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BIM assisted Building Automation System information exchange using BACnet and IFC

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ABSTRACT

Smart buildings are the trend of the next generation's commercial buildings that link different building systems together with the Building Automation System (BAS). Building information modeling (BIM) assists in data exchange and information flow. Previous research has explored BAS and BIM integration for energy management, building design optimization and operation, and building fault detection and diagnostics. However, it is rarely seen to design BAS or exchange BAS information in different project stages using BIM tools. The current design of the BAS system is either using 2D drawings based on AutoCAD or vendor customized tools. Unlike the other building systems, BAS seldom participates in design-build BIM cycle but blends into facility management in the later stage. To tackle this issue, this research aims to set a fundamental step to facilitate information exchange for BIM assisted BAS design and operation using one of the BAS open communication protocol named Building Automation and Control Networks (BACnet) and open BIM standard Industry Foundation Class (IFC). This paper leverages Information Delivery Manual (IDM) and Model View Definition (MVD) methodologies to define an IFC subset schema (a BACnet MVD) so that BAS information conforming to the BACnet protocol can be represented in IFC data model for information exchange throughout various project stages with BIM tools. Revit and a web browser were used to demonstrate the implementation of the BACnet MVD for BAS information exchange. In this way, BAS information represented in the open BIM standard can unlock the potential of future smart building information exchange and integration.

1. Introduction

The Architecture, Engineering and Construction industry cannot escape from the pervasive digital revolution. Smart buildings are the trend of the next generation's commercial buildings, which link different building systems together with Building Automation System (BAS). Smart buildings empowered by smart BAS allow data collection, analysis and control to assist with facility functions and services [1]. BAS is a data acquisition and control system that incorporates various functionalities provided by the control system of a building. BAS is also known as Energy Management Control Systems (EMCS), Building Management Systems (BMS), Building Energy Management Systems (BEMS), Facility Management Systems (FMS) and Building Automation and Control System (BACS) [2]. Common functionalities of BAS are temperature and air quality monitoring, lighting system control, HVAC system control, electricity control, access control, security control, fire control and sending signals when faults occur [3]. BAS relies on sensors to collect the condition or status of control parameters and actuators to conduct physical actions. Different subsystems in BAS and devices manufactured by various vendors need to communicate with each other. Data communication protocols play key roles in information exchange in the BAS domain. Recent protocols, such as Building Automation and Control Networks (BACnet), LonWorks, EIB/KNX, and MODBUS dominate BAS communication networks [2]. Building information modeling (BIM) assists data exchange and information flow among architects, engineers, clients and contractors throughout various project stages. The Industry Foundation Class (IFC) standard acts as a medium for data exchange across domains, stages, and parties for BIM applications [4]. Integration of BAS and BIM has been explored in previous research for energy management [5], building design optimization and operation [6], and building fault detection and diagnostics [7].

However, it is rarely seen to design BAS (i.e. construct 3D BAS models in BIM tools) or exchange BAS information (i.e. exchange BAS

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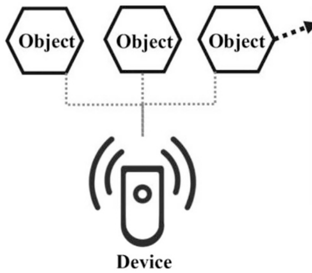

Property Identifier	Property Datatype	Conformance Code
Object_Identifier	BACnetObjectIdentifier	R
Object_Name	CharacterString	R
Object_Type	BACnetObjectType	R
Present_Value	REAL	R
…	…	…
Description	CharacterString	O
Device_Type	CharacterString	O

Fig. 1. BACnet device, object, and properties.

information with IFC) in different project stages using BIM tools [8]. The current design of the BAS system is either using 2D drawing based on AutoCAD or customized tools [9,10]. Unlike the other building systems, BAS seldom participates in the design-build BIM cycle but blends into facility management (FM) in the later stage. Without BIM, issues like information loss, inefficient collaboration, and error-prone construction happen. BAS is part of the building system, if BAS does not participate in 3D design coordination, error-prone design may happen due to various complex building systems. Normally, BAS is the last system to be built in the construction phase, it may suffer from error and corrections made during the setup of other systems. The information sharing between BAS designers, all sub-contractors, and building's general contractors without BIM may be inefficient [11,12].

The great potential can be exploited if BAS information can be declared into BIM from the design stage throughout the operation and maintenance stage. BAS is designed based on communication protocol like BACnet, while BIM information can be represented using open standards like IFC. With the object-oriented modeling characteristic of the BAS protocols and open BIM standard, it is possible to design and modify BAS using BIM tools without specifying device vendors during the design phase [12]. In this way, the BAS information represented in open BIM standard (IFC) can be shared among different stakeholders for construction, software, and various project stages. BAS information does not require the whole IFC schema for data representation, an IFC subschema that corresponds to BAS communication protocol is sufficient for BAS information exchange between various parties, software, and project stages.

To tackle the above-mentioned issue, this research aims to set a fundamental step to facilitate information exchange for BIM assisted BAS design and operation using one of the BAS open communication protocol named BACnet and BIM open standard, known as IFC. This research leveraged the Information Delivery Manual (IDM) and the Model View Definition (MVD) methodologies to define an IFC subset schema (a BACnet MVD) so that BAS information conforming to the BACnet protocol can be represented in IFC data model for information exchange throughout various project stages. In doing so, a BAS system can be modeled based on BIM tools without specifying actual devices. The BAS information, which is included in the models, can be exchanged among different stakeholders or BIM tools using the proposed BACnet MVD. The paper is structured as follows: Section 2 provides background information about BACnet, IFC, IDM/MVD. Section 3 explains the methodology and detail process of creating the BACnet MVD and demonstrates the MVD implementation process. Section 4 discusses the results and limitations. Section 5 concludes the primary outcomes and next steps.

2. Background

2.1. BACnet overview

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has developed the BACnet protocol to address the communication needs of BAS for different applications like heating, lighting control, and fire detection systems. BACnet aims to solve interoperability issues among different devices vendors by modeling exchanged information with object-oriented representations [2]. The function of BAS can be modeled as a collection of BACnet Objects. Currently, there are 60 Object Types defined in ANSI/ASHRAE Standard 135-2016 [13]. The instances of Object Type are Objects. As shown in Fig. 1, a device can be represented as a group of BACnet Objects. BACnet Objects hold information, which relates to a device (i.e. sensor, actuator) as sets of properties. Each property has an identifier, a data type and a conformance code indicating whether this property is required or optional [14].

With the characteristic of the BACnet protocol, it is possible to declare BAS information into BIM throughout the project lifecycle [12]. Starting from the design phase, BAS can be modeled using BIM tools without specifying device vendors (i.e. BAS represented by a collection of BACnet Objects virtually). In this way, BAS design can be conveniently modified if any function or communication design varies. During the construction phase when physical devices are chosen based on vender specification, the BAS model which contains all device-specific information and devices interconnection information, facilitates specifying physical devices. An updated BAS model can be handed to the owners and facility managers during the handover phase for operation and maintenance (O&M). One potential application benefitting O&M is accessing BAS information through the extended BACnet Web Service (BACnet/WS) and integrating it with BIM online. The BACnet/WS is capable of using technologies like REST, JSON and OAuth2 within BACnet and integrating with the BIM models [12]. The information resides in BIM can be accessed through BACnet/WS for energy saving, maintenance management system [7], and etc. [15]. Another potential application benefiting O&M would be to exchange information which resides in the BAS model with FM tools like Metasys and Niagara which directly connect to sensors and controllers as the control system using the MVD created in this paper. The MVD created in this paper is useful for exchange information at BACnet object level which is necessary for FM tools that connect to BAS control systems. Although some FM tools like Archibus and EcoDomus have already integrated BAS model with BIM data, these tools do not connect to sensor control systems using BACnet protocol and are specialized in higher-end management. Unlike the FM tools that connect to the BAS control system, these tools fail to encompass all FM requirements [16].

2.2. IFC/MVD/IDM overview

The most commonly used data exchange format for open BIM is IFC that has been accepted as ISO 16739 standard. The IFC enables data exchange between different software applications across the entire building lifecycle [17]. It is the most suitable median to hold BACnet based BAS information both for technical and practice perspectives.

BIM models can be enormous if the information is fully integrated. A fully populated model is unnecessary for all stakeholders or a certain software at a project stage. To solve this issue, buildingSMART International created IDM and MVD approaches to define subsets of IFC schema for certain Exchange Requirements (ER) [18]. In 2012, buildingSMART released an integrated IDM/MVD approach named "An Integrated Process for Delivering IFC Based Data Exchange" which amalgamate previous IDM approach and MVD approach into one [19]. An IDM firstly captures business processes and ERs at the user level [20]. Then, the MVD defines a subset of IFC schema based on ERs identified by the IDM. In this way, models can be filtered and size-reduced according to an MVD to satisfy specific business processes. The subset of IFC schema (the MVD) created in this paper can potentially encapsulate information to represent BAS and facilitate information sharing among different tools.

BuildingSMART has released official MVDs among which COBie (Construction Operation Building Information Exchange) is used to exchange specifications for life-cycle capture and delivery of information needed by facility managers [21]. Although COBie can capture life-cycle information needed by facility managers, the data entities in COBie MVD documentation particularly focused on IfcConstructionMgmtDomain (e.g. IfcConstructionProductResource, IfcContructionResrouce) [22]. COBie does not emphasize on exchange BAS information that follows the BACnet protocol. Some practitioners suggested that COBie contains universal facility management parameters and fails to selectively filter most relevant data for bespoke operation and maintenance requirements [23]. There is a gap in understanding necessary semantic data to exchange regarding BAS design, construction and operation following an international standard like BACnet.

