Carnegie Mellon University

Master Thesis

Optimizing Building Energy Modeling (BEM) Workflow through Integrating HVAC systems Design and Building Information Modeling (BIM) using gbXML Schema Version 6.01

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by

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"In studying the particularity and relativity of contradiction, we must give attention to the distinction between the principal contradiction and the non-principal contradictions and to the distinction between the principal aspect and the non-principal aspect of a contradiction; in studying the universality of contradiction and the struggle of opposites in contradiction, we must give attention to the distinction between the different forms of struggle. Otherwise we shall make mistakes."

Mao Tse-tung

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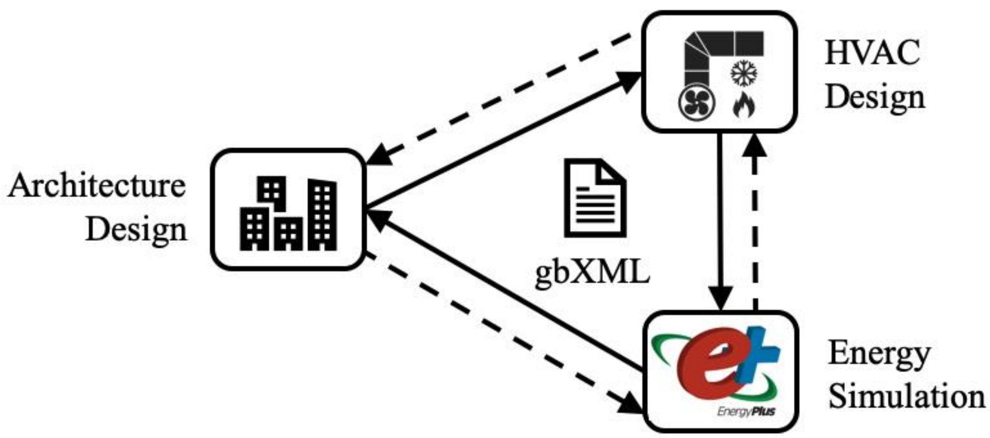

HVAC
Design
Architecture
Design
gbXML
Energy
Simulation
EnergyPlus

Abstract

Heating, Ventilation, and Air-conditioning (HVAC) systems have been adopted in architecture since 1972 for maintaining a comfortable indoor thermal environment. It plays a crucial role in occupants' thermal comfort, health, and productivity. However, most of the office buildings today have a low thermal satisfaction rate (Huizenga, C. et al., 2006), and the energy consumed by HVAC systems for maintaining the indoor environment consists of 48% of the total energy consumption (Pérez-Lombard, L. et al., 2008).

One major cause of the issue is that most HVAC systems are poorly designed based on engineering experience, without enough building information input from architects or without enough HVAC systems data output to energy engineers for performance simulation. Mainstream architecture design and HVAC engineering design workflow is prescriptive and code compliant. With the precedent development of sustainable design standards, performance-based design process integration is expected. The main communication issue between architects and engineers is now being handled by Building Information Modeling (BIM) and Building Energy Modeling (BEM) technology.

This paper proposed an BIM-HVAC-BEM gbXML workflow to enable smooth communication between architects and engineers. Green Building XML

(gbXML) is one of the most prevalent BIM data models. It enables interoperability between BIM to BEM. BEM is mainly used for building performance analysis. However, through interviewing twenty engineers and building energy modeling professionals in the industry, it turned out that most gbXML files are only used for importing and exporting building geometry information. Information such as HVAC systems and internal loads are rarely handled due to the lack of functionality in current BIM software. Taking account of more than 15% of the total energy consumption in the US is used by HVAC systems (DOE 2011), it is crucial to enable seamless HVAC data exchange between BIM software and BEM software.

Firstly, through a detailed data mapping of ASHRAE baseline variable air volume and reheat system between IDF data model (EnergyPlus version 9.0) to corresponding elements in gbXML schema (version 6.01), interoperability issues were discovered and were concluded into three categories: missing components, the difficulty of decoding performance curves, and complex data mapping rules. Secondly, through redefining data mapping rules in current gbXML schema in terms of HVAC systems, the ASHRAE baseline system type seven is coded as a gbXML file. Finally, the gbXML file is validated through a medium office building case study. Revit 2020.1 Architecture is used in this study as the BIM tool. OpenStudio 2.9.1 and EnergyPlus 9.2.0 are used as the BEM tool. They are open-source and cross-platform, being adopted by lots of mainstream building performance analysis software.

Based on the result of this study, current gbXML schema version 6.01 is capable of defining HVAC systems data, but the data mapping rules need to be documented and presented. Redefined data mapping rules and improvement suggestions are proposed to the current gbXML schema in terms of HVAC systems. The improved interoperability will eliminate the duplicate generation of HVAC data and allows a bidirectional information update between BIM and BEM software, supporting a more accurate and efficient building performance analysis process, thus improving indoor thermal comfort and building energy usage.

Contents

1 Introduction

The human being, as a warm-blooded animal, eats food to keep the constant body temperature. Similarly, architecture as a space for shielding human beings, fuels energy to keep the indoor thermal environment consistent and comfortable. Then what’s the interaction between the human body and its surrounding environment?

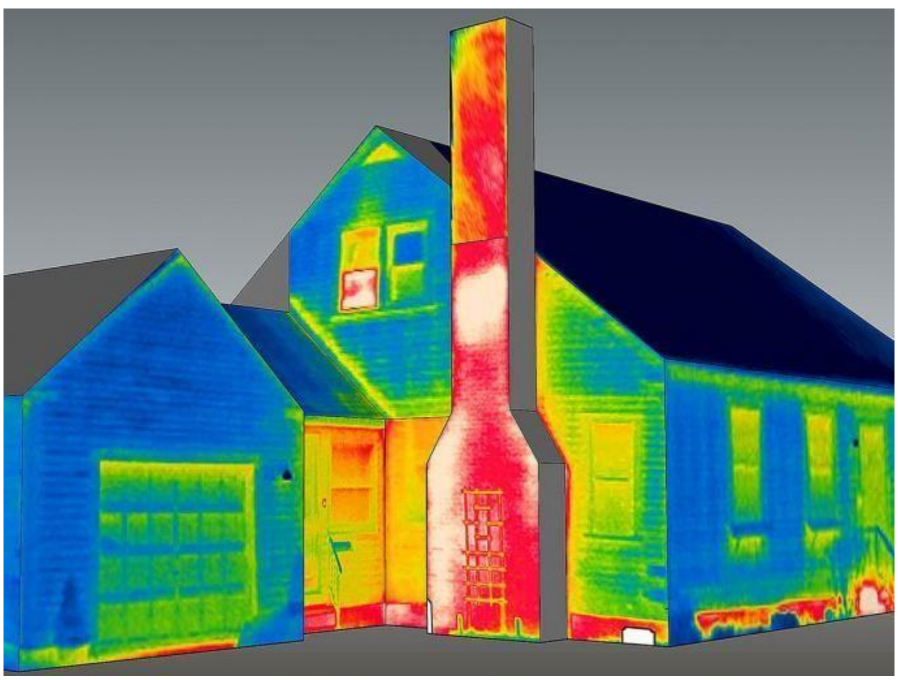


Figure 1.1 Thermography with 3D Modeling (From UMass Amherst)

1.1 Thermal comfort

As ASHRAE defines, thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ASHRAE Standard 55-2017). The importance of thermal comfort to human health, productivity, and well-being has been emphasized in many researches (Samet et al., 2003; Parsons, 2014). The human body can be viewed as a heat engine, and as long as we eat food, the engine will be operative. The Kelvin-Planck statement of the second law of thermodynamics states that *"It is impossible to devise a cyclically operating device, the sole effect of which is to absorb energy in the form of heat from a single thermal reservoir and to deliver an equivalent amount of work"* (Gokcen, N., & Reddy, R., 1996). A human body as a relatively high-temperature heat engine will incur spontaneous heat transfer to the surrounding relatively low-temperature environment. In this perspective, thermal comfort means a constant heat transfer rate between the human body and the environment.

Figure 1.2 Gender Bias in Body Temperature (National Geography, 2015)

The heat transfer consists of latent heat loss and sensible heat loss, then the sensible heat loss can be classified into 3 mechanisms: thermal conduction, thermal convection and thermal radiation. Besides the four factors of thermal environmental, which directly influence the heat transfer, there are two personal factors: metabolic rate and clothing insulation also significantly influence the thermal comfort.

Clothing insulation is the total insulation between the body surface and surrounding air. One clo unit (0.155 $m^2 \cdot K/W$) corresponds to trousers, a long-sleeved shirt, and a jacket. Clothing insulation values for other standard ensembles or single garments can be found in ASHRAE 55 (ASHRAE Standard 55-2017). Estimated metabolic rate values are given in 2013 ASHRAE Handbook: Fundamentals, which is sufficiently accurate for most engineering purposes except precision laboratory measurements.

The most precise method is to measure the rate of respiratory oxygen consumption and the rate of carbon dioxide production. A less accurate way to estimate metabolic rate is to measure Heart Rate, which is based on the relationship between heart rate and oxygen consumption at different levels of physical exertion for a typical person (ASHRAE Standard 55-2017). The standard deviation of this estimate method varies from 10 to 15% (Malchaire, J. et al., 2017).

A statistic model was developed using principles of heat balance and experimental data to define comfort under steady-state conditions (Fanger, P. O., 1970). Standard thermal comfort surveys are based on a 7-point scale of subjective sensation, from cold (-3) to hot (+3). Fanger's equations are used to calculate the Predicted Mean Vote (PMV) of a large group of subjects for a particular combination of air temperature, air velocity, mean radiant temperature, relative humidity, metabolic rate, and clothing insulation. Fanger also developed another function to relate the PMV to Predicted Percentage of Dissatisfied (PPD), shown in Figure 1.1. ASHRAE Standard 55-2017 uses the PMV model to set the requirements for indoor thermal conditions. It requires that at least 80% of the occupants be satisfied. However, many researchers have been arguing this statistic model and developed a wide variety of metrics and methods to assess thermal comfort (Kingma et al., 2015; Karmann, C., Schiavon, S., & Bauman, F., 2017). The PMV function is:

$$\begin{aligned} PMV = {} & (0.303e^{-0.036M} + 0.028) \\ & \times [(M - W') - 3.05 \times 10^{-3}\{5733 - 6.99(M - W') - P_a\} \\ & - 0.42\{(M - W') - 58.15\} - 1.7 \times 10^{-5}M(5867 - P_a) \\ & - 0.0014M(34 - t_a) - 3.96 \times 10^{-8}f_{cl}\{(t_{cl} + 273)^4 \\ & - (t_r + 273)^4\} - f_{cl}h_c(t_{cl} - t_a)] \end{aligned}$$

$$PPD = 100 - 95e^{(-0.03353PMV^4 - 0.2179PMV^2)}$$

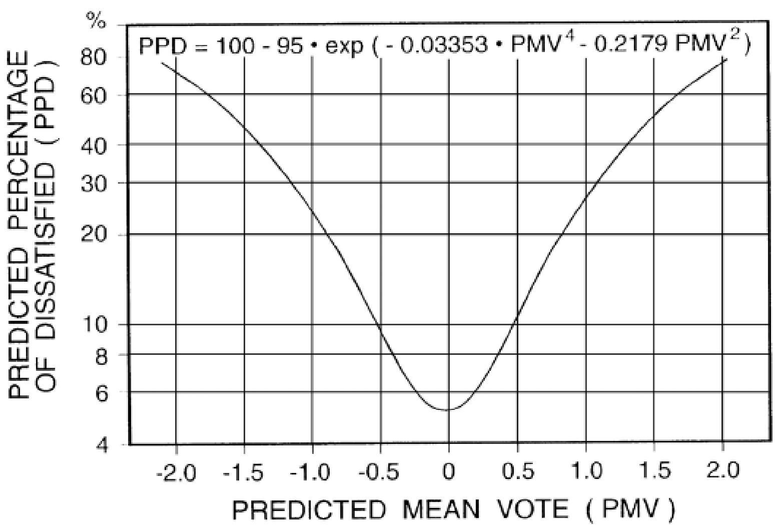


Figure 1.3 Predicted Percentage of Dissatisfied (ASHRAE55-2017)

1.2 Indoor thermal environment

In buildings, the indoor environment can be classified into luminous environment, acoustic environment, and thermal environment. The thermal environment includes dry-bulb air temperature, radiant temperature, relative humidity, and air velocity.

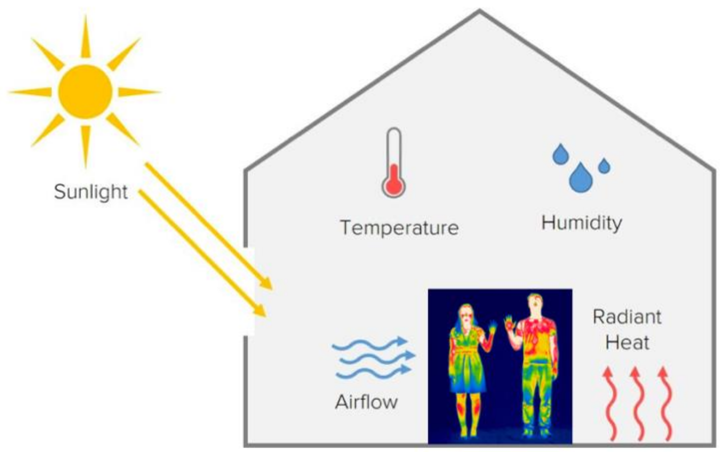


Figure 1.4 Indoor Thermal Environment

The air temperature is the average dry-bulb temperature of the air surrounding the occupant, concerning location and time. The spatial average value considers the ankle, waist, and head levels, which vary for seated or standing occupants, and the average temporal value is based on three-minutes intervals with at least 18 equally spaced points in time.

