SimBuild 2024

Eleventh National Conference of IBPSA-USA
Denver, Colorado
May 21 – 23, 2024

Building Information Modeling-Based Building Energy Modeling: Assessment of Workflows and Tools

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Abstract

Integration of Building Information Modeling (BIM) and Building Energy Modeling (BEM) has potential to provide streamlined and accurate building energy predictions, steering architects towards sustainable building design. Yet, integration and interoperability between BIM and BEM tools pose major challenges to the Architecture, Engineering, and Construction (AEC) industry. In this research, BEM tools from three categories of BIM-integrated (Systems Analysis and Sefaira), BIM-interoperable (IDA ICE and GBS), and BIM-separated (eQUEST) BEM tools were investigated. The study evaluated BEM tools' interoperability and integration with BIM, as well as accuracy in predicting buildings' energy use. The study showed that despite the substantial BIM to BEM improvements, further developments on BIM-BEM integration and interoperability are necessary. If achieved, new developments could result in fully integrated and collaborative workflows.

Introduction

Over the last decade, buildings' energy consumption has been increasing, driven by higher energy demands for buildings' operation and rising population (Kelso 2012). Nevertheless, by implementing energy efficiency targets and strategies during the building design, construction, and operation, the energy consumption of the buildings can be improved. In this regard, application of Building Information Modeling (BIM) for Building Energy Modeling (BEM) is particularly appropriate for the early design stages, where energy-efficient design strategies can be explored.

The transition from the conventional design process to the Integrated Design Process (IDP) allows for the implementation of energy modeling and analysis at the early design stages. However, to provide well-implemented energy-efficient design strategies, it is critical that the building performance analysis is integrated into the digital design process. In recent years, BIM-based BEM has become a prevalent topic in both research and industry, which is mostly due to the improvements it has made to the conventional, tedious, and costly method of energy modeling (Gao et al. 2019). BIM to BEM workflow does not yet benefit from a continuous and seamless exchange of information between the digital modeling software applications. For instance, BEM information, which is already available in BIM, must be manually re-entered as inputs (Gao et al. 2019). This makes the building performance analysis a time-consuming, costly, and labor-intensive task.

The goal of this research study was to investigate various whole building energy analysis tools to evaluate their workflow and integration with BIM. Analysis programs from three categories of BIM-integrated, BIM-interoperable, and BIM-separated BEM tools were selected, aiming to evaluate design-analysis workflows. In addition, to test the accuracy of each analysis tool in providing energy consumption data, simulation results were compared against the actual energy usage data. Case studies were selected to represent different building types, located on the campus of the University of Massachusetts Amherst (UMass Amherst). The building types included three categories of academic, administrative, and recreational buildings.

Background and Previous Work

Building Information Modeling

Building Information Modeling (BIM) was introduced as a multi-dimensional or n-D modeling process in a study focusing on building lifecycle management (Gourlis and Kovacic 2017). The n-D modeling referred to 3D to 7D BIM classifications. 3D BIM represented a parametric object-oriented model, which had an upgrade compared to a 2D CAD plan. 4D BIM included the addition of the construction schedule. 5D BIM addressed cost estimation. 6D BIM is concerned with thermal analysis and environmental assessment. 7D BIM, as a fully mature model, included facility management, maintenance, and operation (Gourlis and Kovacic 2017). Interoperability between BIM and BEM provides a platform to transform building information into a data format used for energy simulations. Seamless data transformation results in a common understanding of the model being exchanged between BIM and BEM, meaning that all critical information is being exchanged (Gao et al. 2019; Steel et al. 2012). However, so far, a reliable BEM-model is only obtained after manual modifications and pre-processing work on the BIM-model, which is considered time-consuming and error-prone (Kim et al. 2015). The root cause of the need for manual modifications is the non-interoperability and incongruity of information stored in BIM and BEM tools (Gao et al. 2019).