Apart from official released MVDs on buildingSMART website, some effort has been made to address the interoperability issue by creating several MVDs. For instance, Arayici et al. [24] utilized IDM/MVD methodology to create interoperability specifications for performance-based design. This research leveraged "An Integrated Process for Delivering IFC Based Data Exchange" method developed in 2012. However, advanced MVD documentation tool named IFC Documentation Generator (IfcDoc) [25] enables a more convenient way to document an MVD compare to the conventional method. Some official MVD (e.g. Design Transfer View) do not necessarily require IDM to identify ERs and business processes. With MVD documentation tool, Pinheiro et al. [26] and Andriamamonjy et al. [27] utilized the MVD methodology to facilitate information exchange between BIM tools and building energy performance simulation tools. Other efforts related to extending and improving IDM/MVD methodology can be seen in [28–31].

3. Methodology

This paper leveraged IDM/MVD methodologies to define an IFC subset schema (a BACnet MVD), so that BAS information complying with the BACnet protocol can be represented in the IFC data model for information exchange between BIM tools and FM tools throughout various project stages. Apart from official IDM/MVD process defined by buildingSMART [19], this study followed similar IDM/MVD methodology in previous research [24,26,27,32,33]. The methodologies taken in this paper can be divided into three parts as shown in Fig. 2.

Firstly, the IDM method defined the information sharing process and a set of information to be exchanged at the user level for BAS design and operation. The IDM contained process model, ER and Functional Parts (FPs). A process model using Business Process Modeling Notation (BPMN) was created. The process model identified the purpose and a set of data for exchange. Based on the process model, ANSI/ASHRAE Standard 135-2016 (the BACnet protocol) [13] was reviewed to initiate the identification of ERs needed for BIM assisted BAS design and operation information exchange. As the BACnet protocol was defined by BAS domain experts, information which needs to be exchanged (ERs) was directly extracted from the BACnet protocol. These ERs defined a group of information units to exchange based on the process model and ANSI/ASHRAE Standard 135–2016. The information units were further breakdown into FPs which described the information in terms of the required capabilities of IFC standard.

The second part involved developing an MVD using the IfcDoc tool. The BACnet MVD focused on the latest release of the IFC schema, IFC4 Addendum 2 (IFC4 Add2) [34]. The MVD enabled IDM outputs to translate into IFC entities, attributes, and properties to facilitate interoperability at the software level. The functions of IDM outputs including process model, ERs, FPs were represented by MVD concepts. A mapping spreadsheet was created to clarify the relationships between each information unit, FP and MVD concept. The last part demonstrated a prototype test of the BACnet MVD using Autodesk Revit and Web browser as importing and exporting tools for BAS information exchange. Several Revit Families were constructed with custom-defined properties. Revit acted as an exporting tool following the BACnet MVD. BACnet Object Types and property identifiers expressed in IfcXML were imported into a Web browser to demonstrate the possibility to exchange BAS information using IFC data model. Detail steps for each part will be described in this section.

3.1. IDM

The aim of IDM is to collect domain knowledge and information needed regarding workflows from experts. IDM specifies process model, ERs and FPs at user level [20]. BuildingSMART provides official templates for IDM documentation including process map template, ER template, and FP template [35]. With modern documentation tools like IfcDoc, creating an MVD does not necessarily require an IDM. However, the conventional templates are useful to streamline the IDM/MVD process and demonstrate various terminologies. Considering the ease of use, templates were improved to cater to the modern tool in this study. Some redundant sections in the templates were removed and combined.

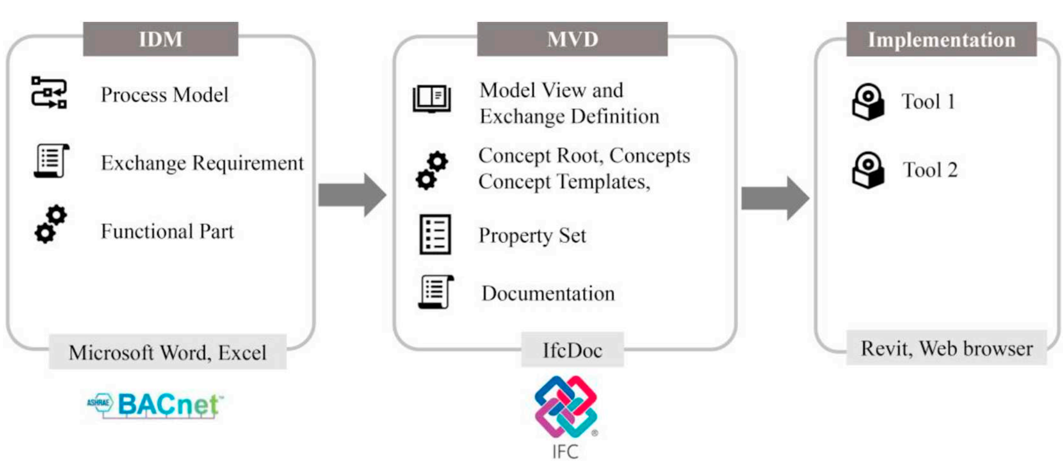

Fig. 2. Overall process of methodology.

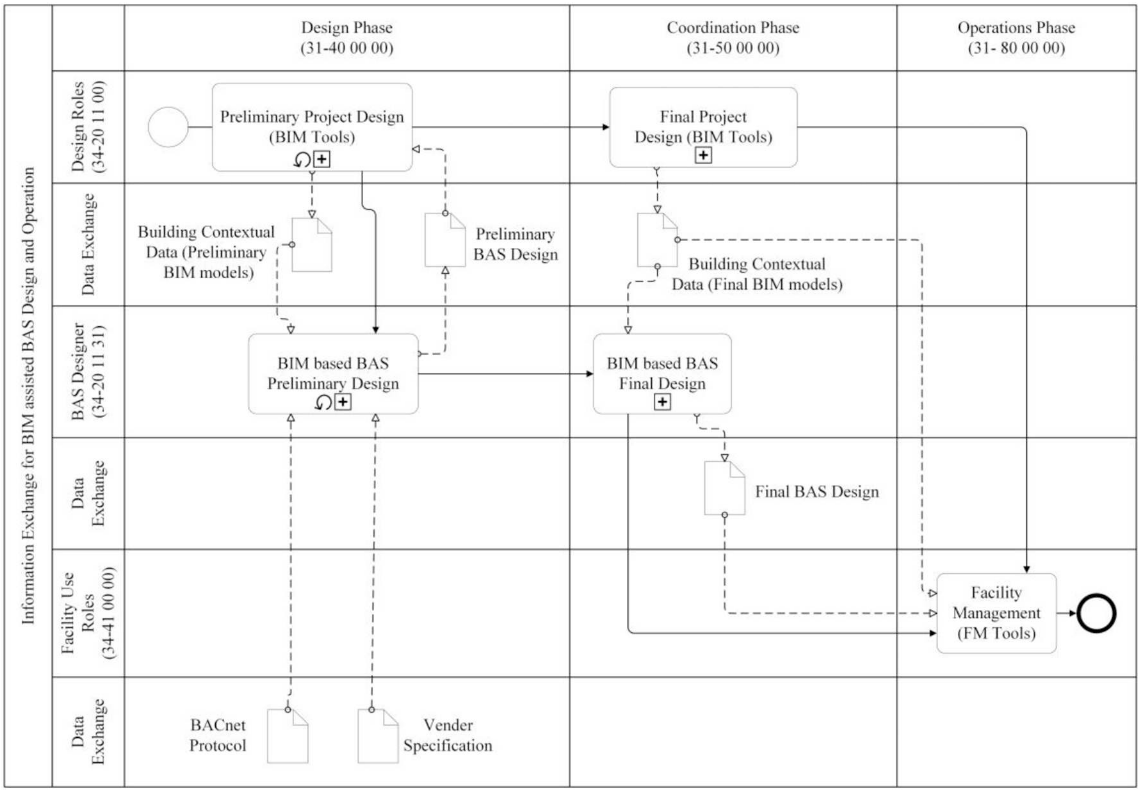

Fig. 3. Process map for BIM-based BAS design and operation information exchange.

3.1.1. Process model

The process model is the initial step to identify the purpose and a specified set of data for exchange. The formalization of the process model describes the activities, related information, logical sequence of activities and roles involved for a particular goal. The Object Management Group (OMG) developed the BPMN for process modeling [36]. It provides a standard diagramming language for mapping flow-oriented representations of the business process, facilitating identification of ERs [20,24].

The process model was created to illustrate the process of BAS design and operation information exchange across project stages. As shown in Fig. 3, the process map represents the process model in BPMN created by Visio. The codes and the phases of this process are based on Omni Class Construction Classification System [37]. During the design phase (31-40 00 00), the process starts with design roles in the project team including architects, structural engineers, MEP engineers designing the preliminary BIM models using BIM tools like Autodesk Revit and Tekla. These preliminary BIM models, containing building contextual data, are submitted to BAS designers for BAS preliminary design. As there are no widely adopted BIM-based BAS design tools available in the market, the BAS design can be done using traditional BIM tools in a less effective way. The process loops around preliminary project design and preliminary BAS design for several iterations in the coordination phase (31-50 00 00) before final models can be handed over to facility use roles. The final BAS model containing BAS metadata can be imported into FM tools for BAS in the operation phase (31-80 00 00). The data exchange swim lanes contain information flow between different parties.