The radiant temperature depends on the amount of radiant heat transferred from a surface, which is related to the material's emissivity. The mean radiant temperature depends on surface temperatures, emissivity of the surrounding surfaces, and view factor.

Air velocity is defined as the flow rate of the air movement at a point, without direction concerning. But it relates to location and time. The temporal average is the same as air temperature, and the spatial average assumes that the body is exposed to a uniform air speed, according to the SET thermo-physiological model.

Relative humidity is the ratio of the amount of water vapor in the air to the amount of water vapor that the air could hold at the specific temperature and pressure. The human body's thermal sense would be affected by relative humidity through conductive heat transfer and evaporation rate, which is related to heat loss rate (ASHRAE Standard 55-2017).

For maintaining the constant heat transfer rate between a human body and its surrounding thermal environment, mechanical systems in a building are used for heating, cooling, and conditioning the space, through working mediums. This process is a reverse Carnot cycle, which usually consumes electricity or other forms of energy to do the work. Most of the time, the air is valued as the primary medium to condition the space, as a human body always interacts with its surrounding air through breathing, evaporation, and thermal convection. Besides, radiant temperature also directly affects the thermal environment without distance or medium consideration.

2 Problem statement

In 90% of buildings, HVAC systems consume 48% energy to maintain indoor thermal environments (Pérez-Lombard, L. et al., 2008). However, 53% of occupants are unsatisfied with the environment (Huizenga, C. et al., 2006). In a word, most of the energy that HVAC systems consumed is wasted. This is definitely not sustainable.

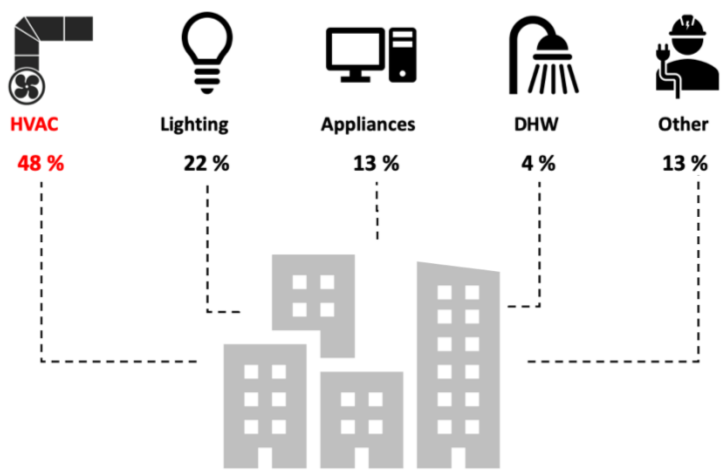


Figure 2.1 Building Energy End Use

2.1 HVAC-dominated indoor environment

The contemporary built environments, especially in the significant commercial and office buildings, have been dominated by Heating Ventilation and Air-conditioning (HVAC) systems. The goal is to provide thermal comfort and acceptable air quality. HVAC systems consume significant energy to proceed to different thermodynamic processes to maintain the indoor thermal environments at a constant level.

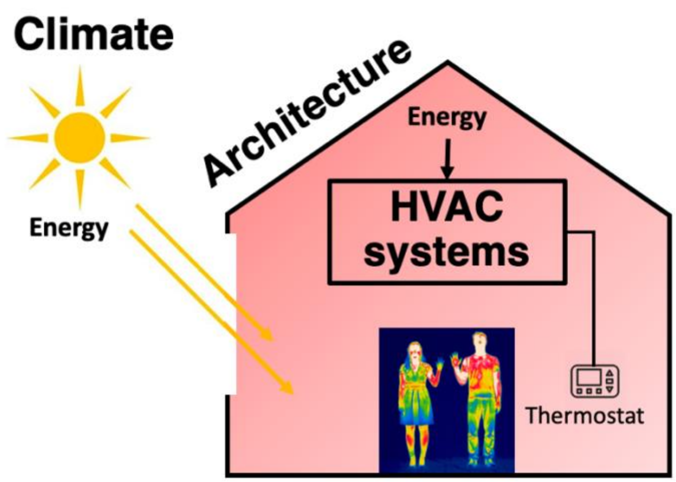


Figure 2.2 HVAC-dominated Indoor Thermal Environment

In the past, most built environments are dominated by outdoor climate, so people desire to keep warm in the winter and cool in the summer. The hypocaust system in the ancient Rome bath is the first example of utilizing active energy for maintaining a comfortable thermal environment. The order of spaces in the architecture is aligned with energy flow. For example, increased energy supply leads to increased temperature of spaces. The function is ordered as first apodyterium, second sudatorium, and finally, natation (KielMoe, 2014).

However, with the development of energy usage technology, it becomes cheap and convenient to adopt mechanical systems in architecture, and the design of the integration of mechanical systems and architecture is called active design.

The passive design is for utilizing the free energy from the sun and through architectural envelope. For example, the traditional buildings at Cairo adopt design like wind-catching windows, rased room floor and wind towers, etc. (Fathy, H., 2010). This energy flow is sustainable but not very useful.

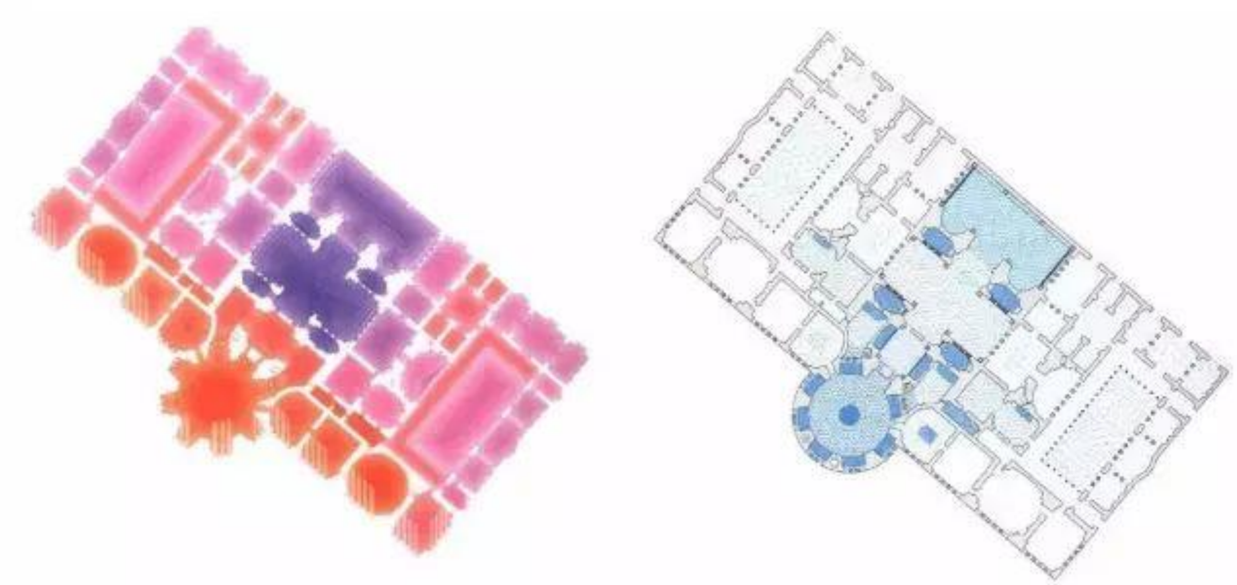


Figure 2.3 Thermodynamic Plan and Humidity Plan of Terme Di Caracalla (KielMoe, 2014)

2.2 Defect of HVAC systems

The energy consumption of HVAC systems is significant, but it doesn't satisfy occupants' thermal needs well. According to a survey of 215 office buildings in North America and Finland in 2006, only 11% of the buildings had at least 80% satisfied occupants (Huizenga, Abbaszadeh, Zagreus, & Arens, n.d.). Among occupants who are dissatisfied with the temperature, 51% of them are dissatisfied in warm weather, and 45% dissatisfaction reasons are "often too cold". 49% of them are dissatisfied in cold weather, and 32% of dissatisfaction reasons are "often too hot".

Therefore, in current air-conditioned the built environment, it is reasonable to conclude that a significant number of occupants prefer warm (feeling of "often too cold") in summers and fewer occupants prefer cool (feeling of "too hot") in winters. What's more, the experience of "often too cold" in summers and "often too hot" in winters also wastes energy.

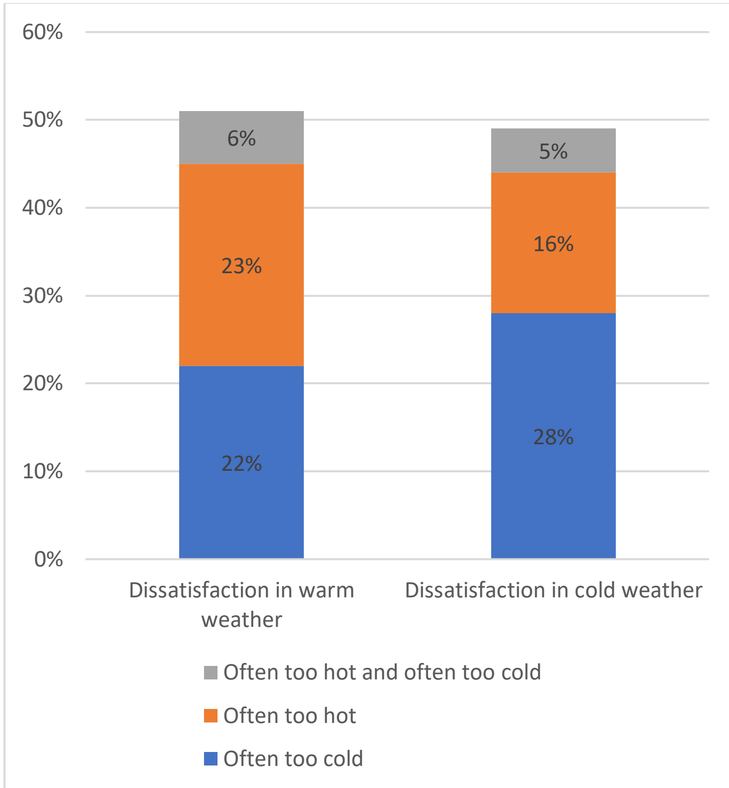


Figure 2.4 Distribution of Thermal Dissatisfaction Reasons in Different Weather

The source of the dissatisfaction with workspace temperature is ranked by frequency of occurrence. For the top 6 causes, each of them has more than 5% frequency, and the highest one is "my area is hotter or colder than other areas" (14%). People might understand this as occupants would like to stay in an isothermal environment.

However, the truth is that occupants have settled workspaces, so they cannot move towards or away from cooling air diffusers. They have different thermal preferences, but they are not services by the thermal environment they want. Mainly, among those sources, 3 of them (No.1, No.4, and No.6) are caused by poor HVAC systems design, and 3 of them (No.2, No.3, and No.5) are caused by ineffective HVAC systems control (operation). Of particular note that between occupants with a thermostat and without a thermostat, the temperature satisfaction percentage difference is 20%.

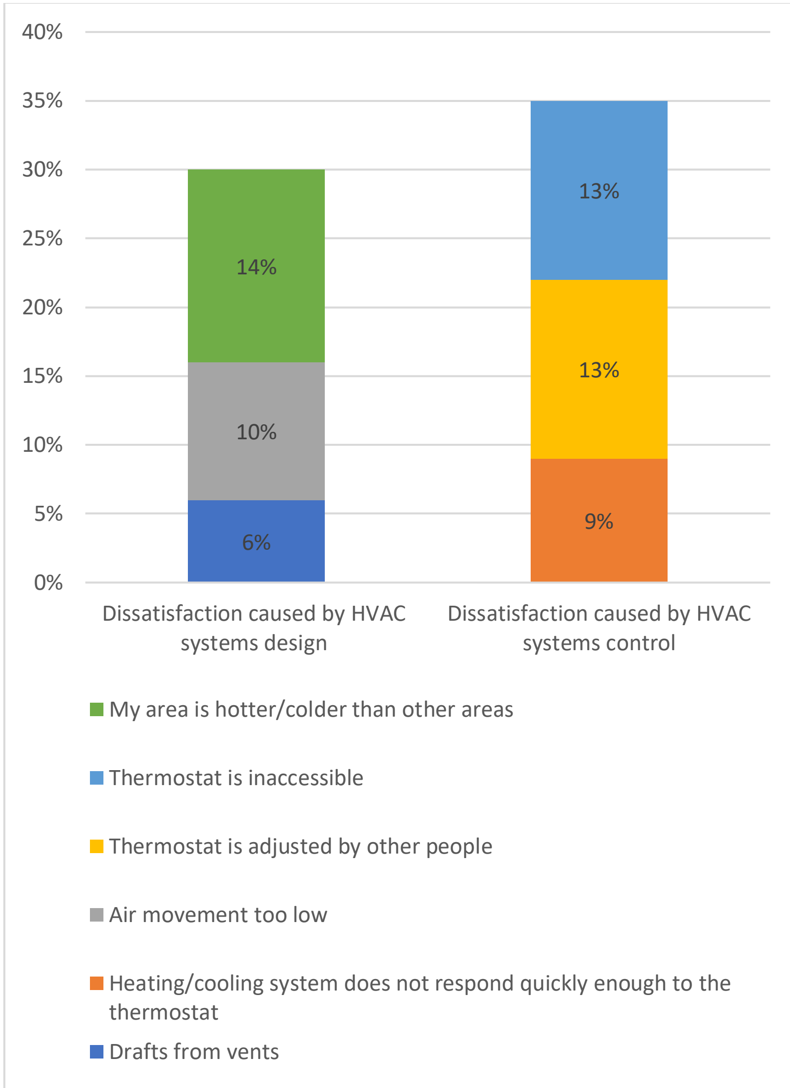


Figure 2.5 Occurrence Frequency of Dissatisfaction with Workspace Temperature Source

3 Problem Analysis

Since 1902, HVAC systems have been popularizing in commercial and residential buildings. Widely used insulating layers on building envelops invented for reducing heat-transfer rate between indoor environment and outdoor environment. The representative building types with significant energy consumption and low thermal satisfaction rate are commercial and office buildings.