Over the past few years, there has been a lot of research within the academic community focusing on limitations and opportunities for data exchange methods. The two current mainstream developments in data exchange methods include Industry Foundation Classes (IFC) and Green Building XML (gbXLM)-based approaches. IFC is an ISO-certified data format, which was first developed by the International Association for Interoperability (IAI) in 1996, and it is now administered by the buildingSMART alliance (Gao et al. 2019). It is an open object-oriented format for data exchange that provides a universal basis for information sharing. IFC schema is used for data exchange among multi-disciplinary team members, aiming to comprehensively represent an entire building project (Dong et al. 2007; Bazjanac and Crawley 1997). IFC schema cannot represent complex schedules and advanced HVAC systems (Pinheiro et al. 2016).

gbXML schema was developed by Green Building Studio (Gao et al. 2019). It is based on the Extensible Markup Language (XML) format, used for storage and transmission of text data both on and off the Green Building Studio web service (Lam et al. 2012; Karola et al. 2002). The main application of gbXML is for building energy simulation, facilitating data sharing between BIM and energy analysis tools (Gao et al. 2019). Compared to IFC, gbXML-based methods are further developed for transferring geometry, material, and space type information. However, gbXML schema only accepts rectangular shapes (Gao et al. 2019; Gourlis and Kovacic 2017).

A study of the current developments on interoperability between BIM and BEM tools found that none of the IFC and gbXML schemas are yet fully developed, providing seamless data exchange between BIM and BEM tools. IFC format mostly provides only geometry and material data exchange between BIM and BEM, while other information is set as default or inserted manually in BEM tools. Even for geometry data, there might be some issues, such as missing objects, duplicated surfaces, and mismatched boundaries. Material data transformation includes extraction of materials' names/IDs and layers, but not their thermal properties. This is because material databases included within BIM tools are different from BEM tools (Hitchcock and Wong 2011). Therefore, external databases are used to provide thermal properties of the material transformed from BIM to BEM.

Overall, the gbXML data format has a better performance than the IFC schema. Most of the gbXML-based data exchange methods provide geometry, material, and thermal zone information sharing. However, manual repair for geometry for large-scale buildings may be needed. Also, some of the gbXML-based methods use simplified material properties, external databases, and/or default information. Furthermore, preparing the room/space sets and/or aggregating spaces/rooms into thermal zones are considered tedious (Gao et al. 2019).

Overview of the Research Study

The objectives of this research work were (i) to explore and evaluate design-analysis workflows, integration, and data sharing mechanisms, and (ii) to evaluate several BEM tools and their capabilities in precisely simulating whole building energy use. Research questions that were addressed in this research are:

- What data sharing format between BIM and BEM tools provides a more robust interoperability capability and workflow?
- How accurate are the existing BEM tools in simulating/predicting building energy data?
- Do BEM tools provide the same level of accuracy in predicting/simulating various aspects of energy data, from a broader lens (i.e., energy usage intensity) to a more specific one (i.e., end-use)?

For the purpose of this research and the necessity of comparing simulated energy data against the actual energy consumption data, three existing buildings, all located at the University of Massachusetts Amherst (UMass Amherst), were selected as case studies. The reason for the selection of on-campus buildings as case studies was the accessibility of information, including buildings' documentation, specifications, and energy data. The case study buildings were selected from various categories, including academic (library), administrative (health services), and recreational buildings, aiming to investigate different building typologies. The limitations of the study are that all investigated case studies are in one climate (heating-dominated), and only three buildings were utilized in the study.

Case Study Buildings

W.E.B. Du Bois Library was built in 1972 and is shown in Figure 1. It has an area of 406,480 ft^2, including library-related spaces, such as book storage, computer laboratories, offices, collaborative, and meeting spaces.

Figure 1 Du Bois library from the east-view.

University Health Services building was originally built in 1962, with an area of 35,088 ft^2. In 1973, additional spaces on its west and south sides were added to the building, resulting in a total area of 58,506 ft^2. In this study, energy data of the total building area is considered. University Health Services is shown in Figure 2.

Figure 2 UHS building from the west-view.

Recreation Center (RC) was built in 2009 and is shown in Figure 3. It is a gymnasium-type building, with an area of 160,191 ft^2 of recreational courts, sport spaces, and offices.