3.1.2. Information exchange requirements

Information or data flow between two or more parties is documented by ERs. An ER connects business processes with relevant information defined within a particular information model [19]. As shown in the process map (Fig. 3), ERs which link two or more tasks, are the data items in data exchange swim lanes. The identification of ERs started with an in-depth analysis of ANSI/ASHRAE Standard 135-2016 [13] by understanding the BACnet protocol architecture, modeling control device as a collection of objects, object types, property identifiers, and property datatypes. The relationships and similarities between BACnet object types/property identifiers/property datatypes and IFC entities/attributes/datatypes were discovered during this analyzing process. As the objective is to declare BACnet data, which represents BAS metadata from the design phase to the operation phase, BACnet object types and properties identifiers are the keys to ERs.

The implementation starts with an official ER template that consists of a header & overview section and information requirements section. Table 1 shows the header & overview section of the ER for a BAS model using the BACnet protocol. The codes and the phases of this process are based on Omni Class Construction Classification System [37]. It specifies general information, project stages, scope, and descriptions regarding the ER. The key to identify ERs is the list of information units in the information requirement section. The information requirement section describes a set of information units to satisfy user requirements. These information units were identified through BACnet object types and property identifiers in ANSI/ASHRAE Standard 135-2016 [13]. Apart from the BACnet information, 3D visualization, location, and relationships between BACnet objects for the BAS system would also benefit the design and operation process. One of the potential usages of the BACnet MVD is to assist design BAS systems using BIM authorizing tools, the BACnet objects can be modeled as virtual instances in BIM tools. The geometric representation, location, space relationships and connectivity between these virtual instances are also important information for BAS design. Hence information units include Object Geometric Representation, Object Placement, Object Contained in Space, Object Connected From, and Decomposes were added to define ERs. Fig. 4 shows the example mapping between information units and ERs. For example, the Properties of BACnet Analog Input Object Type, which were extracted from ANSI/ASHRAE Standard 135-2016, are

Table 1
Exchange requirements header and overview section.

Exchange requirement			
Header section			
Name		ER_exchange final BAS model	
Identifier		BACnet_ER_001	
Change log			
⟨2018-03-20⟩		Created BACnet objects and properties	stang93@gatech.edu
Project stage	31-10 00 00	Inception phase	
	31-20 00 00	Conceptualization phase	
	31-30 00 00	Criteria definition phase	
	31-40 00 00	Design phase	√
	31-50 00 00	Coordination phase	√
	31-60 00 00	Implementation phase	
	31-70 00 00	Handover phase	
	31-80 00 00	Operations phase	√
	31-90 00 00	Closure phase	
Overview			
Scope			
The scope of this ER is the exchange of BAS design information between BIM tools and FM tools in different project stages. The BAS components should be designed using BACnet protocol including object types and property identifiers. The ER also includes the need for shape, location, and connectivity of components.			
General description			
This ER allows BAS component information represented in the IFC standard to be shared between BIM tools and FM tools throughout project phases. The BAS component information can also be shared throughout several design interactions from conceptual design to production information.			
Information description			
Information provided through this ER includes: • BAS components objects, attributes • Shape representation of components • Location and orientation of occurrences of components • Connectivity and composition of components			

illustrated in the left table within Fig. 4. This object type and its property identifiers were listed as information units (first column) in the ER_BACnet Analog Input Object Type Table (see the right table in Fig. 4). The Header section, overview section and the full list of information units can be found in ER_BACnet MVD.xlsx. as linked Mendeley data.

3.1.3. Functional parts

Information units can be broken down into FPs. Each FP describes the information in terms of the required capabilities of the IFC standard to provide technical support for information units. An FP is a reusable information model in its own right as well as being a subset of information model on which it is based on IFC [19]. Each information unit is mapped to an FP, which can be expressed as: i) IFC entity; ii) attribute of IFC entity with specified data type; iii) property in a property set with specified data type; iv) referring to another FP. Additional information regarding importing/exporting requirements for each FP falls into one of these categories, namely mandatory, recommended, optional and not recommended.

To start constructing FPs, the conventional template contains redundant information, which is unnecessary for the modern documentation tool, was modified into a spreadsheet. FPs can be expressed as a mapping table between information units and IFC entities, attributes or properties in property sets. This step required detail exploration of IFC schema and BACnet protocol to discover target IFC entities, attributes, properties, and their data types to represent functions of information units. Fig. 4 shows an example of BACnet analog input object type, the FPs' data types as in the ER_BACnet Analog Input Object Type Table (right table, 2nd column) conform to BACnet objects' property datatypes (left table, 2nd column). The conformance code of BACnet object properties specifies import/export requirement for ERs. The convention defined in IDM for expression of FPs are:

- Object.Attribute → Datatype
- PropertySet.Property → Datatype
- PropertySet.Property → Property Type::Datatype

3.2. MVD

MVDs have been defined as subsets of IFC model specification to support IFC implementation. The IFC implementation should satisfy requirements coming from end-users as defined in IDM [19]. MVDs enable IDM outputs, including process map, ERs, and FPs to translate into IFC schema and to facilitate interoperability at the software level. An MVD consists of Model Views, Exchange Definition, Concept Root, Concepts, Concept templates, and Property Sets. Each of these elements will be explained in detail to generate the BACnet MVD in this section.

BuildingSMART developed an official tool IfcDoc to assist in generating MVDs. IfcDoc improves consistency and computer-interpretability of the MVDs' definition [26]. IfcDoc assists in generating diagrams, defining schemas, and specifying the scope and contents of custom-made specifications [25]. The basic steps to create the BACnet MVD started with the IfcDoc tool and ER_BACnet MVD.xlsx generated from the IDM process in Section 3.2.

3.2.1. Model view and exchange definition

Model View defines the scope of MVD by specifying Exchange Definition, entity usage, concepts usage and importing/exporting requirements. Exchange Definition inherits information in ERs for a certain exchange scenario. Model View groups a set of IFC entities (entity usage) and Concepts (concept usage) to satisfy exchange scenarios. Model View allows development based on other existing Model Views. There are several existing official MVDs defined by buildingSMART, for example, IFC4 Reference View, IFC4 Design Transfer View and IFC2x3 Coordination View [18]. These views are provided as default model views in IfcDoc baseline file, which will be utilized in the following step.

3.2.2. Concept root, concept, concept usage, concept template

Concepts are the technical solutions to exchange a commonly useful package of information identified in ERs. Concepts can be applied to IFC entities as Concept usage including attribute usage, property usage, quantity usage, and mapping usage. Concept Roots collect available Concepts in a hierarchical tree structure. Concept Roots divide Concepts by their context and objectives such as project content, object definition, and object attributes. Concepts can be represented using Concept template as shown in Fig. 6. Concept template specifies entity reference, attribute reference and relationship constraints for a Concept. An instance diagram displays a graph of entities, relationships and constraints to clarify a Concept template.

The operation on IfcDoc started with importing the IFC4 Add 2 baseline file, which contains the full IFC schema, a reusable set of default Concepts and default model views [38]. A new Model View name BACnet View together with its Exchange Definition, entity usage, concepts usage and importing/exporting requirements was created. Fig. 5 shows a matrix of entities usage and concepts usage in the BACnet View. Various colored boxes represent importing/exporting requirements for the concepts applied to each entity. The importing/exporting requirements followed the BACnet conformance code. For example, information units with conformance code “R” (required) and “O” (optional) were set to import/export mandatory (green) and import/export optional (yellow) respectively.

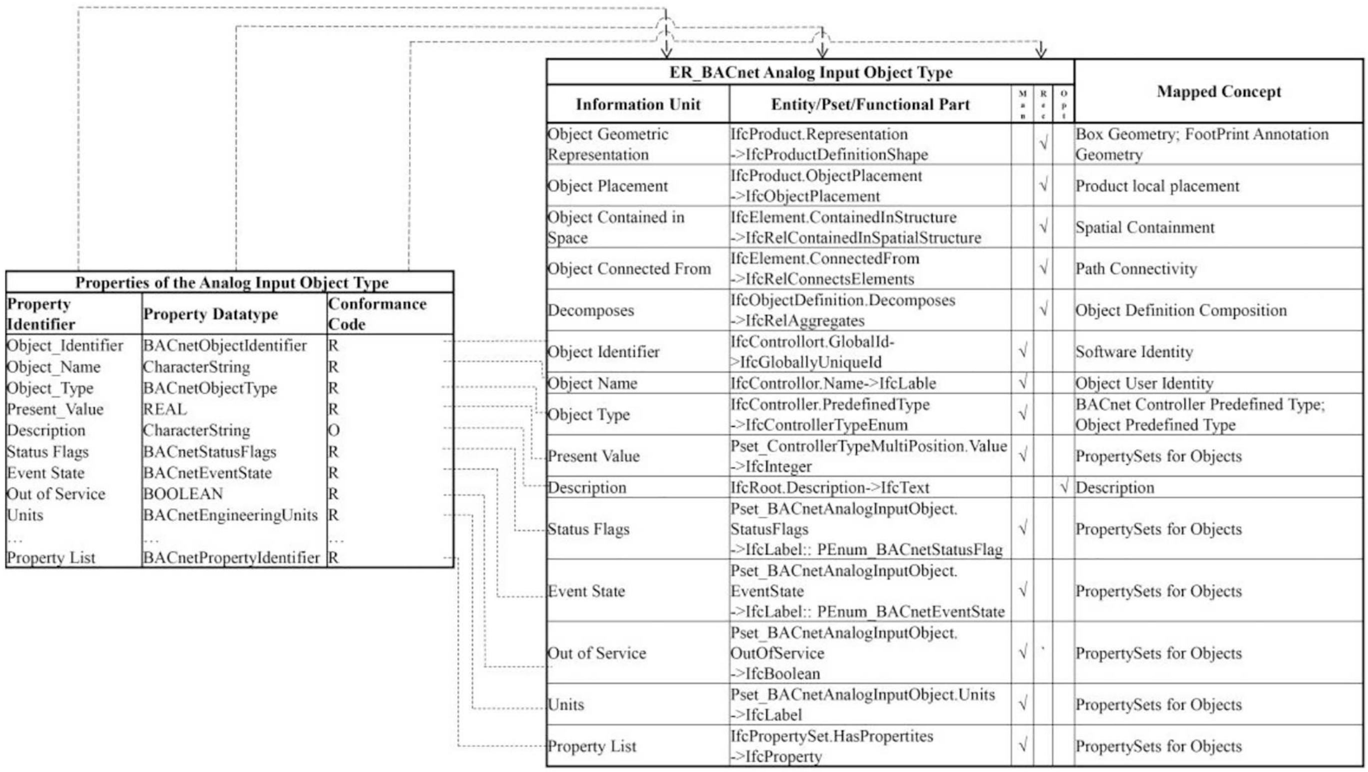

Fig. 4. Example of information unit, functional part and concept mapping.