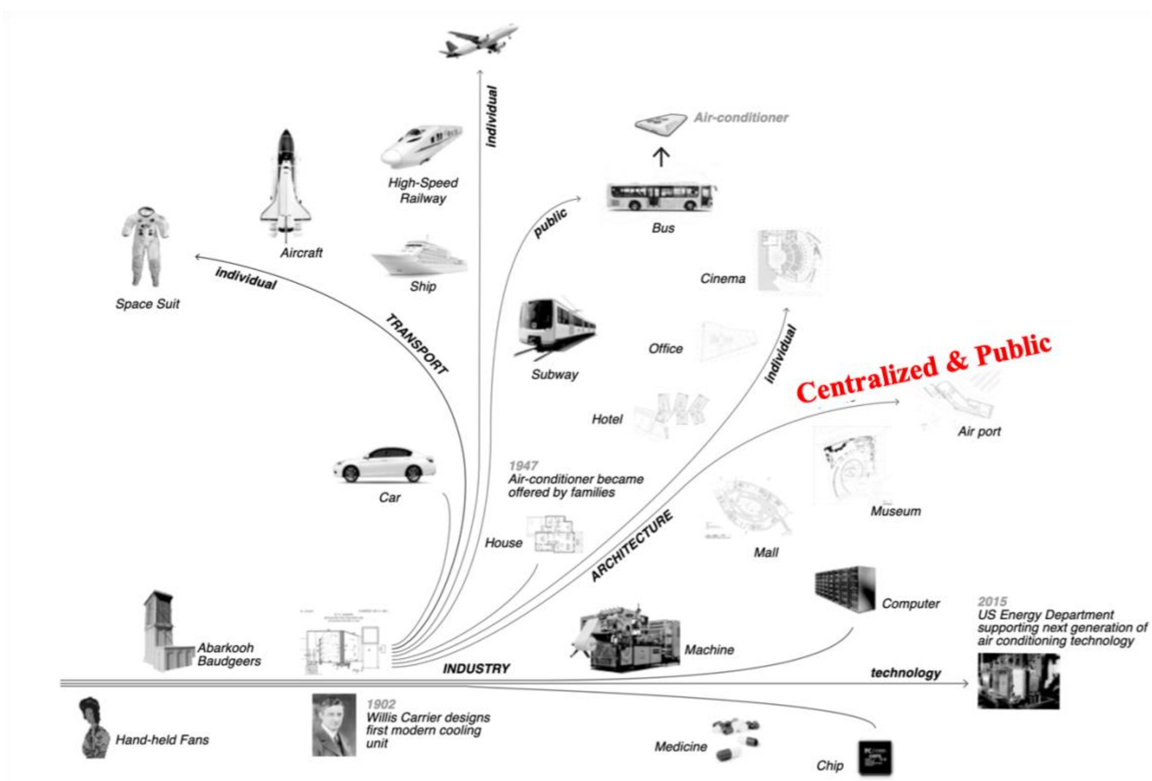


Figure 3.1 HVAC Systems Development Mapping

3.1 Architecture design and HVAC design workflow

One major cause of the issue is that the division of work makes architecture design and HVAC systems design uncontrollable. When several parameters of the building change, if the HVAC systems design is not updated in time, it will be oversized, causing thermal comfort and energy consumption issues during building operation phases.

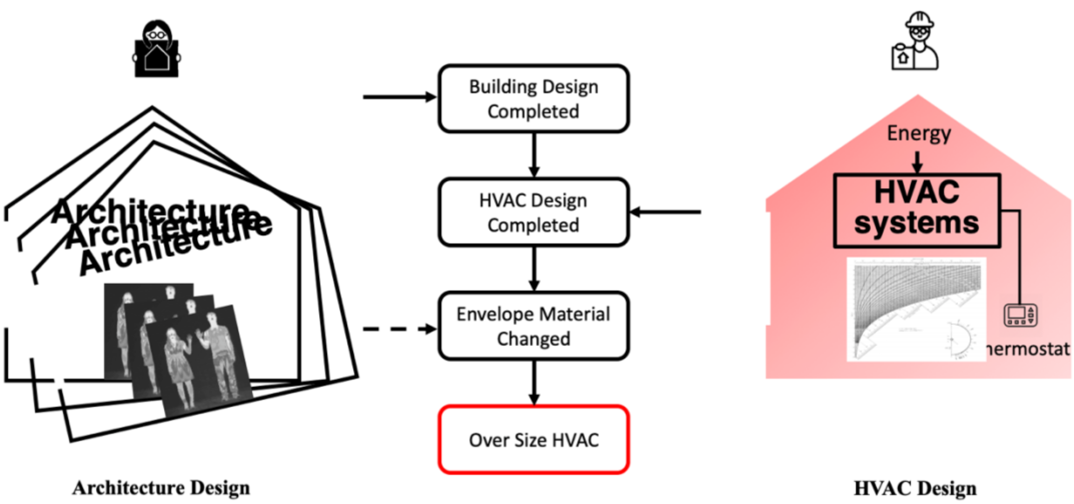


Figure 3.2 Oversized HVAC Systems Issue

The architecture design consists of 4 phases: conceptual design, schematic design, design development, construction documentation. The HVAC systems design consists of 3 steps: system planning, HVAC design, construction documentation. At the architectural conceptual design phase, HVAC engineers start to consider the HVAC systems type and the heating and cooling strategy.

Most HVAC systems design work is conducted during the architectural design development phase. Due to the complicated building design at that phase, HVAC engineers always use rough experience value to size HVAC equipment and calculate system design parameters. Therefore, oversizing has become one of the most frequent issues of HVAC systems.

The idea is that enabling seamless data exchange of building information between architects and HVAC engineers would help improve HVAC systems design, thus improving thermal comfort and energy efficiency.

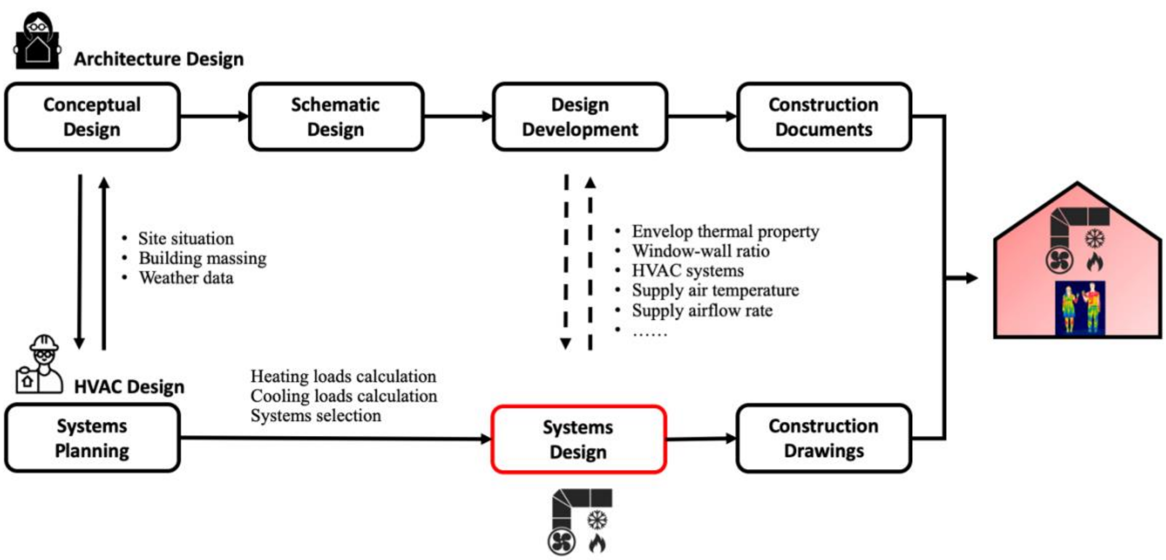


Figure 3.3 Architecture and HVAC Design Workflow

4 BIM and BEM Solution

BIM-based performance analysis workflow makes the building performance analysis process less expensive and labor-intensive and increase the accuracy of the performance simulation results. Especially during design phases, the value of BIM and performance analysis can be maximized (Moon, H. J. et al. 2011). gbXML as one of the most popular data model is selected in this study, as it is designed for green building performance analysis. The Building energy modeling (BEM) is a subset of BIM. It allows more information inputs for building energy simulation such as HVAC systems data, operation schedules, envelope materials.

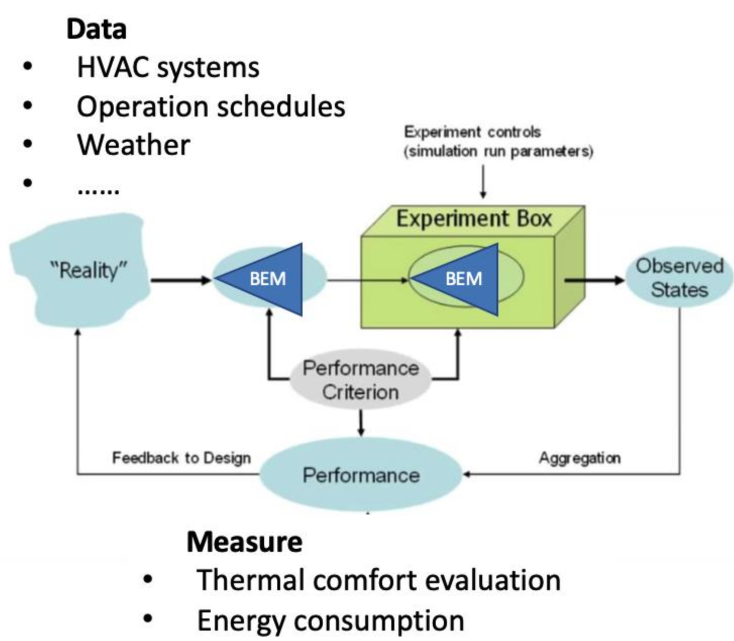


Figure 4.1 Building Energy Modeling

4.1 Building information modeling (BIM)

Building information model (BIM) is a digital representation of a building, including geometry information, construction materials, HVAC systems, etc. It serves as a shared knowledge resource for communication in architecture, engineering, construction (AEC) and facility management (FM) industries (Eastman, C. et al. 2011).

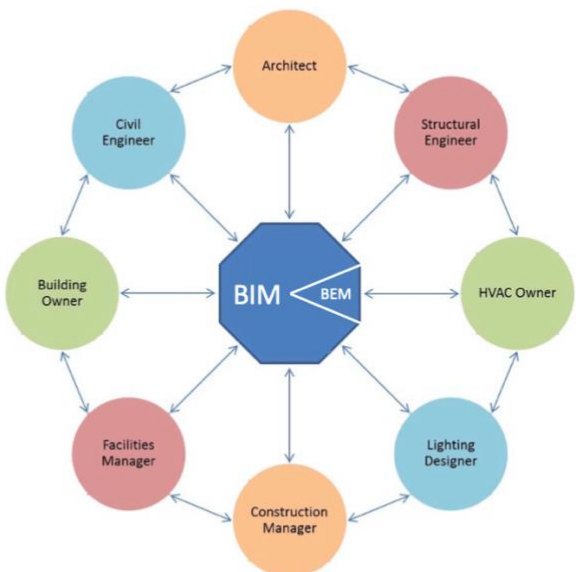


Figure 4.2 Building Information Modeling

4.1.1 gbXML BIM model

gbXML is an XML-based data schema representing building information. XML is an extensible markup language. It is already a mature and powerful data model. Elements are the key objects of this language. They start with the opening tag "<tag>" and end with the closing tag "</ tag>". The attributes included in open tags are used to distinguish elements "<tag attribute = 'something' />". The content between the opening and closing tags may be text, other elements, or a mixture of them (W3Schools, 2017).

Due to the extensibility of the language, XML has many derived forms. For example, based on XML data structures, Hypertext Markup Language (HTML) has developed a set of predefined tags and attributes to help display content on a website. Similarly, gbXML has the same XML data structure. It also has predefined tags and attributes that are specifically designed for green building information modeling (gbXML, 2017). Therefore, only XML files that follow the gbXML schema can be called gbXML.

However, confusion occurs when the BIM model follows part of the gbXML schema and customizes some other elements and attributes. For example, in the Revit 2020.1 system analysis, the exported file follows the gbXML schema in the geometric data, but for HVAC system data, it adds two custom elements. For clarity, the customized gbXML is referred to as an XML file in this article.

4.1.2 Interoperability of gbXML

BEM is mainly used for sustainable architecture design, HVAC systems design and operation, and building performance rating. The interoperability of gbXML between BIM and BEM should be seamless model translations or data exchange among disparate building design and performance analysis software tools.

However, by interviewing more than twenty energy modelers, engineers, software developers, and other stakeholders, the current gbXML workflow only enables geometry data transformation. HVAC systems have to be manually created in BEM tools. In addition to the interviews, eleven current mainstream BIM and BEM software and tools are investigated in the gbXML interoperability from different aspects, shown in Table 4.1.

Table 4.1 Import and Export gbXML in BIM and BEM Software Tools

Software Tools	Geometry	Material Properties	HVAC Systems	Internal Loads
BuildSimHub	Yes	No	No	No
Design Builder v6.1	Yes	Yes	No	No
Open Studio v2.9.0	Yes	Yes	Yes	Yes
HVAC Solution v9.5.1	No			
TRACE 700 v6.3.4	Yes	No	No	Yes
TRACE 3D Plus v2.04.20	Yes	No	No	No
Revit 2020.1 Architecture	Yes	No	No	No
Revit 2020.1 MEP	Yes			
Revit 2020.1 System Analysis	Yes	Yes	Yes	Yes
Spider gbXML Viewer v0.17	Yes	Yes	No	No
Talece BIMPort	Yes	No	No	No

5 Research Hypothesis

The integrated HVAC-BEM workflow will be evaluated by two methodologies: (1) a survey interview of professionals in the architecture, engineering and construction industry; (2) an energy simulation case study of the ASHARE standard baseline system 7. These two methodologies will dress the following two hypothesizes.

