context and the dynamic data of time series will be the focus of BAS development.

3). Two-way interaction and edge computing. Smart buildings embedded with smart sensors and computing devices enable real-time monitoring and feedback of indoor environment, occupancy prediction, energy management, and other functions to improve human health and optimize energy use. To achieve continuous building intelligence, a framework that combines cloud and edge computing to enable complex data management is one approach. Once the edge nodes capture the physical environment information through sensors and perform certain data processing, the cloud computing platform can subscribe to the real-time data from the edge nodes for further computation and storage, this process can enable BAS to further provide two-way interaction services such as prediction and optimization.

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