Figure 3 RC building from the south-view.

Energy Data Collection and Calibration

The UMass Amherst's Central Heating Plant (CHP) produces district-level steam, providing heating and domestic hot water for buildings. The UMass Facilities and Campus Services track the energy consumption of all campus buildings. For the purpose of this study, each case study building's primary energy data (i.e., monthly steam and electricity) was collected from the UMass Amherst Facilities & Campus Services' reports (Small 2018). It is noteworthy that it was not possible to make an assessment about the level of accuracy in tracking and recording campus buildings' energy data. Therefore, it is acknowledged that the raw energy data may not be completely accurate and representative of the actual energy consumption of the case study buildings, given the many factors involved in the process of measuring and reporting their energy data.

The primary energy data was then regulated (from fiscal year to calendar year) and calibrated (i.e., weather-normalized), as reviewed in the following sections. The primary energy data was a collection of fiscal years' energy data, starting from July of the previous year to June of the following year. In this research study, fiscal years 2016 to 2019 were the time span of the collected energy data, covering July 2015 through June 2019.

The reason for this time limit was, firstly, the availability of energy data, which determined the upper time limit being fiscal year 2019. Secondly, access to calendar years' weather data through UMass Computer Science Weather Station, dictating the lower time span to be the calendar year 2016 (UMass Amherst Computer Science 2020).

Next, fiscal years' energy data was regulated to calendar years' energy data. The reason for this regulation was the fact that energy simulations and analysis studies are conducted based on calendar years, making fiscal years inapplicable to building performance studies. To make data regulation for the fiscal year 2016, only energy usage from January 2016 to December 2016 was considered, eliminating data from July 2015 to December 2015. The same procedure was applied to fiscal years 2017, 2018, and 2019 energy data, as shown in Figure 4. This provided monthly energy data of each case study building for three successive calendar years (2016 to 2018).

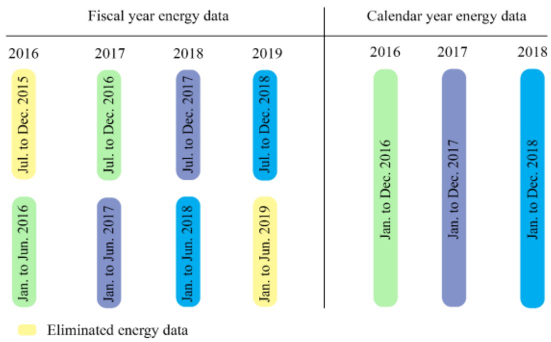

Figure 4 Fiscal years to calendar year energy data.

The main criterion in selecting the three specific case study buildings was to execute research studies on buildings whose energy data was significantly impacted by weather conditions, which proved weather-normalization as an applicable method for energy data calibration. Data calibration provided a breakdown of the raw energy data, which otherwise was solely an indicator of the total gas and electricity usage for each case study building. Here, energy data was broken into weather-driven loads (e.g., heating and cooling loads) and non-weather sensitive loads (e.g., hot water, equipment, lighting, etc.), which will be reviewed in the following section.

In this method energy data for the year 2018 was selected and weather-normalized for the purpose of energy simulations and analysis. Weather-normalization of the energy data removed the effect of weather conditions on energy data, by eliminating the impact of deviance in dry-bulb temperature on energy consumption.

One critical criterion to evaluate the applicability of the weather-normalization method was the correlation of energy data with degree-days, presented in the regression analyses (Farid Mohajer and Aksamija 2021a). In the regression analysis of each case study building, monthly energy data (i.e., gas or electricity) of the years 2016 to 2018 were plotted against the monthly degree-days (i.e., heating or cooling degree-days) of the same years, evaluating the impacts of outside temperature on buildings' energy usage.

Regression models represented the best coefficient of determination (R^2) between dependent and independent variables. R^2 in the scatter plot of energy vs. degree-days variable represented percentage of variation in energy data caused by the variability of degree-days. It also reflected the goodness of fit test ("good" R^2) in the regression models (Chung, Hui, and Lam 2006). One shortcoming of the regression method was that it only considered dry-bulb temperature, ignoring other climatic factors that can influence energy performance. These factors include insolation, humidity, and wind speed (Eto 1988).