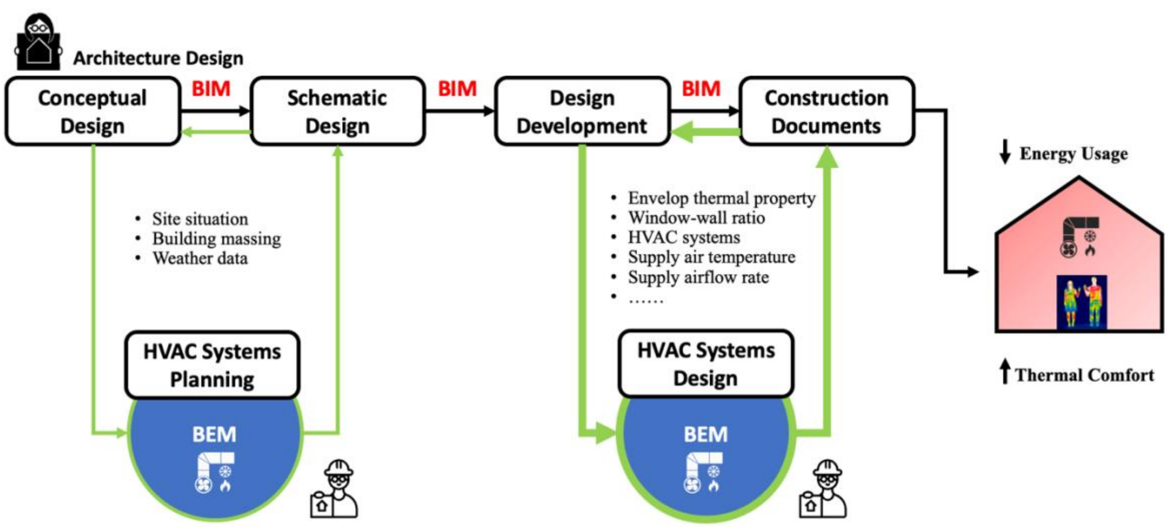


Figure 5.1 Integrated BIM, BEM and HVAC Design Workflow

5.1 Main Hypothesis

The integrated HVAC-BEM workflow with gbXML data model, taking HVAC systems data as the inputs and outputs in building information modeling software and building performance analysis software, will effectively improve the efficiency of HVAC engineering design and building energy modeling, thus effectively optimizing the accuracy of thermal comfort and energy simulation during architecture design phases.

5.1.1 Hypothesis 1

The gbXML model with HVAC systems data guarantees a faster energy modeling process in building performance analysis software tools, compared with mainstream manually HVAC systems modeling processes.

5.1.2 Hypothesis 2

The integrated HVAC-BIM workflow can achieve higher accuracy of building energy simulation and indoor thermal comfort evaluation, compared with the analysis based on ideal HVAC systems set up.

6 Interview

The hypothesis has been partially validated trough interviewing twenty professionals of BIM and BEM in the industry. It turned out that most data imported into BEM is building geometry, and information such as materials, HVAC systems and internal loads are manually created in BEM software due to data schema issues. A survey interview was designed to gather feedback from the BIM and BEM software tool end-users.

Figure 6.1 Interviewed Company

6.1 Interview question sets

The interview has three question sets: (1) interviewee's the workflow from building information modeling to building performance analysis; (2) description of problems that the interviewee has met in the workflow, focusing on details of the BIM and BEM model; (3) the suggestion of current mainstream workflow from BIM to BEM, and expectation of gbXML data schema development. A standard interview lasts for 45 minutes.

After each interview, problems encountered by the interviewees were reproduced following the details provided. Then, the source gbXML codes were analyzed to identify the origin of the problem.

6.2 Distribution of interviewees

Interviewees were searched and invited to participate in this survey through a variety of channels, including inviting through groups on social networks, industry organization mailing lists, academic mailboxes, and interpersonal acquaintances. The receivers of the invitation were assumed to be more knowledgeable users in the BIM and BEM than most in the AEC industry and related academic communities.

According to the reading data, the post of the online survey in the multiple promotion channels has received more than 1,550 readings. According to the feedback of the push, a total of 54 people received an official invitation to the interview. Among the 54 invitations, 20 were rejections, and 6 did not respond after three rounds of follow-ups. On the other hand, 28 people accepted the invitation. However, 6 out of 28 interviews were through an interview questionnaire in text form due to time constraints. The success rate of the invitation is 41.8%. The Figure depicts the occupation distribution of these 28 interviewees. Most of the feedback is from the AEC industry and software developers targeting BIM and BEM platforms. The constitution of the occupation implies that the survey results can not only explore the feedbacks from the AEC industry and the users but also give an insight into the data schema from the computer science aspect.

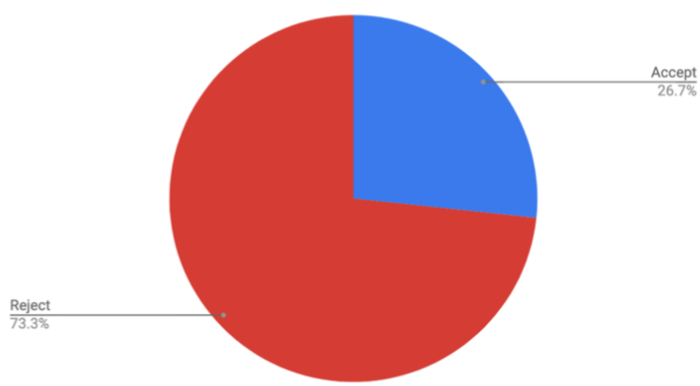


Figure 6.2 Interview Invitation Accept Rate

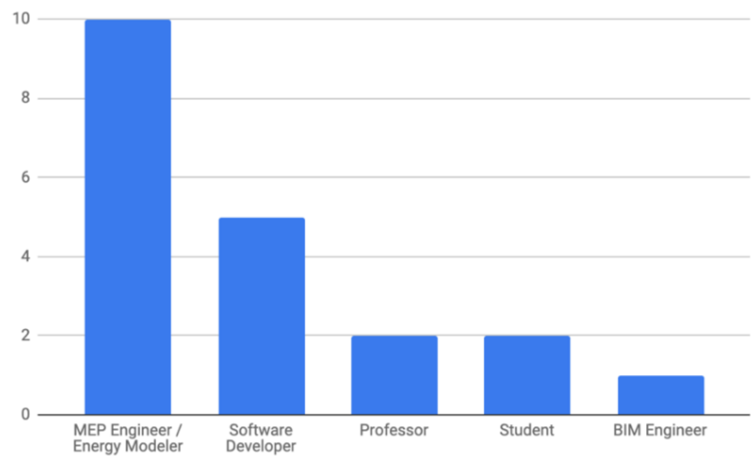


Figure 6.3 Interviewee Employment

6.3 Issues and suggestion feedback

6.3.1 Geometry Issue

According to the interviewees, most gbXML files are only used for geometry data import and export, but it can only handle simple building geometry. If the geometry is too complicated, the gbXML file would crash or has uncompleted surfaces. To improve the gbXML interoperability in terms of geometry data, researchers are developing test cases for software developers as well as energy modelers to validate their workflows.

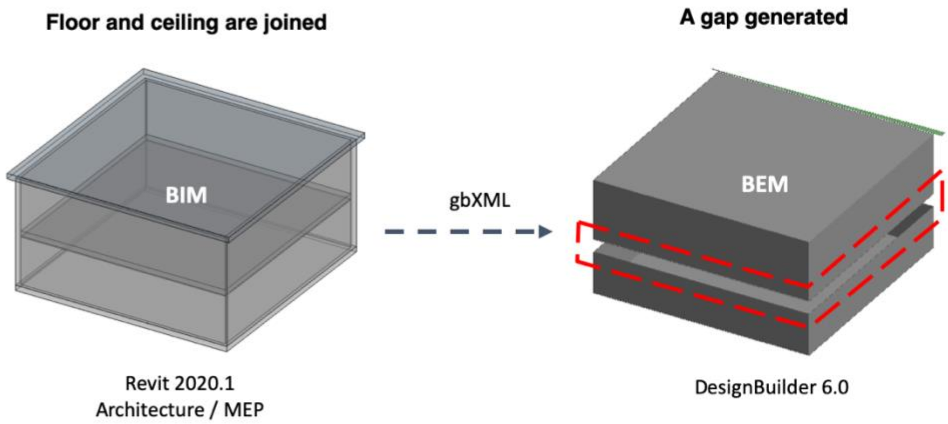


Figure 6.4 gbXML Workflow Issue of Geometry

6.3.2 HVAC systems Issue

Interviewees said that they would always like to manually redraw the primary HVAC system and equipment in BEM software, instead of importing them as gbXML files. Due to the limited functionality of current BIM software, HVAC systems data is rarely handled as gbXML from BIM to BEM. For example, in Revit Architecture and Revit MEP, though users can choose HVAC systems at the gbXML exporting interface, as shown in Figure 6.5, the exported file doesn't include any HVAC related data. Therefore, in gbXML green building design workflow, the thermal comfort and building energy consumption related HVAC systems data are dominated by BEM modeler or MEP engineer.

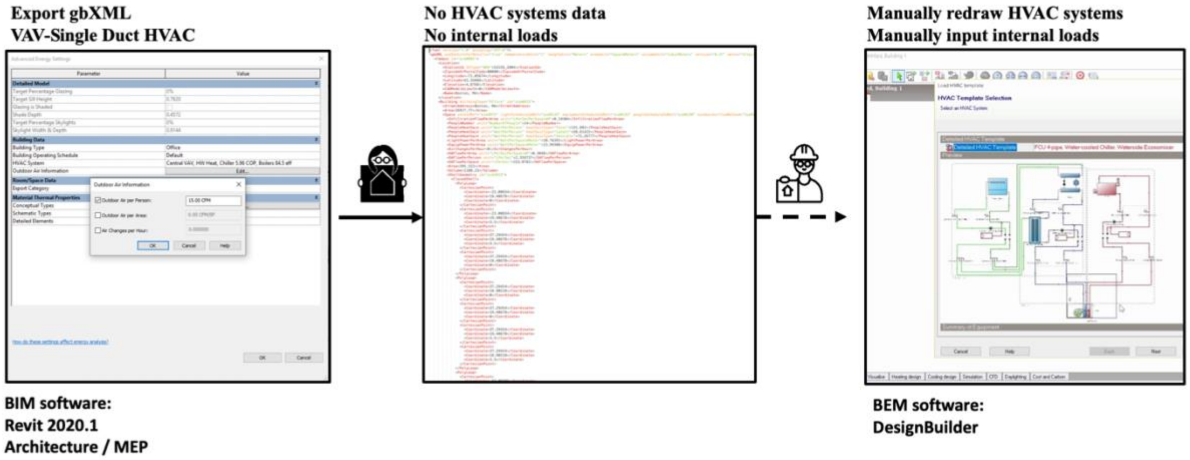


Figure 6.5 gbXML Workflow Issue of HVAC systems

7 Data Mapping

A research of current gbXML data schema was conducted through mapping the baseline HVAC system type seven data one by one from the IDF model to the gbXML schema. To achieve the concept of closing the loop between architecture design and HVAC systems design through BEM. Improving HVAC systems data interoperability between BIM and BEM software tools is the most important task. The data mapping research is the basis of this task.