The entities usage, concepts usage and importing/exporting requirements for the BACnet View followed the rules below:

- BACnet object types → IfcEntities → entities usage
- BACnet object property identifiers → IfcEntity. Attributes → concepts usage

BACnet object types along with their property identifiers are information units with corresponding FPs. The FPs were further mapped to MVD elements as entity usage or concept usage. Concepts, when

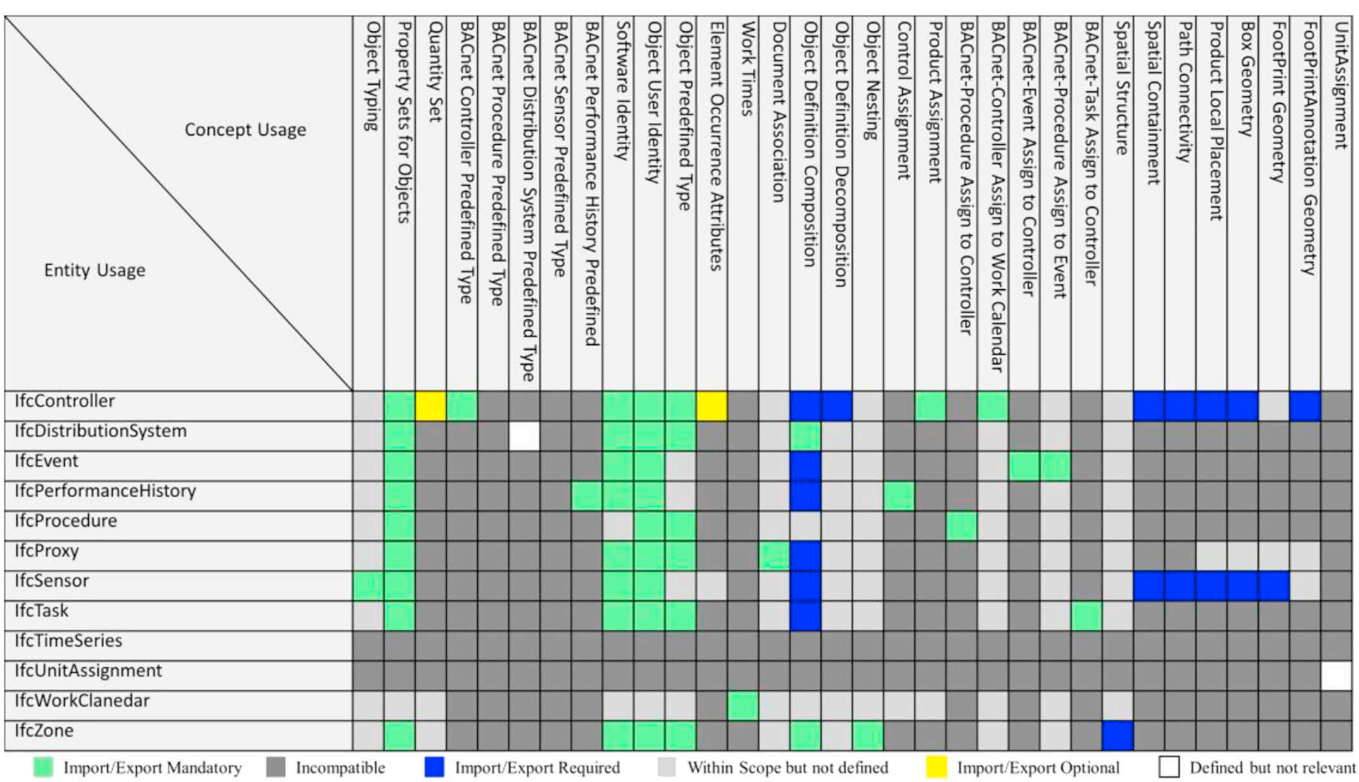

Fig. 5. BACnet view exchange requirement view.

applied to IfcEntities, are concept usages. The concept usages contained both default concept templates from the baseline file and custom-made concept templates. For example, as shown in Fig. 4, the BACnet analog input object type and its property identifiers were mapped to MVD entities usage and concept usage respectively (full list of the mapping table is in ER_BACnet MVD.xlsx). The BACnet Analog Input Object type was appointed to IfcController, which pointed out the IfcController entity usage in the BACnet View. The Object Type property identifier was mapped to IfcController.PredefinedType, which corresponded to BACnet Controller Predefined Type concept usage in the BACnet View. To follow the expression of the above rules, the BACnet Analog Input Object Type example can be described as below:

- BACnet Analog Input Object Type → IfcController → IfcController (entity usage)
- BACnet Analog Input Object Type. Object Type → IfcController.PredefinedType → BACnet Controller Predefined Type (concept usage)

Although the baseline file contains a default set of concept templates, which can express certain relationships between some IfcEntities, limitation to fully express relationships between BACnet Object Types and their property identifiers still exist. The default concept templates such as software identity, spatial containment, and object user identity fulfill the need to represent relationships between some BACnet Object Types and their property identifiers, however, some relationships cannot be represented. For example, BACnet Calendar Object Type was mapped as IfcController, some of BACnet Calendar Object Type's property identifiers were mapped as attributes in IfcWorkCalender, so an assignment relationship between IfcController and IfcWorkCalendar is necessary. As shown in Fig. 6, a custom-made concept template named *BACnet-Controller assign to Work Calendar* was added. The instance diagram in Fig. 6 shows the assignment relationship between IfcController and IfcWorkCalendar. A full list of custom-made concept templates is shown in Table 2 in Section 4.

Property sets group various properties, which contain the name, access state, property type, data type, and secondary data type. Property sets were applied to entities. The baseline file has default property sets and properties that can be assigned to entities using the property usage Concept. All BACnet Object Types and their property identifiers have been mapped as information units, however, part of these information units cannot be represented using default IFC schema and property sets. Hence, user-defined property sets and properties were created to emulate the BACnet protocol. The access state, property type, primary data type, and secondary data type observed the description for the property identifiers in the BACnet protocol.

Some of the information units in BACnet Analog Input Object Type example in Fig. 4 were mapped as properties in custom-made property sets named *Pset_BACnetAnalogInputObject* (Fig. 7). The access state, property type, data type of custom-made properties were defined to correspond to the BACnet protocol. For example, in the BACnet protocol, the “Status Flag” BACnet property identifier, which represents Boolean flags to indicate object health, is of data type BACnetStatusFlags. The BACnetStatusFlag data type is an enumeration of IN_ALARM, FAULT, OVERRIDEN and OUT_OF_SERVICE. In corresponding to the BACnet protocol, the custom-made Status Flag property in *Pset_BACnetAnalogInputObject* was set with property type as P_ENUMERATEDVALUE and primary data type as IfcLabel. The secondary data type was a custom-made enumeration value named *PEnum_BACnetStatusFlags* that inherited values from the BACnetStatusFlag data type. A full list of custom-made property sets and property enumeration is shown in Table 3 in Section 4.

3.2.3. Documentation

An automatic documentation process enables additional descriptions and constraints to be encoded into MVD using HyperText Markup Language (HTML). IfcDoc generated an HTML documentation containing entity usage, concepts usage, and properties for BAS design and operation information exchange (Fig. 8). This documentation acts as an indication of information that is necessary to import/export between different BIM tools and FM tools. It expedites the process to adopt IFC to targeted uses. The IfcDoc tool also automates the generation of the mvdXML file that can be used for buildingSMART certification process or consumed by software for data transformation [39]. The sample MVD documentation (BACnet-MVD Documentation folder) in the HTML version is attached as Mendeley data. The MVD can be accessed by open the index HTML document in the folder.