In addition, depending on buildings' space loads, climate impact could be less influential, making the linear regression method not applicable for energy data normalization in internally driven buildings, such as research laboratory buildings (Farid Mohajer and Aksamija 2021b).

For the case study buildings where linear regression was the surrogate for all influences, climatic or otherwise, on energy use, a satisfying coefficient of determination was considered to be equal to or higher than 0.73 (Lee 2008). Here, weather normalization was used for adjusting the energy data. Energy usage regression models that correlated monthly energy consumption with monthly degree-days are shown in Equation 1, where "*a*" was the non-weather-driven loads (i.e., hot water, lighting, equipment, etc.), "*b*" was Btus/DDs of weather-driven component (i.e., heating or cooling load), and "*x*" was regression coefficient (HDD or CDD) (Makhmalbaf, Srivastava, and Wang 2013).

$$Monthly\ energy\ usage = a + bx \tag{1}$$

For the case study buildings where weather normalization was an applicable method for data calibration, energy data of the year 2018 was used. First, the Typical Metered Year's (TMY_3) HDDs/CDDs of the closest weather station, located in Chicopee Massachusetts, were collected (EnergyPlus 2020).

Using the calculated TMY_3's DDs removed the effect of one specific year's weather condition on the case study building's energy data. Considering the given values of the fitting function (Equation 1) and the TMY_3's DDs, weather-normalized energy data (i.e., gas or electricity consumption) for each case study building was calculated, which then was used to conclude weather-normalized Energy Usage Intensity (EUI). EUI is the total annual energy consumed (in thousand British Thermal Units or kBtu) per gross square footage of the case study building.

Regression analysis divided the case study buildings into two categories, where (i) both gas and electricity were impacted by weather conditions or (ii) only gas was significantly influenced by weather conditions, while electricity consumption was driven by other factors.

For the latter, the average energy data for the three successive years (2016 to 2018) was used. The reason for using average data was to prevent the potential unpredicted weather circumstances or metering errors of a specific year to impact the data, as the meters may infrequently go off or become inaccurate. Here, the average monthly and annual energy usage, for each case study building, was the data used in the energy comparison and simulations analysis. Unlike the data calibration method, which provided energy data breakdowns using regression models, average data only presented total energy consumption that was used to calculate the adjusted EUI (i.e., total of weather-normalized gas and average electricity usage per building area).

BIM and BEM Tools

In this study, a predominant architectural 3D modeling tool (i.e., Autodesk Revit) was used as a BIM platform. For the purpose of whole building energy analysis, six BEM tools encompassing three categories of BIM-integrated (i.e., Systems Analysis, Sefaira, and Insight), BIM-interoperable (IDA ICE and GBS), and BIM-separated (eQUEST) software programs were investigated.

To address the first research question regarding the capabilities of different data exchange mechanisms, two different data sharing file formats (IFC and gbXML) were investigated. To address the second and third research questions, regarding the accuracy of BEM tools in predicting building energy data, simulation results were compared against each other and the actual data. The results were evaluated in three layers, capturing broad to more specific levels of energy data (i.e., EUI, energy and end-use data). The assessments that were made based on the research findings were then used to address the fourth question and suggest how to make the simulation process less time-consuming and labor-intensive. In Figure 5, BEM tools, their engine, and data transfer formats are shown.