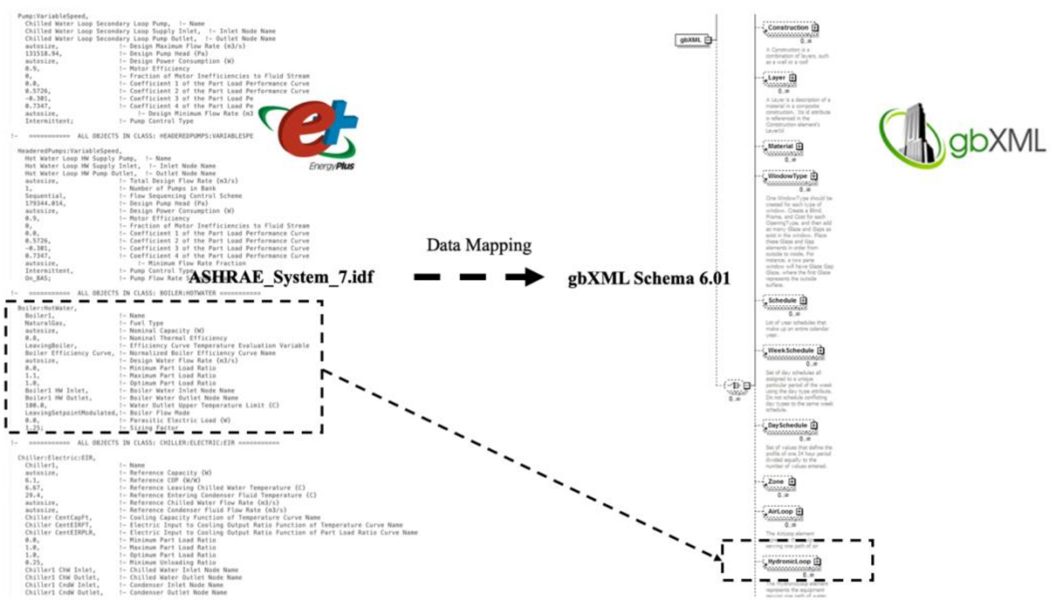


Figure 7.1 Data Mapping from IDF to gbXML

7.1 IDF representation

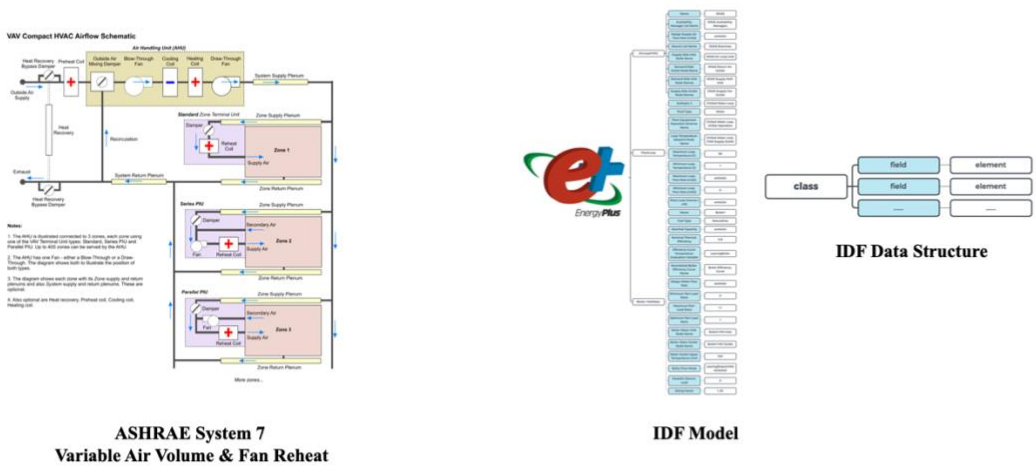


Figure 7.2 ASHRAE System 7 and IDF Data Model

The IDF data structure is flattened to three levels: “class”, “field”, and “objective”. Fields are used to define the characteristics of a class. Objectives are different objects, belonging to the same class. In the original IDF data model of the ASHRAE baseline system seven, HVAC related classes are “PlantLoop”, “CondenserLoop”, “Boiler: HotWater”, etc. Classes have predefined IDF fields and each respective object has its customized value, following the fields. The “Boiler: HotWater” class is selected as an example, shown in Table 7.1.

Table 7.1 IDF Representation of a Boiler

Class	Field	Units	Object1
Boiler: HotWater	Name	-	Boiler1
Boiler: HotWater	Fuel Type	-	NaturalGas
Boiler: HotWater	Nominal Capacity	W	autosize
Boiler: HotWater	Nominal Thermal Efficiency	-	0.8
Boiler: HotWater	Efficiency Curve Temperature Evaluation Variable	-	LeavingBoiler
Boiler: HotWater	Normalized Boiler Efficiency Curve Name	-	Boiler Efficiency Curve
Boiler: HotWater	Design Water Flow Rate	m3/s	autosize
Boiler: HotWater	Minimum Part Load Ratio	-	0
Boiler: HotWater	Maximum Part Load Ratio	-	1.1
Boiler: HotWater	Optimum Part Load Ratio	-	1
Boiler: HotWater	Boiler Water Inlet Node Name	-	Boiler1 HW Inlet
Boiler: HotWater	Boiler Water Outlet Node Name	-	Boiler1 HW Outlet
Boiler: HotWater	Water Outlet Upper Temperature Limit	C	100
Boiler: HotWater	Boiler Flow Mode	-	LeavingSetpointModulated
Boiler: HotWater	Parasitic Electric Load	W	0
Boiler: HotWater	Sizing Factor	-	1.25
Boiler: HotWater	End-Use Subcategory	-	-

7.2 gbXML representation

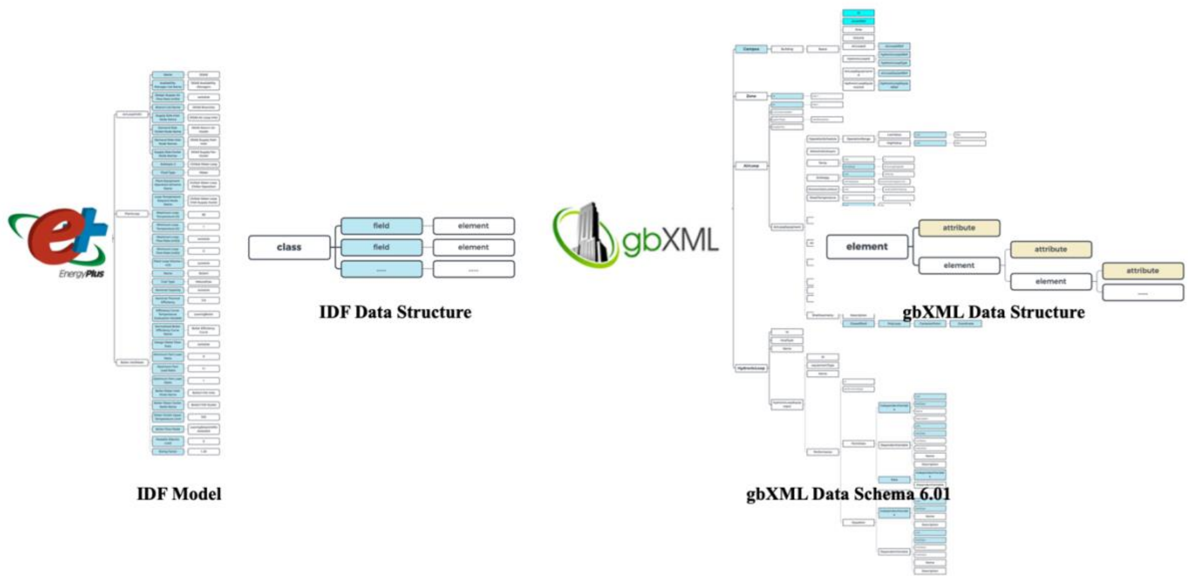


Figure 7.3 IDF and gbXML Data Model Comparison

gbXML has a hierarchy data structure, compared with IDF. All fields of the "Boiler: HotWater" class in the IDF data model are mapped to elements and their attributes in the gbXML data schema. To define the boiler as a "HydronicloopEquipemt", its parent element "HydronicLoop" is required and needs to be defined individually, as shown in Table 7.2. gbXML defines HVAC systems in a hierarchy way. "AirLoop" and "HydronicLoop" are used to define the primary system data, which is heating and cooling center plant information. "AirLoopEquipemt" and "HydronicloopEquipemt" are used to define the secondary system data or equipment data. "Zone" and "Space" are used to assign HVAC systems to specific areas.

Table 7.2 gbXML Representation of a Boiler

1st Element	2nd Element	3rd Element	4th Element	Attributes	Object1
gbXML	HydronicLoop	-	-	loopType	HotWater
gbXML	HydronicLoop	-	-	fluidType	Water
gbXML	HydronicLoop	-	-	id	DHW1
gbXML	HydronicLoop	HydronicLoopEquipment	-	id	DHW1-B1
gbXML	HydronicLoop	HydronicLoopEquipment	-	equipmentType	Boiler
gbXML	HydronicLoop	HydronicLoopEquipment	Name	-	Boiler1
gbXML	HydronicLoop	HydronicLoopEquipment	Temp	unit	C
gbXML	HydronicLoop	HydronicLoopEquipment	Temp	tempType	Max
gbXML	HydronicLoop	HydronicLoopEquipment	Power	unit	Watt
gbXML	HydronicLoop	HydronicLoopEquipment	Power	useType	Heating
gbXML	HydronicLoop	HydronicLoopEquipment	Power	powerType	NaturalGas
gbXML	HydronicLoop	HydronicLoopEquipment	Efficiency	efficiencyType	BoilerEff
gbXML	HydronicLoop	HydronicLoopEquipment	Control	controlType	Boiler
gbXML	HydronicLoop	HydronicLoopEquipment	Control	minPowerRatio	0
gbXML	HydronicLoop	FlowControl	DesignFlow	unit	LPerSec

7.3 Issue one

During the data mapping process from the IDF data model to the gbXML schema. It turned out that some IDF fields don't have corresponding elements or attributes in gbXML. Take the "Boiler: HotWater" IDF class as an example, in the IDF data model, the "Maximum Part Load Ratio", "Optimum Part Load Ratio", "Boiler Flow Mode" and "Sizing Factor" are clearly defined and they critical to boiler performance as well as building energy simulation. But in current gbXML schema, they cannot be defined using existing elements or attributes, unless custom elements or attributes are created. Some other missing components are unnecessary for gbXML data exchange due to the hierarchy structure, such as “Boiler Water Inlet Node Name”, “Boiler Water Outlet Node Name” and “End-Use Subcategory”. They can be defined by the order of “HydronicLoopEquipment” elements.

7.4 Issue two

The performance of HVAC equipment is important to the acoustic quality, thermal quality, and energy efficiency of a building. However, in the gbXML schema, it is difficult to express performance curves information. Take a pump as an example, in “Pump: VariableSpeed” IDF class, a pump’s performance curve is defined by values at different coefficients of the part-load performance curve respectively. It is clearly defined as linear, quad linear or quadratic equation, etc. Take biquadratic curves as an example, the IDF representation is shown in Table 7.3. The biquadratic equation is:

$$z = a + bx + cx^2 + dy + ey^2 + fxy \qquad (1)$$

Table 7.3 IDF Representation of a Quadratic Curve

Class	Field	Units	Object1
Curve:Biquadratic	Name	-	CoolCapFTExample
Curve:Biquadratic	Coefficient1 Constant	-	0.757382
Curve:Biquadratic	Coefficient2 x	-	0.014666
Curve:Biquadratic	Coefficient3 x**2	-	0.000459
Curve:Biquadratic	Coefficient4 y	-	-0.00095
Curve:Biquadratic	Coefficient5 y**2	-	-0.00067
Curve:Biquadratic	Coefficient6 x*y	-	-0.00015
Curve:Biquadratic	Minimum Value of x	-	17.22222
Curve:Biquadratic	Maximum Value of x	-	21.66667
Curve:Biquadratic	Minimum Value of y	-	18.33333
Curve:Biquadratic	Maximum Value of y	-	46.11111
Curve:Biquadratic	Minimum Curve Output	-	-
Curve:Biquadratic	Maximum Curve Output	-	-
Curve:Biquadratic	Input Unit Type for X	-	Temperature
Curve:Biquadratic	Input Unit Type for U	-	Temperature
Curve:Biquadratic	Output Unit Type	-	Dimensionless

However, in gbXML, the whole equation is written as one expression. Though the independent and dependent variables are defined, it is still difficult to differentiate the curve class and to extract the coefficients of each independent variable using current schema elements. Extra work is needed. There is another method called "PointData", using multiple "data" elements to represent points on a performance curve in order. This method is neither accurate nor efficient. Two gbXML representation schema is shown in Figure 7.4.

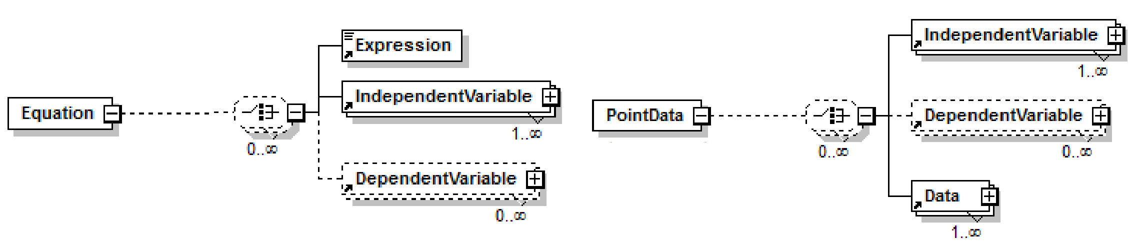


Figure 7.4 gbXML Representation of a Performance Curve

7.5 Issue three

In IDF, HVAC systems data are categorized into different classes. But in the gbXML schema, data is not independent of each other. Most elements have complicated reference relationships, and the gbXML documentation doesn't explain this well. For example, a zone is made up of one space or multiple spaces and is served by one HVAC system (McDowall, R. 2007). In the IDF, the "ZoneHVAC: AirDistributionUnit" class is named by zones. But in gbXML schema, HVAC systems and equipment are identified by "id" attributes. A primary system connects with a zone, the "AirLoop" and "HydronicLoop" elements have a "controlZoneIdRef" attribute. At the same time, the "Zone" element also has "AirLoopId" and "HydronicLoopId" children elements. However, for HVAC equipment, the "AirLoopEquipement" and "HydronicLoopEquipment" elements don't have a zone or space reference. Instead, "Space" elements in gbXML are connected with HVAC equipment. They have "AirLoopEquipementId" and "HydronicLoopEquipmentId" children elements. The complex relationships are shown in Figure 7.2. They would cause missed connections between zones or spaces with HVAC equipment, raising interoperability issues.