3.3. Implementation of the prototype test

A prototype test following the BACnet MVD was carried out with both the exporting tool and importing tool. Fig. 9 shows the basic steps of the BACnet MVD prototype test. These steps are described below:

1. As the most commonly used 3D BIM modeling tool, Revit was used to create BACnet objects as families. In the prototype test scenario, the list of created Revit families representing the BACnet object types is shown in ER_BACnet MVD.xlsx. as linked Mendeley data attached to this paper. These Revit families representing the BACnet Object types are also shown in Fig. 10 as *.rfa files. All these BACnet

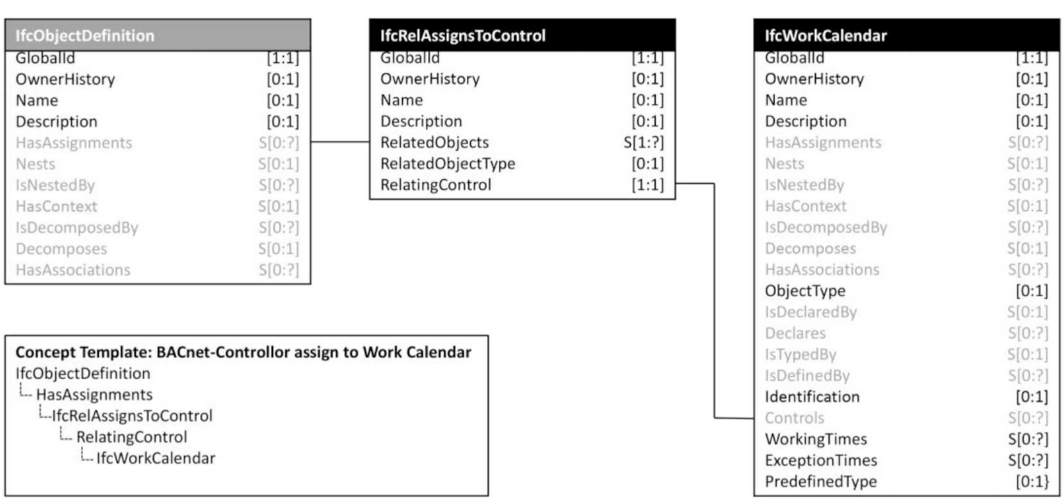

Fig. 6. Concept template and instance diagram of *BACnet-Controller assign to Work Calendar*.

Table 2
Limitations and custom-made concept templates.

Limitation	Custom-made concept templates	Concept templates
Decomposition of BACnet devices and objects	BACnet object definition composition	IfcObjectDefinition.IsDecomposedBy—IfcRelAggregates.RelatingObject—IfcController.Decomposes
Composition of BACnet devices and objects	BACnet object definition decomposition	IfcObjectDefinition.Decomposes—IfcRelAggregates—IfcController.IsDecomposedBy
Property identifiers in BACnet calendar object type	BACnet controller assign to work calendar	IfcObjectDefinition.HasAssignments—IfcRelAssignsToControl.RelatingControl—IfcWorkCalendar
Property identifiers in BACnet command object type	BACnet procedure assign to controller	IfcProcedure.HasAssignments—IfcRelAssignsToControl.RelatedObjects—IfcObject
Property identifiers in BACnet event enrollment object type	BACnet event assign to controller	IfcEvent.HasAssignments—IfcRelAssignsToControl.RelatedObjects—IfcController

Property Set Name: Pset_BACnetAnalogInputObject				
Property	**Access State**	**Property Type**	**Primary Data Type**	**Secondary Data Type**
StatusFlag	READWRITE	P_ENUMERATEDVALUE	IfcLabel	PEnum_BACnetStatusFlag
EventState	READWRITE	P_ENUMERATEDVALUE	IfcLabel	PEnum_BACnetEventState
OutOfService	READWRITE	P_SINGLEVALUE	IfcBoolean	-
Unit	READWRITE	P_SINGLEVALUE	IfcLabel	-

Property Enumeration			Property Constant	
PEnum_BACnetStatusFlag	IN_ALARM	FAULT	OVERRIDEN	OUT_OF_SERVICE
PEnum_BACnetEventState	NORMAL	OFFNORMAL	FAULT	

Fig. 7. Example of custom-made property sets *Pset_BACnetAnalogInputObject* and property enumeration *PEnum_BACnetStatusFlag* & *PEnum_BACnetEventState*

Table 3
Summary of custom-made property sets and property enumeration.

Property set	Property enumeration
Pset_BACnetAnalogInput Object	PEnum_BACnetAction
Pset_BACnetAnalogOutput Object	PEnum_BACnetDestination
Pset_BACnetAnalogValueObject	PEnum_BACnetDeviceObjectPropertyReference
Pset_BACnetAveragingObject	PEnum_BACnetDeviceStatus
Pset_BACnetBinaryInputObject	PEnum_BACnetEventParameter
Pset_BACnetBinaryOutputObject	PEnum_BACnetEventState
Pset_BACnetBinaryValueObject	PEnum_BACnetEventTimeStamp
Pset_BACnetCommandObject	PEnum_BACnetEventTrasitionStamp
Pset_BACnetDeviceObject	PEnum_BACnetEventTrasitionBits
Pset_BACnetEventEnrollmentObject	PEnum_BACnetEventType
Pset_BACnetFileObject	PEnum_BACnetFileAccessMethod
Pset_BACnetLifeSafetyPointObject	PEnum_BACnetLifeSafetyMode
Pset_BACnetLifeSafetyZoneObject	PEnum_BACnetLifeSafetyOperation
Pset_BACnetLoopObject	PEnum_BACnetLifeSafetyState
Pset_BACnetMulti-stateInputObject	PEnum_BACnetLoggingType
Pset_BACnetMulti-stateOutputObject	PEnum_BACnetLogRecord
Pset_BACnetMulti-stateValueObject	PEnum_BACnetNotifyType
Pset_BACnetNotificationClassObject	PEnum_BACnetPolarity
Pset_BACnetProgramObject	PEnum_BACnetPolarityArray
Pset_BACnetPulseConverterObject	PEnum_BACnetProgramState
Pset_BACnetScheduleObject	PEnum_BACnetReliability
Pset_BACnetTrendLogObject	PEnum_BACnetSegmentation
	PEnum_BACnetServiceSupported
	PEnum_BACnetSilencedState
	PEnum_BACnetStatusFlag

Object type families contain their BACnet property identifiers as user-defined attributes in Revit. The complete list of BACnet property identifiers is shown in ER_BACnet MVD.xlsx. as linked Mendeley data attached to this paper. Several Revit families include BACnet Analog Input Object Type, BACnet Analog Output Object Type, and BACnet Device Object Type were modeled. The constructed BACnet objects were annotated using abbreviations like "AO", "AI" and "D" in the 2D view. One of the modeled BACnet Object types (BACnet Analog Input Object Type) is shown in Fig. 10 as an explanation for part of the sample testing scenario. As shown

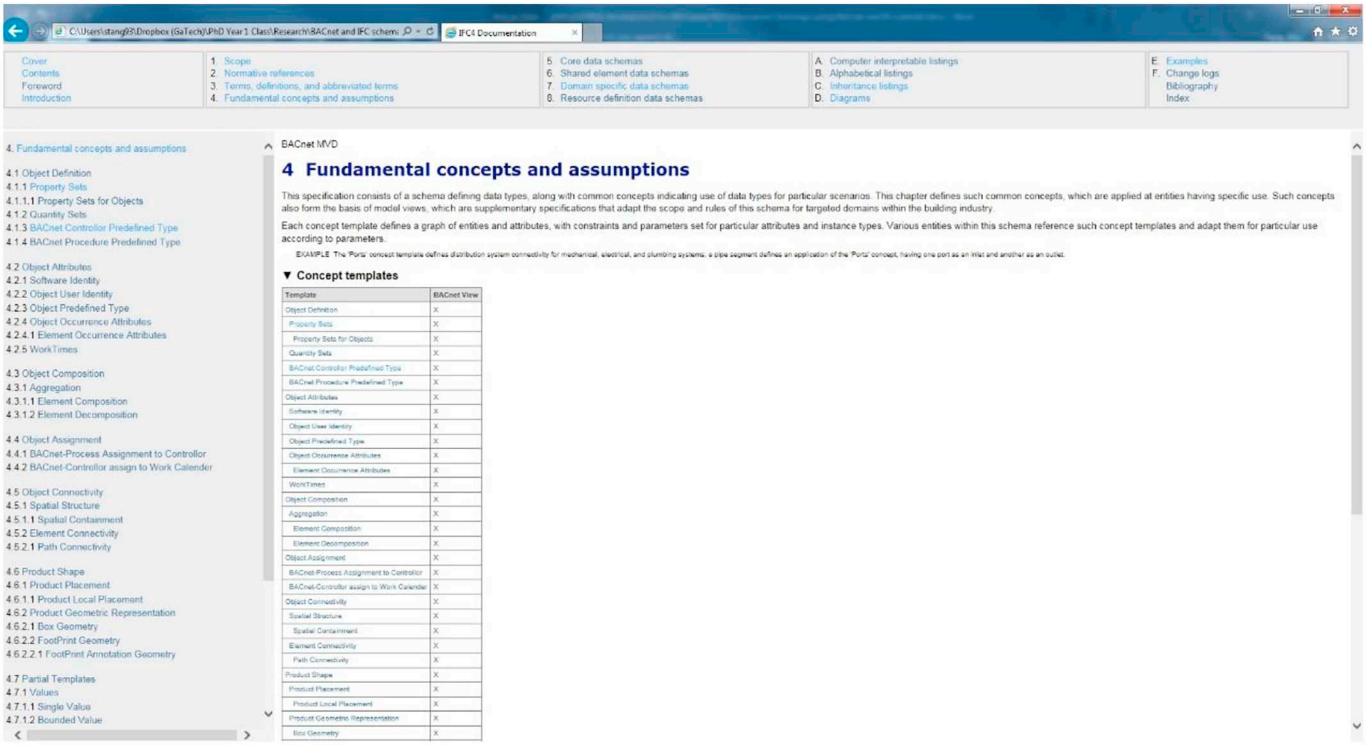

Fig. 8. The BACnet MVD documentation in HTML.

on the right-hand side of Fig. 10, both type properties and instance properties were added as user-defined attributes that match the BACnet Analog Input Object Type's property identifiers.