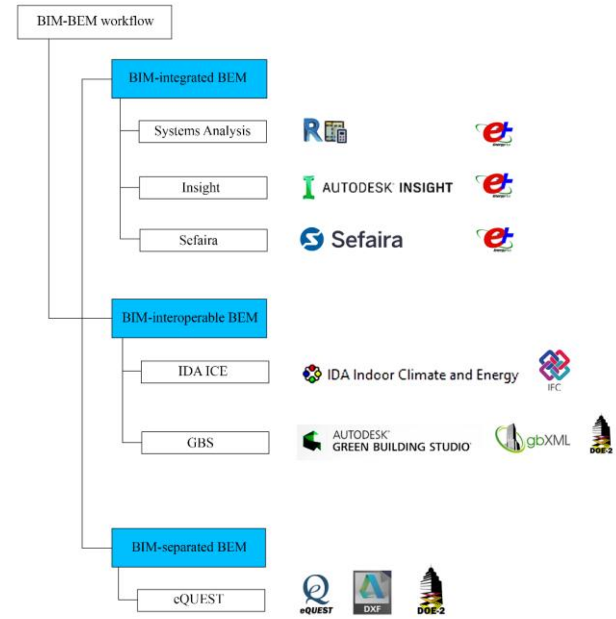

Figure 5 BEM tools, engines, and data schemas.

In Figure 6, the research study framework and methodologies are shown.

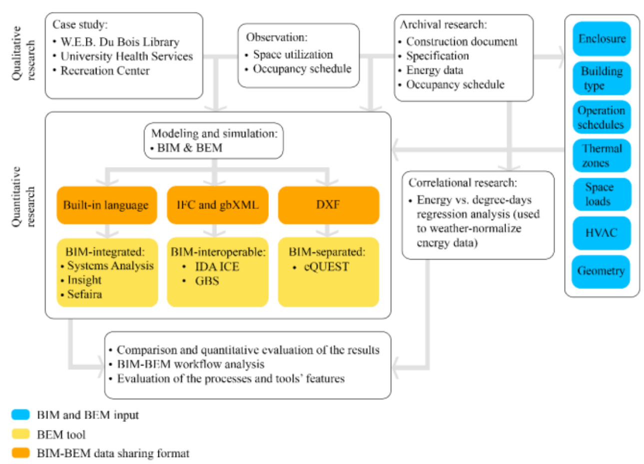

Figure 6 Research study and methodologies.

Simulations

For each case study building, regression analysis of the monthly energy data vs. monthly degree-days is reviewed, which is followed by assessing the applicability of the energy data weather-normalization method. Next, building characteristics that were used as inputs to develop the BEM-models for each case study building are discussed. Lastly, BEM-models that were developed using the selected BEM tools and simulation results are presented.

W.E.B. Du Bois Library was one of the two case study buildings where its scatter plots of monthly energy data on monthly degree-days indicated a strong correlation between weather conditions and energy consumption. Du Bois Library's regression scatter plots of gas vs. heating degree-days and electricity vs. cooling degree-days are shown in Figure 7.

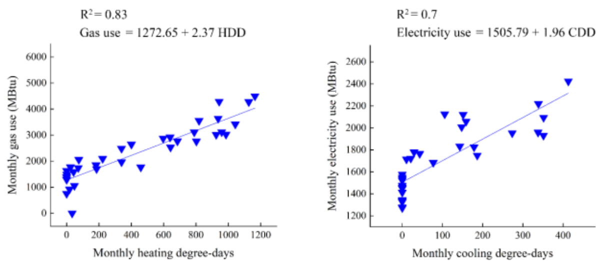

Figure 7 Du Bois library regression plots.

Based on the regression scatter plots, the linear fitting functions used in weather normalizing Du Bois building's monthly energy data were determined, as shown in Figure 7. Using Du Bois Library fitting function, weather-normalized energy data and Energy Usage Intensity (EUI) of the year 2018 were calculated. In Figure 8, BIM to BEM inputs for Du Bois Library, including BIM-model developed in Autodesk Revit are shown.

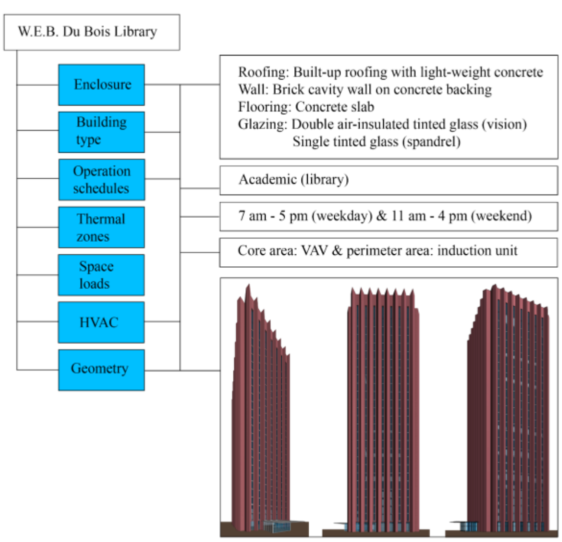

Figure 8 Du Bois BIM to BEM inputs.