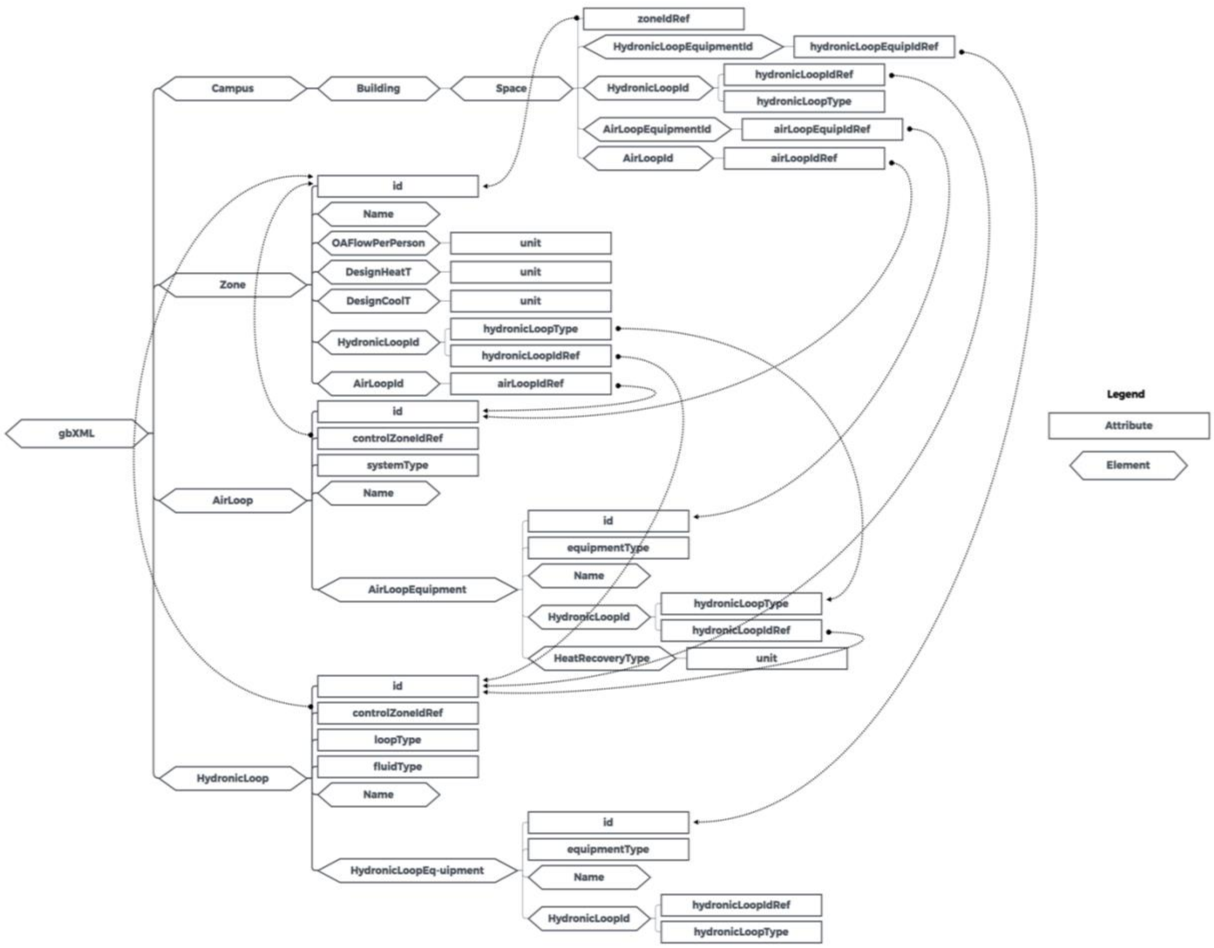


Figure 7.5 Complex gbXML Data Mapping Rules of HVAC Systems

8 Redefinition Data Mapping Rules

Compared with missing components, decoding performance curves, the problem of complex data mapping rules is the most critical issue and needs to be redefined. The rule of thumb for defining HVAC systems in gbXML schema is bottom-up. First of all, defining “HydronicLoopEquipment”, “AirLoopEquipment”, “AirLoop” and “HydronicLoop” in order. Secondly, connecting spaces and HVAC equipment by “HydronicLoopEquipmentId” and “AirLoopEquipmentId” in “Space” element; connecting zones and primary system by “HydronicLoopid” and “AirLoopId” in “Zone” element. Additionally, connecting spaces and zones by “zoneIdRef” in the “Space” element. In this way, zones are connected with their spaces’ equipment indirectly. For example, there are three spaces in a zone, but only one of them has a VAV box. Then this zone is connected with the VAV box. Figure 4 shows redefined data mapping rules, which are more effective and efficient than the relationships shown in Figure 8.1.

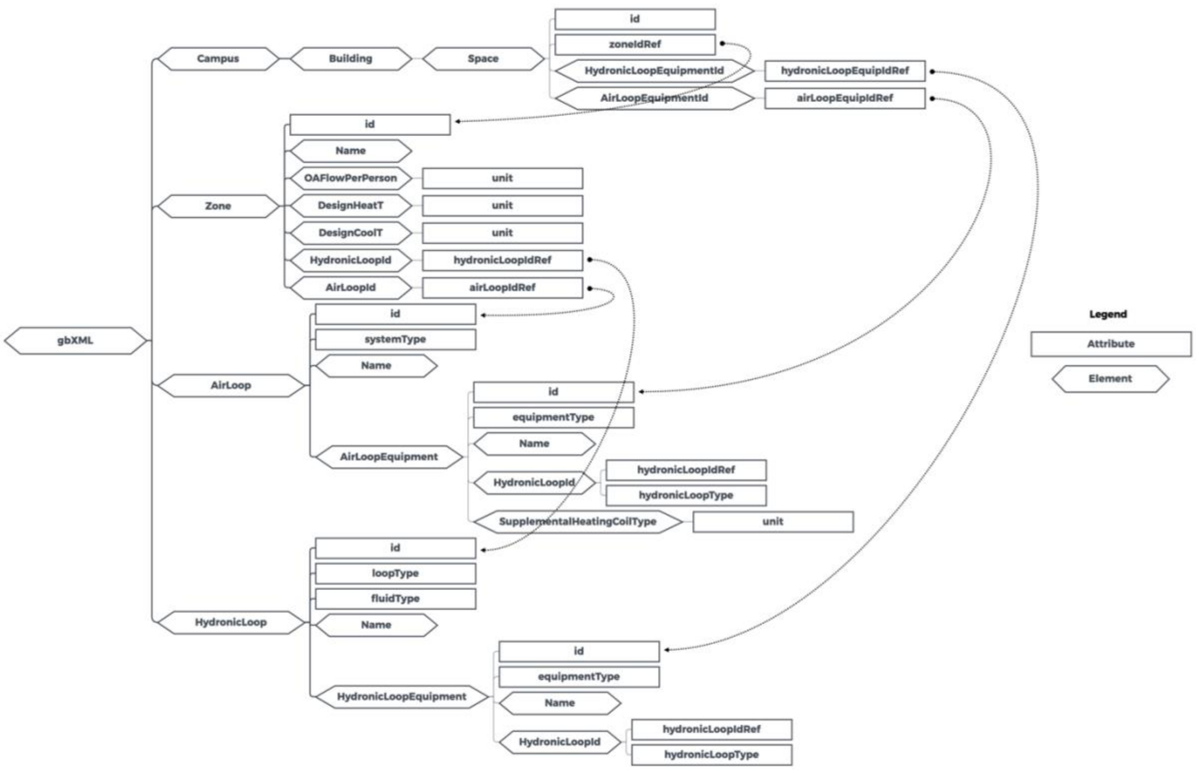


Figure 8.1 Redefined gbXML Data Mapping Rules of HVAC Systems.

9 Case Study Validation

In this chapter, the improved interoperability of gbXML data schema will be validated through an energy simulation case study of the office building in ASHRAE standard baseline HVAC system 7. Compared to ideal HVAC systems set up, the integrated BIM-HVAC-BEM workflow based on redefined data mapping rules of gbXML schema enables standardized information exchange and more HVAC equipment data modification, thus achieving a higher accuracy of building energy simulation and indoor thermal comfort evaluation.

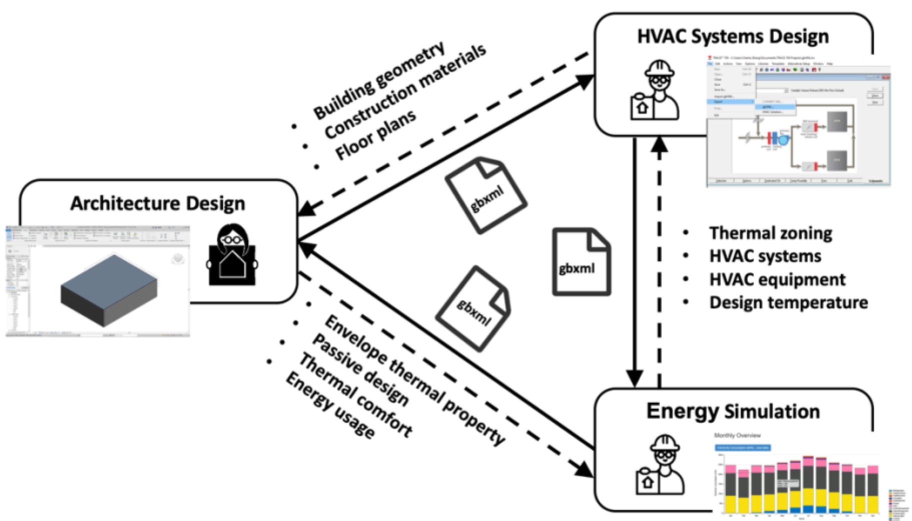


Figure 9.1 HVAC Systems Integrated BIM to BEM

9.1 Building model

The building model was created in Revit Architecture 2020.1, based on geometry data extracted from the ASHRAE system 7 IDF data model. It is a six-floor medium office building with total 22,431 square meter interior floor area. Each orientation has one window on each floor. The model was then exported as a gbXML file format, using energy settings. Thermal zones were assigned by the core-perimeter method, as shown in the Figure 9.1 below.

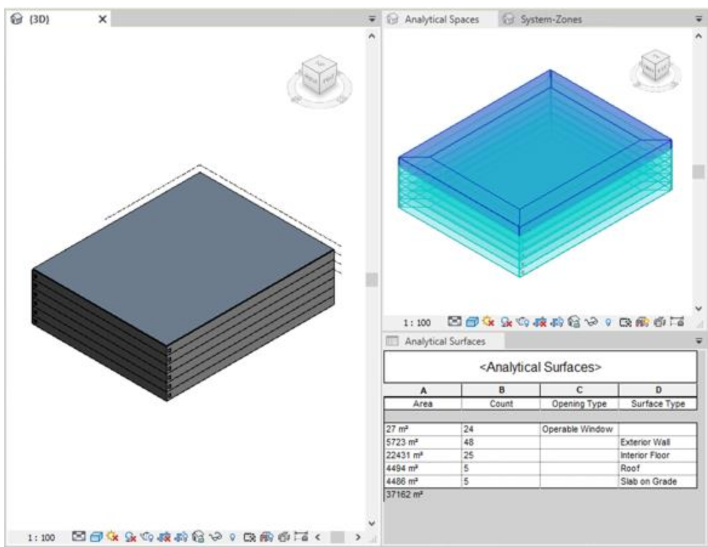


Figure 9.2 Defining building geometry in BIM software

9.2 HVAC systems data

Revit2020.1 System Analysis was just released during this research. It is the first software tool that allows users to define rough HVAC systems in a BIM model. However, it still doesn’t support exporting the HVAC systems as gbXML format. The data model it uses in backend is a customized XML format. The comparison between Revit 2020.1 system analysis XML representation and redefined gbXML representation in terms of HVAC systems has been conducted.

9.2.1 gbXML representation

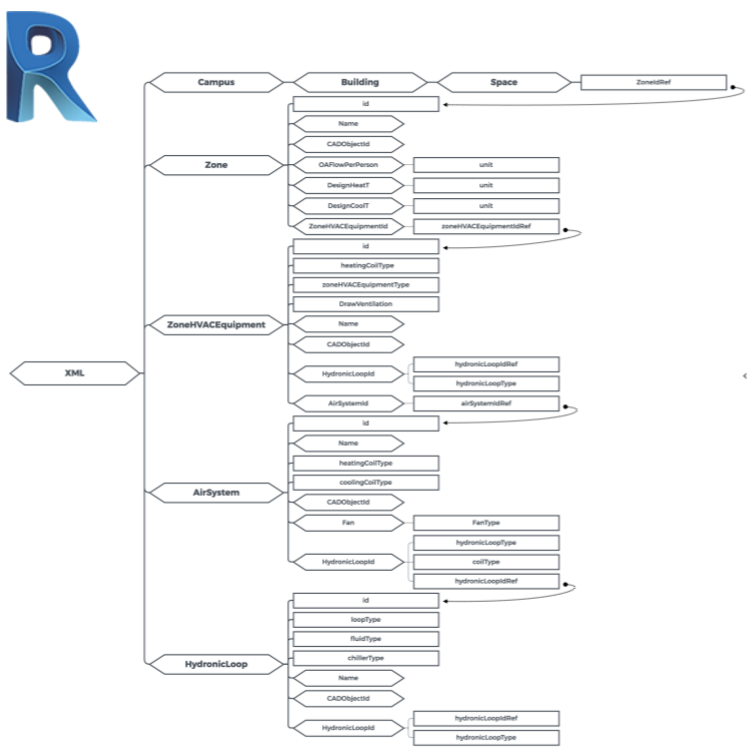
The ASHRAE system type 7 was translated from IDF data model to gbXML data model by a python script, following redefined HVAC data mapping rules. A part of the file is shown in the Figure 9.3, The HVAC systems data was then combined with exported building geometry data in gbXML file.

```
<!-- Whole Building, hot water loop -->
<HydronicLoop id="aim1111" loopType="HotWater" fluidType="Water">
  <Name>HW1</Name>
  <HydronicLoopEquipment id="aim1112" equipmentType="Boiler">
    <Name>HW1-Boiler1</Name>
    <Temp tempType="HighTempLockout">100</Temp>
    <Temp tempType="HeatDesign">82</Temp>
    <Temp tempType="Range">28</Temp>
    <Power unit="Watt" powerType="NaturalGas" useType="Heating" />
    <Efficiency efficiencyType="ThermalEff">0.8</Efficiency>
    <Control controlType="Boiler" minPowerRatio=0.0 />
  </HydronicLoopEquipment>
</HydronicLoop>
```

Figure 9.3 gbXML Representation of ASHRAE System Type 7

9.2.2 Revit2020.1 gbXML representation

The ASHRAE system type 7 was manually drawn and assigned to corresponding zones in Revit2020.1 System Analysis. At the backend, Revit added new customized elements in the XML data model. For example, as shown in Figure 9.4, the “AirSystem” element replaces “AirLoop” element in gbXML, and “ZoneHVACEquipment” element are created by Revit, using for representing “AirLoopEquipment” and “HydronicLoopEquipment”. The reason of creating the customized elements for representing HVAC systems might be same as the interoperability issues found in this study. However, the solution Revit chose is to develop a completely new schema, rather than following the mainstream rules. The XML code of the HVAC systems is shown in Figure 9.5.