2. Apart from basic geometry representation, placement, and connection, BACnet properties identifiers were added as user-defined attributes for all families. For each of these BACnet object families, Revit share parameters named "IFCExportAs" and "IFCExportType" (in Fig. 10) were defined to specify target IFC export entities following the BACnet MVD. E.g. in Fig. 12, the BACnet Device Object has "IFCExportAS" share parameter value = *IfcControllerType* and "IFCExportType" share parameter value = *IfcDistributionController-Element*. In this way, the target exporting IFC entities for BACnet object families and BACnet property identifiers were assigned. When loading these BACnet object families into Revit projects based on various test cases, an "In-session" exporting setup was required to follow the previously assigned share parameters. User-defined properties were also exported with the "In-session" export settings in Revit as shown in the top dialog in Fig. 11. Guidance for specifying exporting IFC entities for families using share parameters and "In-session" exporting setup can be found in Revit user guide.

3. The exported *.ifc file followed the exporting instruction specified by share parameters in step 2. For example, the values of "IFC Export As" and "IFCExportType" of BACnet Analog Input Object Type were "IfcCotroller" and "MULTIPOSITION" respectively. The

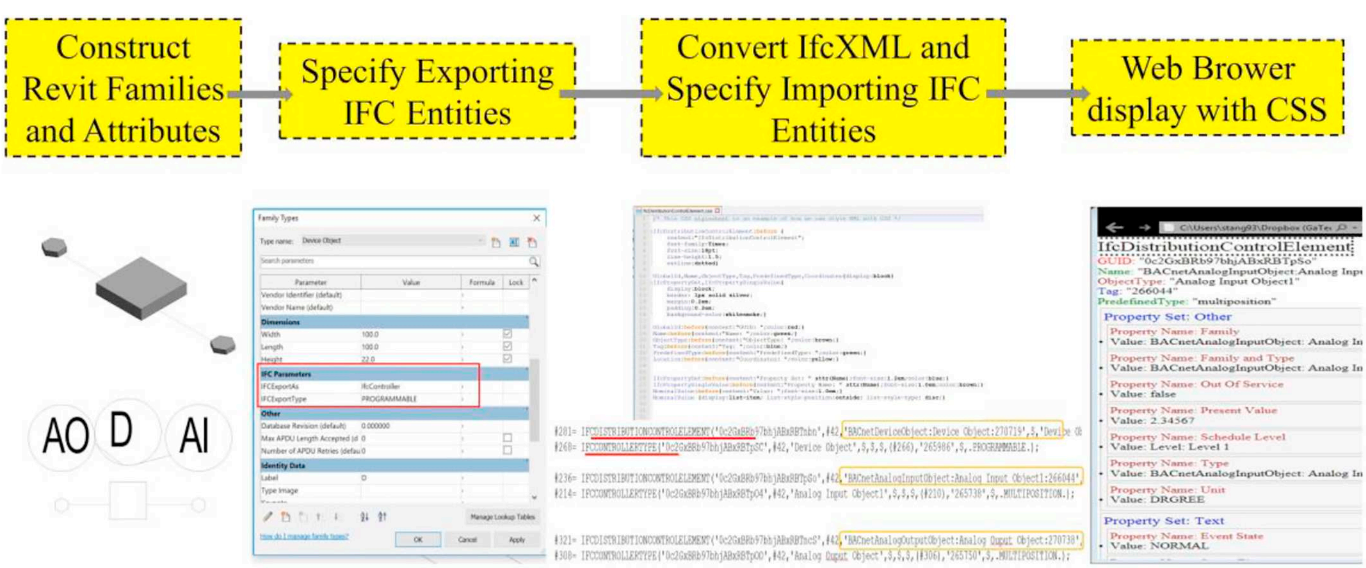

Fig. 9. The BACnet MVD implementation steps.

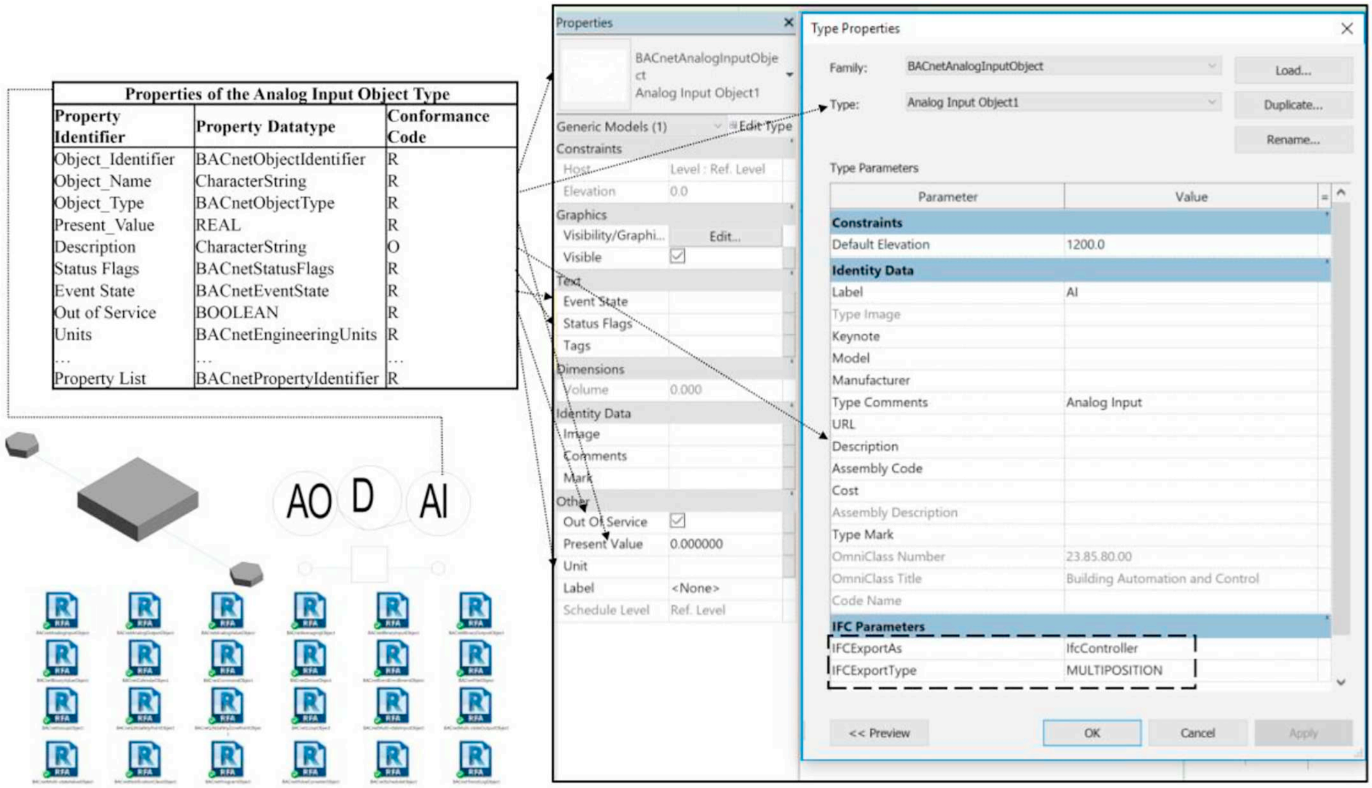

Fig. 10. Sample testing scenario (BACnet analog input object type).

exported IFC instance file was screened to check whether the mandatory BACnet data was included. For example, in Fig. 11, the sample exported IFC instance file matches with the BACnet Analog Input Object Type's property identifiers. IfcDoc converted *.ifc file into *.ifcXML file before specifying the importing IFC entities.

4. To demonstrate the possibility of importing BAS information in the IFC data model into FM tools, a web browser was used as a replacement since current BIM assisted FM tools are not open source.