University Health Services (UHS) showed a strong correlation between weather conditions and energy consumption. UHS' regression scatter plots of gas vs. heating degree-days and electricity vs. cooling degree-days are shown in Figure 9.

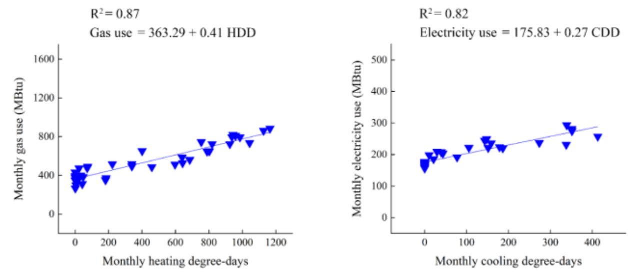

Figure 9 UHS regression plots.

Linear fitting functions used in the weather normalization of UHS's monthly energy data are shown in Figure 9. Using UHS fitting function, weather-normalized energy data and EUI of the year 2018 were calculated. BIM to BEM inputs for UHS case study building, including the BIM-model that was developed in Autodesk Revit are shown in Figure 10.

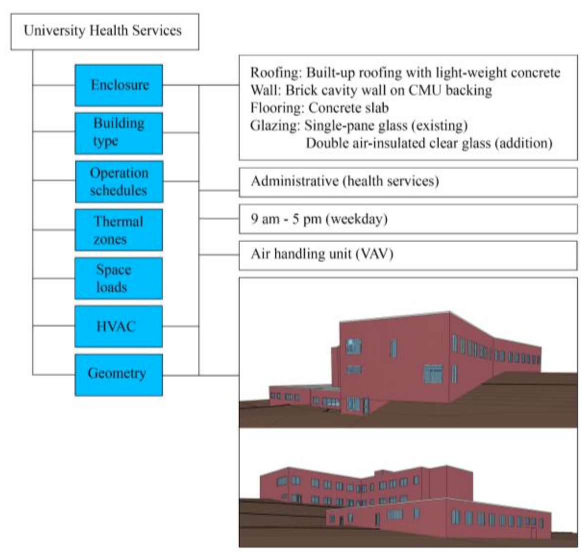

Figure 10 UHS building BIM to BEM inputs.

Recreation Center (RC) is another case study building where regression of monthly gas use on heating degree-days showed the significance of weather condition impact on energy data, as shown in Figure 11. However, regression of electricity on cooling degree-days did not indicate a strong correlation between the independent and dependent variables (low R^2), meaning that normalization of energy data based on the weather was not applicable .

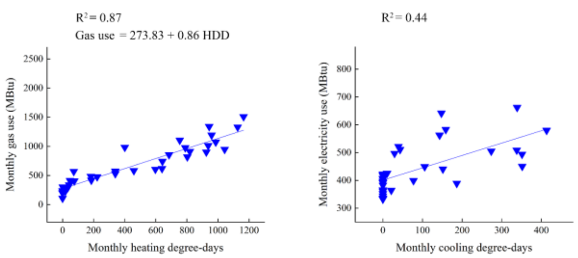

Figure 11 RC building regression plots.

Based on the scatter plot of gas consumption in this case study building, the linear fitting function used in weather normalizing RC's monthly energy data was determined, as shown in Figure 11. Using this fitting function, weather-normalized gas data for the year 2018 was calculated. Here, electricity data was averaged, using the data for three successive years (2016 to 18) and adjusted annual energy data and EUI were calculated. In Figure 12, BIM to BEM inputs for Recreation Center case study building are shown.