Zones -> Space -> ZoneEquipment -> Air systems -> Hydronic

Figure 9.4 Revit 2020.1 XML Data Model

```xml
▼<ZoneHVACEquipment zoneHVACEquipmentType="VAVBox" DrawVentilation="False" heatingCoilType="HotWater" id="aim4751">
   <Name>VAV 29-1</Name>
   <CADObjectId>358030-1</CADObjectId>
   <AirSystemId airSystemIdRef="aim4662"/>
   <HydronicLoopId hydronicLoopIdRef="aim4633" hydronicLoopType="HotWater"/>
 </ZoneHVACEquipment>
▼<ZoneHVACEquipment zoneHVACEquipmentType="VAVBox" DrawVentilation="False" heatingCoilType="HotWater" id="aim4754">
   <Name>VAV 30-1</Name>
   <CADObjectId>358031-1</CADObjectId>
   <AirSystemId airSystemIdRef="aim4662"/>
   <HydronicLoopId hydronicLoopIdRef="aim4633" hydronicLoopType="HotWater"/>
 </ZoneHVACEquipment>
▼<AirSystem heatingCoilType="HotWater" coolingCoilType="ChilledWater" id="aim4637">
   <Name>AHU 1</Name>
   <CADObjectId>357980</CADObjectId>
   <HeatExchanger/>
   <Fan FanType="VariableVolume"/>
   <HydronicLoopId hydronicLoopIdRef="aim4633" hydronicLoopType="HotWater" coilType="Heating"/>
   <HydronicLoopId hydronicLoopIdRef="aim4635" hydronicLoopType="PrimaryChilledWater" coilType="Cooling"/>
 </AirSystem>
▼<AirSystem heatingCoilType="HotWater" coolingCoilType="ChilledWater" id="aim4642">
   <Name>AHU 2</Name>
   <CADObjectId>358002</CADObjectId>
   <HeatExchanger/>
   <Fan FanType="VariableVolume"/>
   <HydronicLoopId hydronicLoopIdRef="aim4633" hydronicLoopType="HotWater" coilType="Heating"/>
   <HydronicLoopId hydronicLoopIdRef="aim4635" hydronicLoopType="PrimaryChilledWater" coilType="Cooling"/>
 </AirSystem>
▶<AirSystem heatingCoilType="HotWater" coolingCoilType="ChilledWater" id="aim4647">...</AirSystem>
▶<AirSystem heatingCoilType="HotWater" coolingCoilType="ChilledWater" id="aim4652">...</AirSystem>
▶<AirSystem heatingCoilType="HotWater" coolingCoilType="ChilledWater" id="aim4657">...</AirSystem>
▶<AirSystem heatingCoilType="HotWater" coolingCoilType="ChilledWater" id="aim4662">...</AirSystem>
▼<HydronicLoop loopType="HotWater" fluidType="Water" id="aim4633">
   <Name>HW</Name>
   <CADObjectId>357973</CADObjectId>
 </HydronicLoop>
▼<HydronicLoop loopType="CondenserWater" fluidType="Water" id="aim4634">
   <Name>CDW</Name>
   <CADObjectId>357975</CADObjectId>
 </HydronicLoop>
▼<HydronicLoop loopType="PrimaryChilledWater" fluidType="Water" chillerType="WaterCooled" id="aim4635">
   <Name>CHW</Name>
   <CADObjectId>357974</CADObjectId>
   <HydronicLoopId hydronicLoopIdRef="aim4634" hydronicLoopType="CondenserWater"/>
 </HydronicLoop>
```


Figure 9.5 Revit 2020.1 XML Representation of ASHRAE System Type 7

9.3 Energy simulation

9.3.1 gbXML-OpenStudio-EnergyPlus

The combined gbXML file with both geometry data and HVAC system data is imported into OpenStudio through applying customized measures, using Ruby, as shown in Figure 9.6. The boiler equipment data stored in gbXML elements is parsed by the Ruby code and is assigned to different Ruby functions to build the OSW OpenStudio model.

```ruby
def add_boiler
  boiler = OpenStudio::Model::BoilerHotWater.new(self.model)
  boiler.setName("#{self.name} Boiler")
  boiler.setEfficiencyCurveTemperatureEvaluationVariable('LeavingBoiler')
  boiler.setFuelType(self.powerType)
  boiler.setDesignWaterOutletTemperature(self.design_loop_exit_temp)
  boiler.setNominalThermalEfficiency(self.thermal_efficiency)
  boiler.setMinimumPartLoadRatio(0)
  boiler.setMaximumPartLoadRatio(1.1)
  boiler.setOptimumPartLoadRatio(1)
  boiler.setWaterOutletUpperTemperatureLimit(self.upper_temp_limit)
  boiler.setBoilerFlowMode('LeavingSetpointModulated')
  boiler
end
```

Figure 9.6 Ruby Code for Customized OpenStudio Measures

The HVAC system then was translated to an OpenStudio OSW model file, as shown in Figure 9.7. As following the method of variable controlling, except the boiler design parameters, all other HVAC systems and equipment data are same as the data of the baseline mode. After manually assigning weather, schedules and other required information in OpenStudio, the OSM file can be successfully translated to an IDF file and is ready to run EnergyPlus at the backend to simulate the building energy consumption.

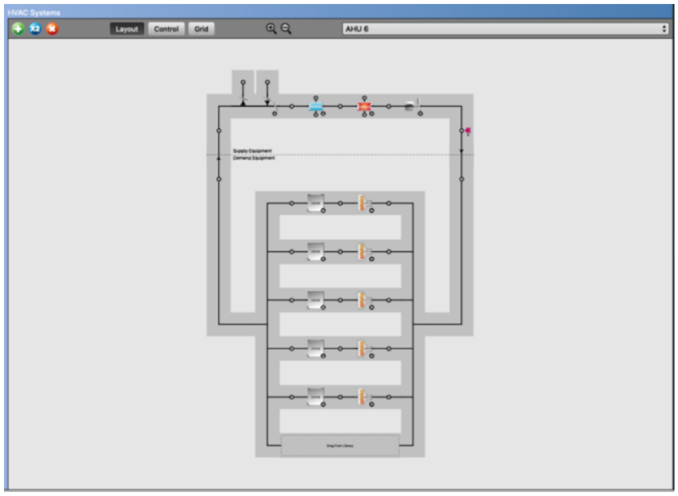


Figure 9.7 HVAC systems imported into OpenStudio

9.3.2 Revit 2020.1 System Analysis

Revit 2020.1 System Analysis follow the same workflow as explained in the last paragraph, translating its customized XML file to an OSW OpenStudio model file through applying its own customized measures. In terms of schedules and HVAC equipment details, it utilizes ideal values. Then OSW model file runs EnergyPlus to simulate the building energy consumption. The Figure 9.8 is credited by Revit2020.1 Systems Analysis webinar. It shows the workflow and customization.

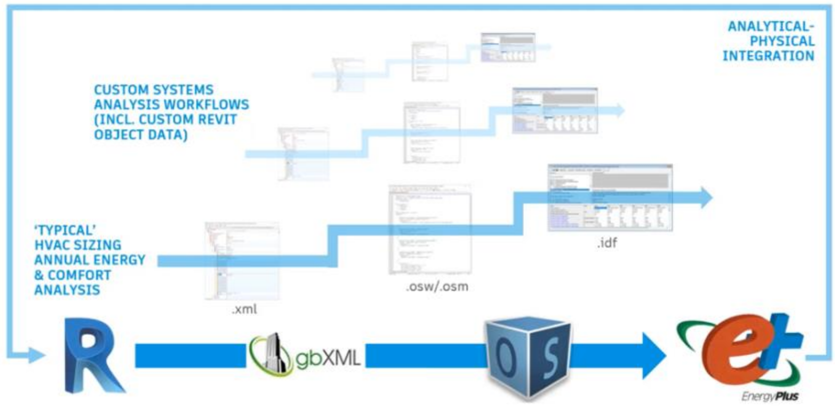


Figure 9.8 Revit 2020.1 System Analysis Workflow

9.4 Result analysis

The energy simulation result of the redefined gbXML file is supposed to be the same as the energy simulation result of the ASHARE system seven IDF model. Due to time limitations, the customized measures didn’t cover all HVAC equipment. However, the successful import of boiler data and primary HVAC systems is enough to prove the effectiveness of the redefined data mapping rules and the capability of the gbXML schema.

In addition to the gbXML data imported, detailed modification was conducted in OpenStudio, keeping same as the default values in the Revit baseline model. Finally, the simulated Energy Usage Intensity (EUI) achieves a slightly higher accuracy of the original file. Therefore, compared with Revit 2020.1 System Analysis, the BIM-HVAC-BEM method is more accurate and efficient.

9.4.1 Energy Usage Simulation

The ground truth of the total energy usage of ASHRAE standard baseline system type 7 is the direct simulation of the IDF file in EnergyPlus. It is 26089796.38 kWh. The simulation of the baseline model was conducted in Revit 2020.1 system analysis, with default values. The simulation environment is OpenStudio and EnergyPlus. The baseline energy usage is 3312437.88 kWh. Therefore, the baseline accuracy is 12.70%. The simulation of the proposed gbXML model was directly conducted in OpenStudio and EnergyPlus environment. Except the boiler data, other parameters in the proposed model are same with the default values in Revit 2020.1 System Analysis. The proposed total energy usage is 3344188.89 kWh. Therefore, the proposed accuracy is 12.82%. Though the improvement is only 0.12%, it is enough to prove that the effectiveness of the gbXML model with customized boiler data.

Site and Source Energy **26089796.38 kWh**

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	26089796.38	1003.82	1003.82
Net Site Energy	26089796.38	1003.82	1003.82
Total Source Energy	45567173.75	1753.23	1753.23
Net Source Energy	45567173.75	1753.23	1753.23

ASHRAE standard baseline system type 7

Site and Source Energy **3312437.88 kWh**

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	3312437.88	123.06	123.06
Net Site Energy	3312437.88	123.06	123.06
Total Source Energy	9987743.80	371.05	371.05
Net Source Energy	9987743.80	371.05	371.05

Revit 2020.1 xml with HVAC systems data

Site and Source Energy **3344188.89 kWh**

	Total Energy [GJ]	Energy Per Total Building Area [MJ/m2]	Energy Per Conditioned Building Area [MJ/m2]
Total Site Energy	12039.08	447.25	447.25
Net Site Energy	12039.08	447.25	447.25
Total Source Energy	36031.14	1338.56	1338.56
Net Source Energy	36031.14	1338.56	1338.56

Redefined gbXML with HVAC systems and boiler data

Figure 9.9 Total Energy Simulation Result

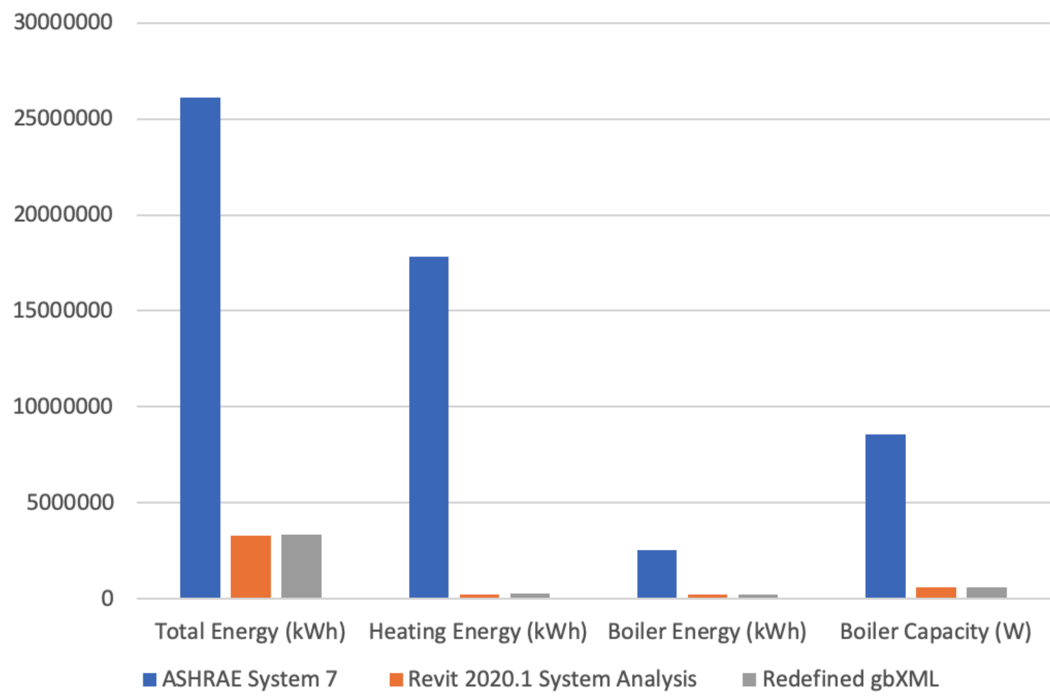


Figure 9.10 Boiler-related Energy Simulation Result Comparison

The considerable difference between the ground truth energy and the baseline model, as well as the proposed model, should be the difference of other HVAC design parameters. The slight improvement of the energy simulation accuracy might be due to the only modification of the design temperature value in the proposed model. Other critical factors, such as performance curves and optimum part load ratio, are not handled.