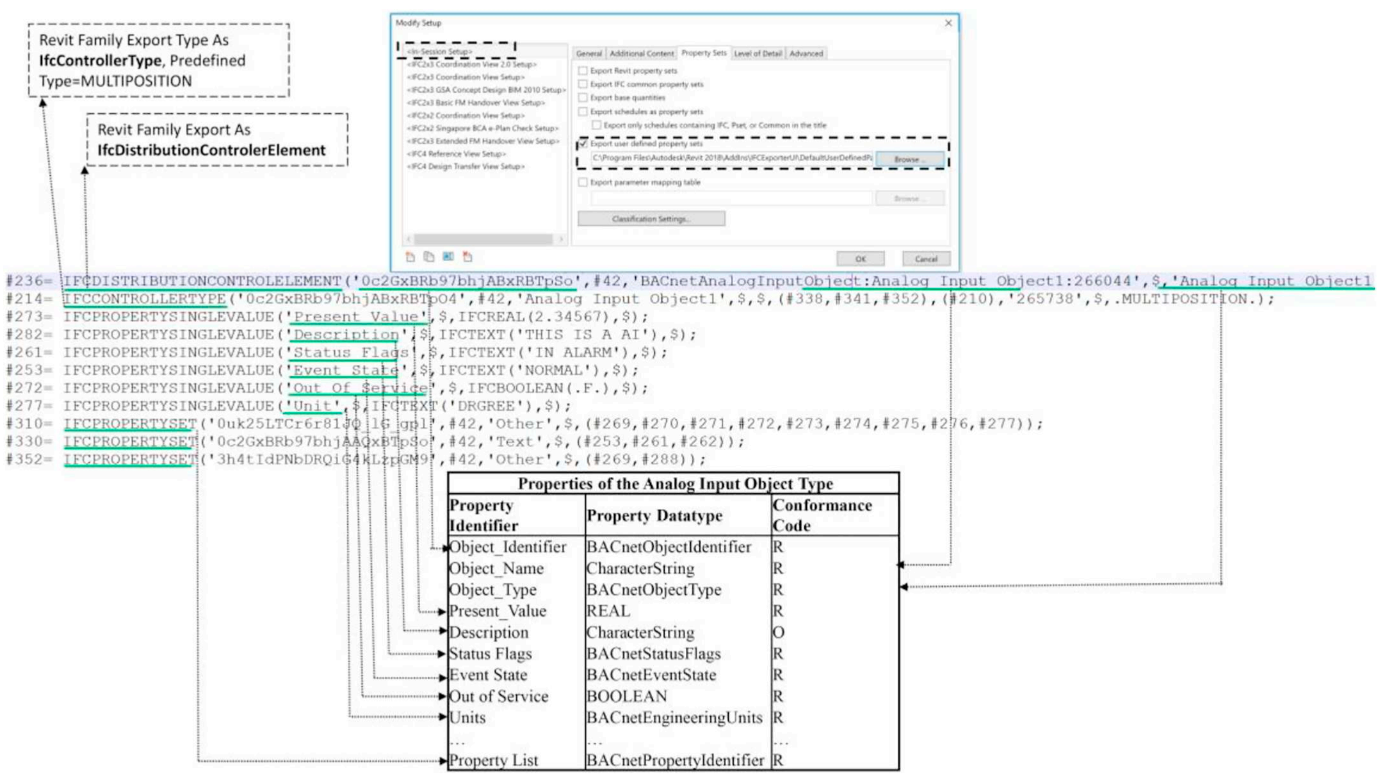

Fig. 11. Sample exported IFC instance file with corresponding BACnet data (BACnet analog input object type).

The web browser is a demonstration of possible importing tools that can utilize the BACnet MVD. IfcDoc or other tools can be alternative options. However, IfcDoc requires special expertise while the web browser is more widely adopted. In addition, web browser provides other potential applications such as integration with data in other domains, connecting with online resources, and integration with other data models. It is necessary to convert the *.ifc file into *ifcXML file since the web browser was chosen to be the importing tool. ifcXML show better integration capability with other software and data model than STEP Physical File (SPF) [4,40]. It also provides enhanced readability and benefits from other tools [41]. To display useful information in importing tool, the authors specified importing IFC entities and displayed XML file using Cascade Styling Sheet (CSS) file. The useful IFC entities and their attributes were automatically parsed and extracted into the web browser. In this way, BACnet object types and properties identifiers can be visualized through a web browser.

4. Results and discussion

This study has successfully represented BACnet Object Types and property identifiers with the defined subset of IFC schema. As a result, it demonstrated the possibility to exchange BAS information conforming to the BACnet protocol with IFC data model in various project stages. The result of this study showed that IFC is suitable for representing BAS metadata, whether representing BAS control, communication, constraints, and other data sources like real-time data using the IFC data model is appropriate or not remains to be a concern. Limitations in data mapping, prototype test implementation, tools, and representing other data sources are discussed in this section. The result of this study includes IDM, MVD, and implementation of a prototype test.

4.1. IDM

A process model (Fig. 3) was created to capture the BAS information exchange from the design phase to operation phase. This process model together with the BACnet protocol was explored to identify ERs. Altogether, the authors identified 395 information units including 25 BACnet Object Types and 370 property identifiers as listed in the ER_BACnet MVD.xlsx. as linked Mendeley data attached to this paper. Corresponding FPs were mapped to these information units with importing/exporting requirements. The IDM process facilitated information exchange from user level to technical schema level. Consequentially, the Object Types, Property Identifiers, Property Datatype and Conformance Code in BACnet protocol transformed into IFC entities, attributes, IFC datatypes and importing/exporting requirements.

4.2. MVD

A BACnet View was created using IfcDoc to document all collected information in the IDM process. Twenty-five BACnet Object Types indicated 12 entity usages in the BACnet View. Concept usages were applied to entity usages with importing/exporting requirements as shown in Fig. 5. Concept usages hosted information about BACnet Object Types and property identifiers. However, default Concept Templates had limitations to fully express the relationship between targeting IFC entities. To tackle these limitations, several custom-made Concept Templates were defined in Table 2. Although there are some similar default Concept Templates in the baseline file, these default concept templates expressed relationships for IFC entities that fall in various inheritance branches with mapped BACnet entities. The complete custom-made concept templates were documented in BACnet_MVD_Final.ifcdoc file as linked Mendeley data attached to this paper. As some BACnet property identifiers cannot be represented with default IFC properties, custom-made property sets, properties, and property enumeration were made to solve this issue as shown in Table 3. Altogether 22 property sets and 362 properties were defined, a complete list of property sets, properties, and property enumeration was shown in BACnet_MVD_Final.ifcdoc file. In addition, the sample MVD documentation (BACnet-MVD Documentation folder) in the HTML version is attached as Mendeley data. The MVD can be accessed by open the index HTML document in the folder.

4.3. Implementation of prototype test

BACnet object types were modeled as Revit families. Several Revit families include BACnet Device, Analog Input Object, and Analog Output Object were constructed with user-defined attributes and share parameters indicating exporting settings as a test scenario. The prototype test has successfully exported IFC entities, predefined types and other attributes following the BACnet MVD. As shown in Fig. 12, the extracted IFC physical file showed exported IFC entities' names and predefined types obeying the exporting settings. In terms of importing tool, based on the BACnet MVD, IfcXML file was automatically parsed with CSS file into the web browser. In this way, the importing tool has achieved the goal to display desired BAS information including IFC entities, global unique identification, name, predefined type and other required properties in BACnet protocol. In addition, the exported ifcXML or IFC models can facilitate BAS information exchange in: i) integrate with BAS tools like Metasys and Niagara; ii) connect with data in other domain such as real-time sensor readings; iii) integrate with different data models such as Linked Data [42] and JSON [43]; iv) sharing information between various project stages including design, construction, operation, and etc. for BAS systems.

4.4. Limitations

IFC enables information exchange throughout the entire project lifecycle. A single software or a procedure cannot produce all useful data. Thus, data integrated from multi-software and project stages is a necessity. IFC plays a critical role in information exchange and interoperability for the construction industry. This study has leveraged IDM/MVD methodologies to represent BAS information conforming to the BACnet protocol in the IFC data model so that BAS information can be exchanged among BIM tools and FM tools throughout various project stages. However, there are several limitations which may bring insights to future studies.

4.4.1. Data mapping

Although this study has mapped 25 BACnet Object Types and 370 property identifiers to IFC entities, attributes, and properties, only part of the BACnet Object Types and required property identifiers were involved to demonstrate the possibility of representing BACnet data in IFC data model. Limited information regarding official mapping between BACnet protocol and IFC was only found in IFC 2 × 4 [44] without updating in recent years. There were only 25 Object Types been mapped without providing any information about BACnet property identifiers and services on the IFC website. ASHRAE keeps adding addendums every 2–4 years to update BACnet Object Types and property identifiers to keep up with the evolving BAS world. There are > 60 BACnet Object Types in the latest BACnet protocol. Since this study has partially mapped BACnet Object Types and property identifiers due to the limited official mapping information provided in IFC 2 × 4, an additional effort for all Object Types, property identifiers is necessary. This study demonstrated the possibility to represent BACnet data in IFC data model, most data mapping between BACnet Object Types/property identifiers and IFC entities/attributes was manually achieved, automatic ways for data mapping are worth exploring. Another limitation in terms of data mapping is the lack of representation for BACnet services in IFC data model. BACnet services enable BACnet objects and devices to issue commands for accessing and manipulating information as well as providing additional functions for applications [45]. The