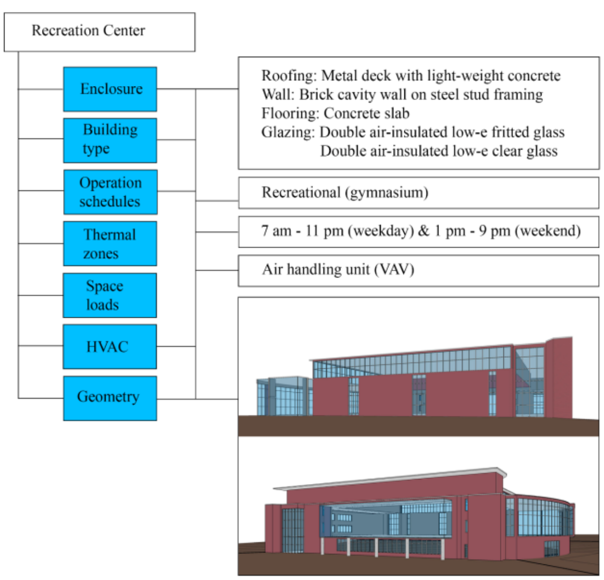

Figure 12 RC BIM to BEM inputs.

Discussion and Analysis of Results

In the following sections, case study buildings' simulation results and their comparative analysis against the actual and predicted data are presented. Case study buildings' simulated energy data are assessed in three layers, approaching energy data evaluation from a broader lens (i.e., EUI comparison) to a more specific perspective (i.e., energy and end-use data). The three-layered structure presents a multi-angle understanding of the BEM tools' capability in predicting energy data, where the accuracy of the tools differs based on the type of energy data analysis. Energy Usage Intensity (EUI) evaluation intends to comparatively analyze the capability of the BEM tools in calculating building area and annual total energy consumption. For the purpose of EUI comparison, the actual EUI of each case study building was considered as the baseline, and the simulated EUIs were compared against it. Here, the baseline building area was considered to be the area of BIM-models rather than the actual buildings' area. The reason for this consideration was to evaluate BIM-integrated and BIM-interoperable BEM tools in reading and interpreting the BIM-model's spaces. To make the area of the BEM-models comparable, the ones that were developed in a BIM-separated BEM tool (i.e., eQUEST models) had a similar building area as their BIM-model. In Figures 13 to 15, building area and EUI comparisons are illustrated. Here, the percentage of deviation from the baseline EUI (i.e., actual EUI) and baseline area (i.e., BIM-model's area) are shown, capturing the increases or decreases in the simulation data.

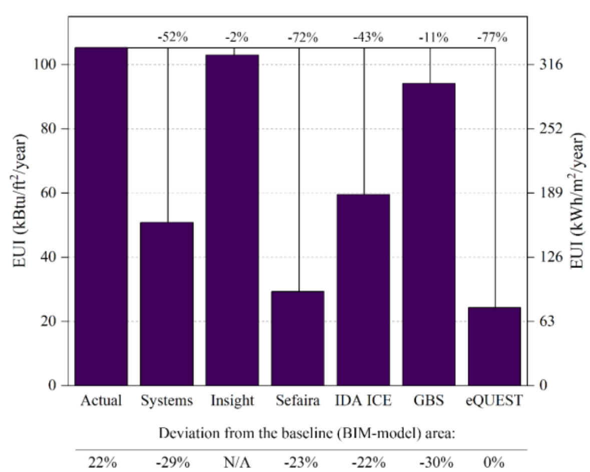

Figure 13 EUI deviation percentage for Du Bois.

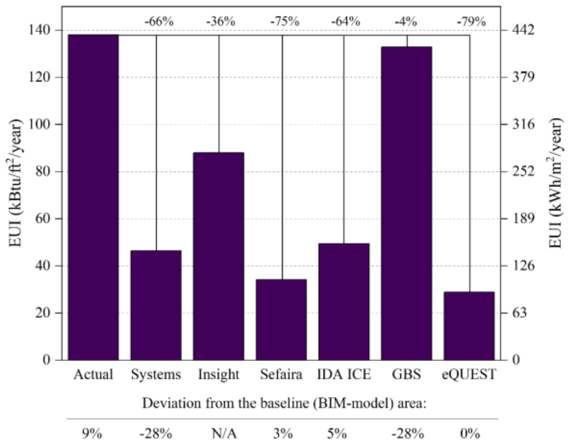

Figure 14 EUI deviation percentage for UHS.