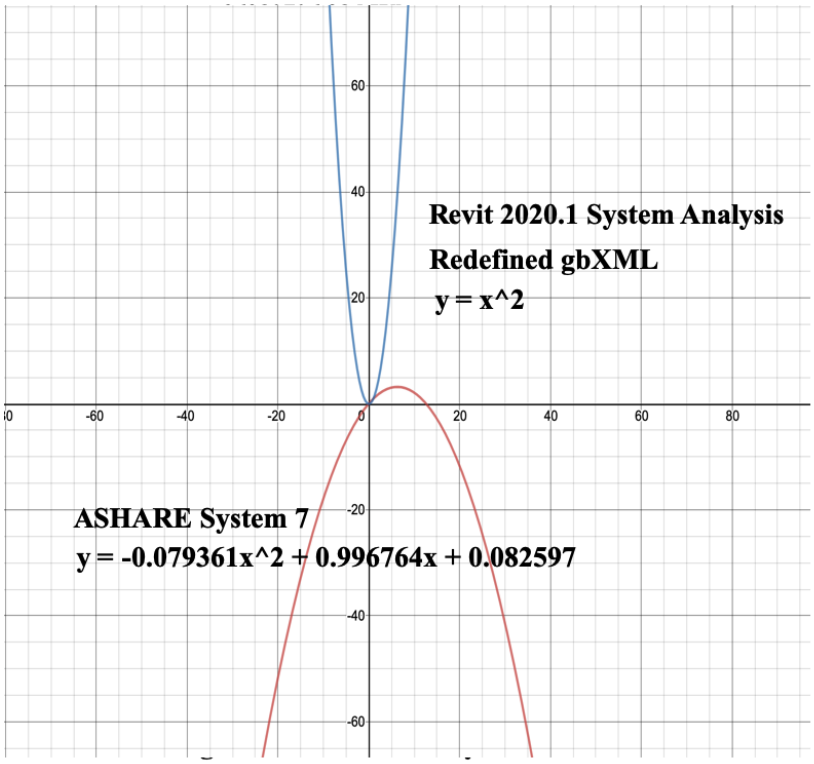


Figure 9.11 Performance Curve Comparison

9.4.2 Thermal Comfort Evaluation

The thermal comfort evaluation method is comfort not met summary based on ASHRAE 55-2004. As shown in Figure 9.12, the thermal comfort value at the same zone between the ground truth and the baseline model is significantly different. However, compared with the baseline, the proposed study has a slightly higher uncomfortable rate. This is probably due to the only variable of the boiler data. All other HVAC equipment data in the proposed model is the same as the corresponding data in the baseline model. Therefore, not until all HVAC equipment data is changed to the ground-truth value, the thermal comfort evaluation won't be accurate.

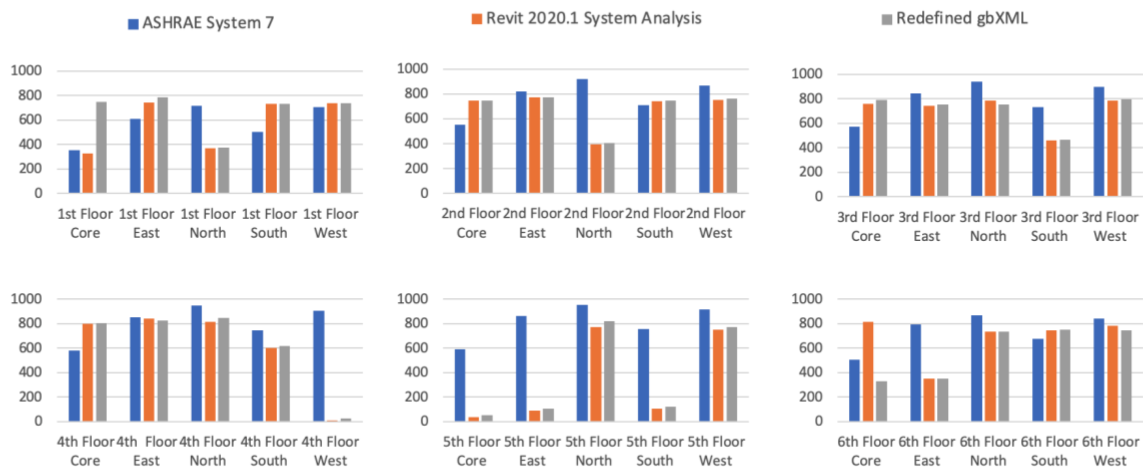


Figure 9.12 Thermal Comfort Not Met Hours

10 Conclusion

10.1 Contribution

There are three interoperability issues of current gbXML data model were found: missing components, difficulty of decoding performance curves information and complex data mapping rules.

The current gbXML schema (Version 6.01) is rarely used for HVAC systems representation mainly due to complex data mapping rules. It has been one of the most critical obstacles to gbXML interoperability improvement. Through detailed data mapping of the ASHRAE standard system type seven from the IDF model (Version 9.0) to current the gbXML schema, gbXML should be able to define HVAC systems.

The complex data mapping rules have been redefined, using four elements: “Space”, “Zone”, “AirLoop” and “HydronicLoop”. The “AirLoop” and “HydronicLoop” elements are used for primary HVAC system data. Their children elements “AirLoopEquipment” and

“HydronicLoopEquipment” are used for HVAC equipment data. “Space” can be connected to the HVAC equipment by its children elements “HydronicLoopEquipmentId” and “AirLoopEquipmentId”. “Zone” can be connected to the HVAC primary system by its children elements “HydronicLoopId” and “AirLoopId”. In terms of the other two interoperability problems: missing components and the difficulty of decoding performance curves. They could be handled as an updated schema in the future.

It is reasonable to say that Architecture, Engineering, and Construction fields are three isolated islands of knowledge. The BIM technology was invented to construct the bridge between the islands. However, the professional knowledge barrier between these fields has made lots of traffic jams on the bridge. The objective of this study is eliminating the HVAC systems roadblock and building gbXML data mapping rules as a traffic sign for communicating between architecture design and engineering performance analysis fields. In this way, we can build energy efficient, comfortable and sustainable built environments.

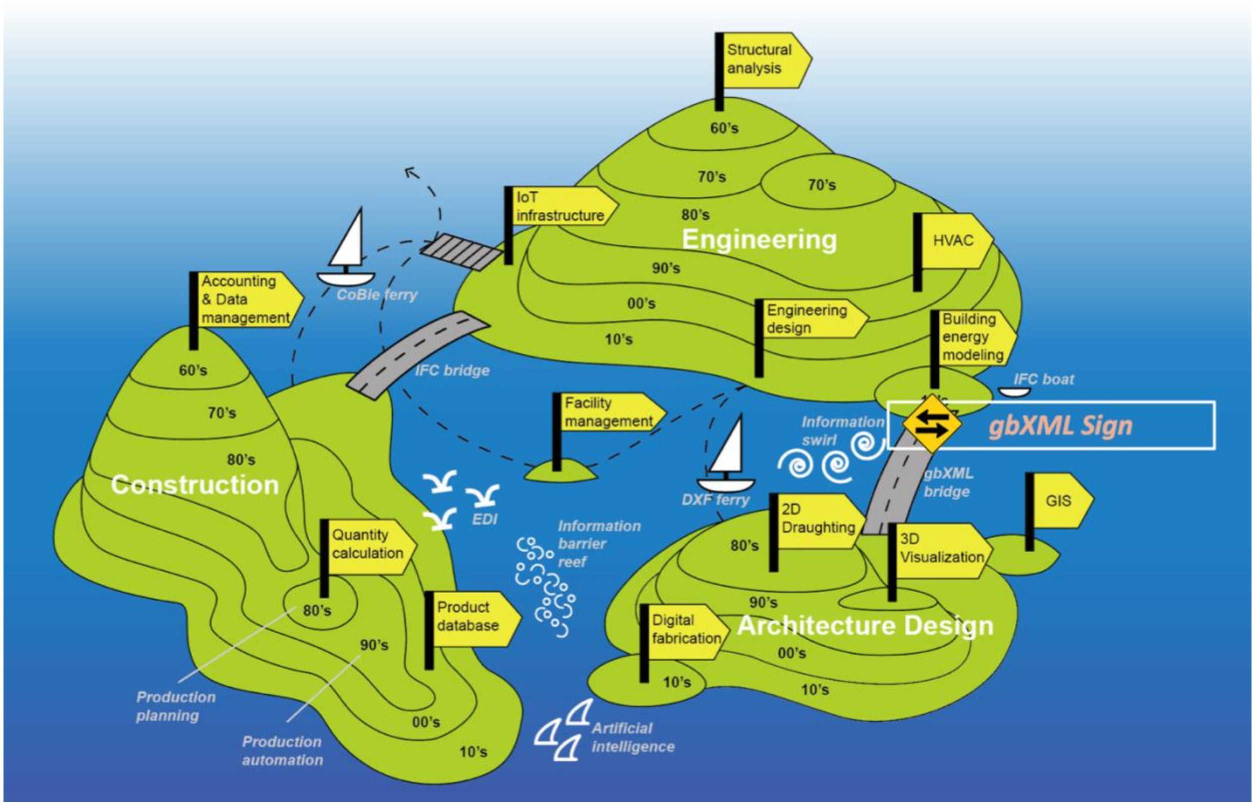


Figure 10.1 Traffic Sign for the gbXML Bridge Between Architecture and Engineering Fields

10.2 Limitation and Future Work

First of all, the redefined gbXML data mapping rules in terms of the HVAC systems is limited to current gbXML data schema, without adding new customized elements. Future work would be suggesting the gbXML director board to handle the interoperability issues found in this study for the next gbXML data model generation. Particularly, the documentation work of the data mapping rules of HVAC systems or other building systems is highly recommended based on this study result.

Secondly, the energy simulation accuracy improvement is limited due to the only variable of the boiler data, compared with the baseline model. The future work is adding performance curve data, adding missing components data from IDF to gbXML. Besides, more HVAC equipment data is supposed to be covered as a proposed study to validate the improvement of the HVAC systems data in the gbXML model.

Last but not the least, the current thermal comfort evaluation method is only unmet hours based on ASHRAE 55 due to the time limitation. Future work would be operative temperature calculation and visualization, as well as PMV values calculation and display based on energy simulation results.

Bibliography

ASHRAE, A. (2017). Standard 55-2017, Thermal comfort Conditions for Human Occupancy, ASHRAE. Atlanta.

ASHRAE handbook : fundamentals. (2013) (SI edition.). Atlanta, GA: ASHRAE.

DOE, U. (2011). 2011 Building energy data book. US Department of Energy.

Dong, B., Lam, K. P., Huang, Y. C., & Dobbs, G. M. 2007. A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments. In Tenth International IBPSA Conference (pp. 1530-1537).

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. 2011. BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. Chapter. John Wiley & Sons.

Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort. Analysis and applications in environmental engineering.

Fathy, H. (2010). Architecture for the Poor An Experiment in Rural Egypt. Chicago: University of Chicago Press.

gbXML Current Schema 2017. http://www.gbxml.org/Schema_Current_GreenBuildingXML_gbXML

Gokcen, N., & Reddy, R. (1996). Thermodynamics (Second Edition.). https://doi.org/10.1007/978-1-4899-1373-9

Huizenga, C., Abbaszadeh, S., Zagreus, L., & Arens, E. A. (2006). Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey.

Kingma, B., & van Marken Lichtenbelt, W. (2015). Energy consumption in buildings and female thermal demand. Nature climate change, 5(12), 1054.

Karmann, C., Schiavon, S., & Bauman, F. (2017). Thermal comfort in buildings using radiant vs. all-air systems: A critical literature review. Building and Environment, 111, 123-131.

KielMoe, Insulating Modernism Isolated and Non-Isolated Thermodynamics inArchitecture [M] Berlin: Birkhäuser, 2014.

Malchaire, J., ALFANO, F. R. D. A., & Palella, B. I. (2017). Evaluation of the metabolic rate based on the recording of the heart rate. Industrial health, 55(3), 219-232.

McDowall, R. 2007. Fundamentals of HVAC systems, SI edition. Chapter 5, Zones. Academic Press.

McGraw Hill. 2009. The business value of BIM: Getting building information modeling to the bottom line. Smart Market Report (2009): 1-50.

Moon, H. J., Choi, M. S., Kim, S. K., & Ryu, S. H. 2011. Case studies for the evaluation of interoperability between a BIM based architectural model and building performance analysis programs. In Proceedings of 12th conference of international building performance simulation association (Vol. 2011).

Malchaire, J., ALFANO, F. R. D. A., & Palella, B. I. (2017). Evaluation of the metabolic rate based on the recording of the heart rate. Industrial health, 55(3), 219-232.

Wendy K. (2015, Aug.). Here's Why Your Office May be Too Hot or Cold: Gender Bias. National Geography https://www.nationalgeographic.com/news/energy/2015/08/150803-gender-bias-affects-office-heating-cooling-temperatures/#close

Parsons, Ken. Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort, and performance. CRC press, 2014.

Pérez-Lombard, Luis, José Ortiz, and Christine Pout (2008). "A review on buildings energy consumption information". In: Energy and buildings 40.3, pp. 394–398.

Samet, Jonathan M., and John D. Spengler. "Indoor environments and health: moving into the 21st century." American Journal of Public Health 93.9 (2003): 1489-1493.

Seyam, Shaimaa. 2018. Types of HVAC Systems. In HVAC System. IntechOpen.

W3Schools Online Web Tutorials. 2017. https://www.w3schools.com/

Xu, W., Chong, A. & Lam, K. P. 2019. A new BIM to BEM framework: the development and verification of an open-Source gbXML to EnergyPlus translator for supporting building life cycle performance analysis. In building simulation 2019 conference.

Zhang, Z., Chong, A., Pan, Y., Zhang, C., Lu, S., & Lam, K. P. (2018, September). A deep reinforcement learning approach to using whole building energy model for hvac optimal control. In 2018 Building Performance Analysis Conference and SimBuild.