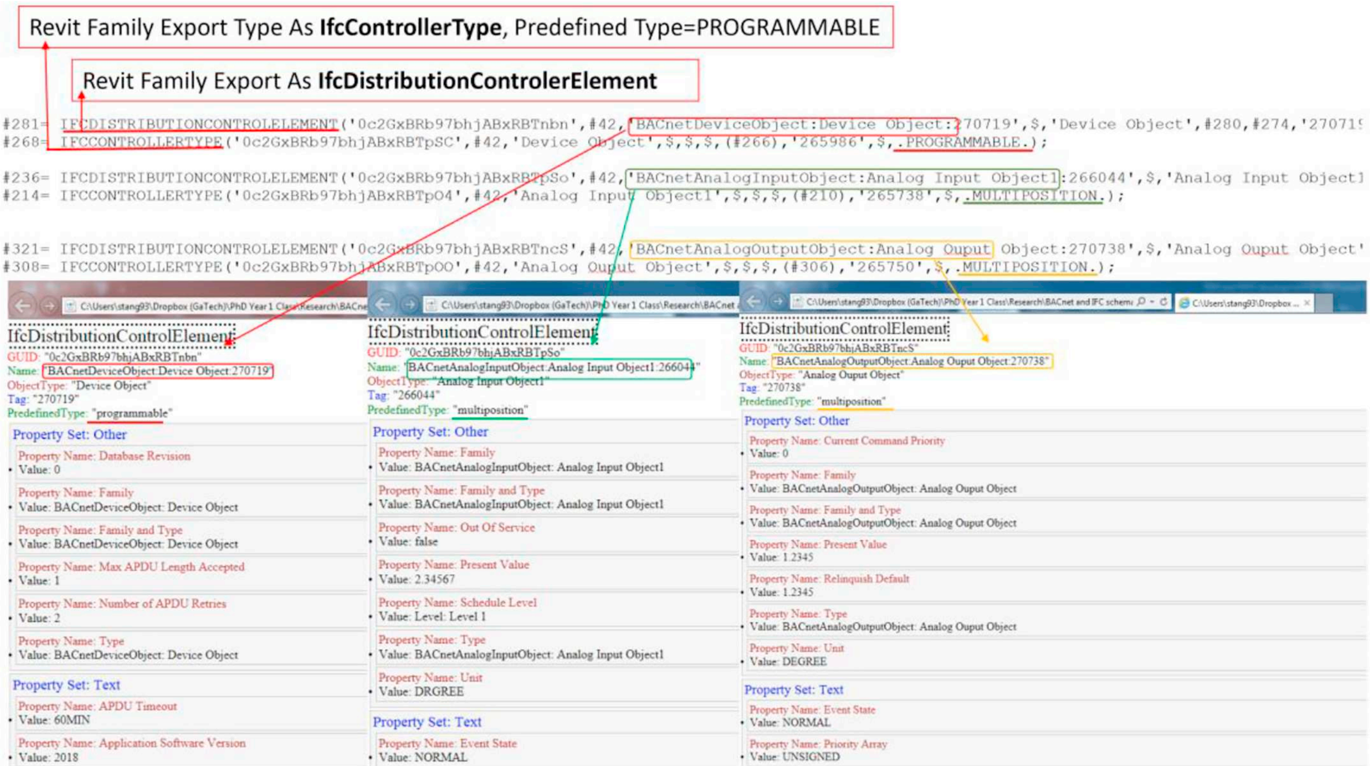

Fig. 12. Exporting and importing BAS information in prototype test.

BACnet services, which hold information about control and communication between BACnet objects, were not represented using the IFC data model. Both BACnet and IFC represent BAS information using object-oriented modeling. The result of this study showed that IFC is suitable for representing BAS metadata, whether representing BAS control and communication using the IFC data model is appropriate or not remains to be a concern. Moreover, this study has a limitation in fully representing constraints of relationships between BACnet Object Types and property identifiers. Some constraints between BACnet properties were not represented using the IFC data model. For a constraint instance, when property identifier A has a value "true", property identifier B needs to be value "b", cannot be represented. Furthermore, existing IFC entities did not satisfy representing all BACnet Object Types, either creating new IFC entity or using IfcBuildingElementProxy is the current solution. Nevertheless, the certification process for adding new IFC entities is complex and the IfcBuildingElementProxy entity may cause exporting issues for similar objects, new solutions are needed for further exploration.

4.4.2. Implementation of prototype test

This research has utilized a BIM tool and a web browser to demonstrate the implementation of BACnet MVD for BAS information exchange. During the prototype test, some limitations were identified: i) the prototype test was based on limited test scenarios and BACnet Object Types. Only a few BACnet Objects were constructed and were modeled based on non-practical cases. Extending the test scenario with a more complex project can guarantee more robust research result. In addition, for a more complex testing scenario, a quantified measurement and systematic evaluation are necessary to assess the efficiency of this method. In addition, more complex testing cases are necessary to evaluate the completeness and robustness of this IDM and MVD; ii) export settings in Revit contains official buildingSMART MVD like IFC4 Design Transfer View, IFC 2 × 3 Coordination View, and IFC4 Reference View. Since the BACnet view was newly proposed, the exporting process required manual set up for each object. This process is time-consuming and cannot create a one-fits-all solution. In addition, Revit has a limitation in exporting family properties to desired IFC entities. An export plug-in following the BACnet MVD may be a potential solution for automatic data transformation; iii) to check whether the exported IFC instance file contains necessary BACnet data, the data validation process was done manually. Although the mandatory BACnet data was included in the exported instance file, this process was inefficient and might cause errors. An automatic MVD-based data validation process using tools like IfcDoc should be explored in the future [16,46]; vi) most of the current BIM tools including Revit have the limitation in creating object connectivity so that BACnet objects/devices decomposition and composition cannot be explicitly indicated.

4.4.3. Tool limitation

The implementation of the prototype test for this study was based on Revit and a Web Brower, as BIM-based BAS tool is rare. The current design of the BAS system is either using 2D drawings based on AutoCAD or vendor customized tools. Design BAS using Revit required custom-made families and the manual connection between objects. This process is time-consuming and may not satisfy industry needs. Most available FM tools like Metasys and Niagara are not BIM-based so that IFC data format is not compatible which may cause interoperability issues. Some BIM-based FM tools like EcoDomus and Archibus are not open source to test the BACnet MVD, further collaboration with software vendors may be the next step.

4.4.4. Other data source

BAS information exchange is more complex than just metadata. Time-series data, which record continuous readings from BAS sensors and meters, is another important source of data. IFC was designed to store building contextual data such as building geometry, material properties, as-built construction detail, and HVAC specifications. As this study shows, the IFC data model is suitable to represent BAS metadata. However, representing real-time data in IFC data model may not be an appropriate approach. Real-time data recorded from BAS sensors are time-series data, which can be effectively stored and manipulated in a relational data model [47]. Hence, integration between the time-series data model and IFC needs further studies. Besides, this study only explored information exchange between design and operation at a macro level. There are other data sources relating to BAS require consideration. For example, BAS construction phase data and data produced from interaction with other disciplines. In addition, there are other communication protocols such as LonWorks, EIB/KNX, and MODBUS for BAS. This study only considered the BACnet protocol. Future studies regarding other BAS protocols and the integration of data generated from different domains are worth exploring [48].

5. Conclusion

This research demonstrates the possibility to exchange BAS information conforming to the BACnet protocol with the IFC data model for BAS design and operation. This study has successfully leveraged IDM/MVD methodologies to define a subset of IFC schema, which represents BACnet Object Types and property identifiers. The IDM method was utilized to identify the BAS information sharing process and ERs at the user level. ANSI/ASHRAE Standard 135–2016 was used to initiate identification of ERs needed for BIM assisted BAS design and operation information exchange. The BACnet MVD created in this study has utilized IfcDoc tool for documentation of exchange definition, entity usage, concept usage, importing/exporting requirement and property sets. The IfcDoc also enables the defined subset schema to be displayed in HTML and exported as mvdXML for software vendors when transforming data. A prototype test was carried out with a BIM tool and web browser to demonstrate the implementation of BACnet MVD for BAS information exchange between BIM tools and FM tools. In this way, the BAS information represented in IFC standard can be shared among different stakeholders and BAS software through various project stages, connect with data from other domains, and integrate with different data models.

Several limitations involving data mapping, available tools, various data sources integration, and data validation were identified during the implementation of the prototype test. These limitations bring insight for future studies. As the BACnet protocol keeps evolving, data mapping to the IFC data model needs to keep up with the pace. Since this study has partially mapped BACnet Object Types and property identifiers, an additional effort for all Object Types, property identifiers is necessary depending on a use case. This research provides insight into the methodology for enabling such an exchange. BACnet service and constraints between property identifiers are the other aspects to consider. A potential study can be extending IFC data model and integration with other data models to represent BACnet services and constraints. In terms of prototype test implementation, complex real projects or more test scenarios should be tested. An automatic data validation process for exporting BIM-based BAS data based on BACnet protocol should be explored. Besides, there is a great opportunity to create BIM-based BAS design tools or a plug-in for both importing and exporting requirements following the BACnet MVD. An API or plugin in BIM tools that allows automatic data mapping when exporting and importing BAS information following the BACnet MVD is necessary to guarantee a reliable data validation process [46,49,50]. Further collaboration with current BIM-based design and FM tools vendors may be the next step to enable the seamless exchange of BAS information using IFC data model between BIM tools and FM tools. Moreover, different data sources such as real-time data, data generated during various project stages and data produced from interaction with other disciplines need the most suitable data models for representation. Integration between building contextual data, BAS information and the Internet of Things using extended BACnet/WS and other open-source data models like Project Haystack deserve future investigation [51,52].

The research work presented in this paper brings BAS information that conformed to the BACnet protocol into the IFC realm. The contributions of this paper are listed below:

1. The significance of designing BAS using BIM tools is addressed, brining insights for the potential of using BIM tools for BAS information exchange.
2. Information units for the BAS design and operation that conformed to the BACnet protocol were extracted from ANSI/ASHRAE Standard 135-2016 to identify ERs. It brings the buildingSMART effort in mapping data between BACnet and IFC a step forward. This study made detail IFC representation of BACnet protocol including BACnet objectsand associated property identifiers using IFC entities, properties, and relationships. Custom-made property sets and concept templates were made in addition to the IFC baseline file to fully represent BAS information.
3. The BACnet MVD created allows BAS information to be represented in IFC data models which enable information sharing among various BIM tools and project stages.
4. The prototype test demonstrates the possibility to design BAS using BIM tools by selecting BACnet objects with BACnet property identifiers, and exchange BAS information using the IFC data model.
5. The prototype test sets a foundation for software vendors to develop automatic data importing and exporting in BIM tools for BAS information exchange. It also can be the starting point of the software certification process and the data validation process.
6. Limitation for data mapping, tool implementation, and process of prototype test was identified to shed light on future work to bring the BAS design and operation into the BIM cycle. It facilitates data exchange in other domains like Electrical Computer Engineering with the AEC industry, and for the development of IoT and BIM integration.

This research laid a solid foundation for exchanging BAS information conforming to the BACnet protocol with the IFC data model for BAS design and operation. In this way, BAS information represented in the open BIM standard can unlock the potential of future smart building information exchange between various tools throughout multi-project stages and information integration with other domains.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript.

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