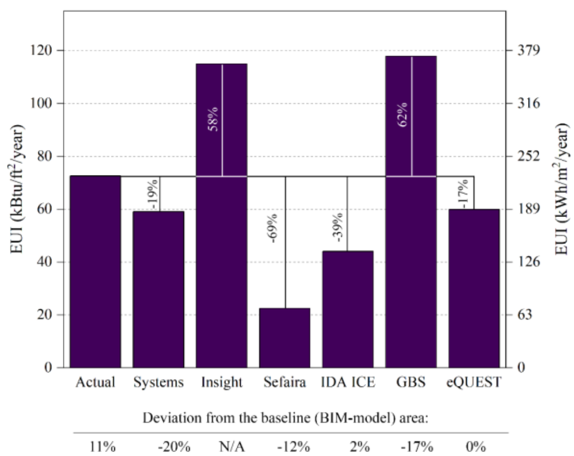

Figure 15 EUI deviation percentage for RC.

In Figure 16, EUI deviations from the baseline for all the case study buildings are shown. These values are presented as absolute values to compare the EUIs regardless of their increase or decrease from the baseline.

As shown, in all three case study buildings, Sefaira had one of the highest EUI deviations. For Du Bois and UHS case study buildings, the trend of absolute-value deviations was the same, with the lowest for Insight, followed by GBS, IDA ICE, Systems Analysis (shown as Systems), Sefaira, and eQUEST. For RC, except for the highest EUI deviation that was for Sefaira, the trend was almost the opposite of the other two case study buildings. Here, the lowest absolute-value deviation was for eQUEST, followed by Systems Analysis, IDA ICE, Insight, GBS, and Sefaira.

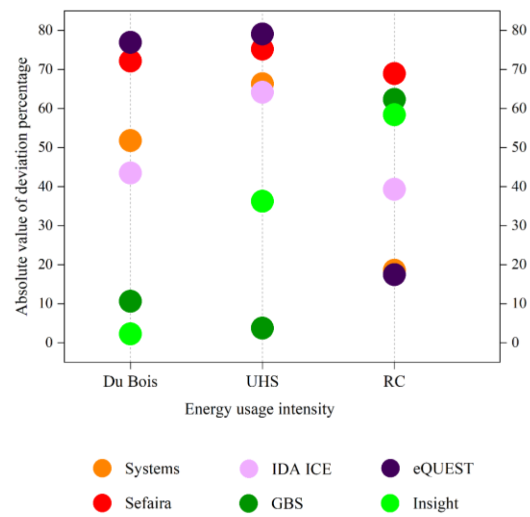

Figure 16 Absolute values of EUI deviation percentages.

EUI comparisons showed that EUI calculations in BEM tools can differ based on the building functionality. It is also influenced by the capability of the BEM tools in reading the BIM-models. As shown in Figures 13 to 15, building area in almost all of the BEM models, including Systems Analysis and Sefaira (i.e., BIM-integrated BEM) and GBS and IDA ICE (i.e., BIM-interoperable BEM) had a negative deviation from the baseline area. The exceptions were UHS and RC's IDA ICE models, where deviations were positive, which will be further discussed in the following sections.

In Figure 17, absolute value of deviation percentages for the total annual energy use (i.e., total electricity and gas) in all three case study buildings are shown. These values are presented in absolute values to recap the BEM tools' capability in simulating/predicting energy use data, regardless of increase or decrease in energy use. Based on the absolute value of deviations, concluding remarks are as follows:

- In the category of BIM-interoperable BEM tools, GBS prediction of total annual electricity use was more accurate than IDA ICE.
- BIM-interoperable and BIM-separated (i.e., GBS, IDA ICE, and eQUEST) were more accurate in predicting annual gas consumption, compared to BIM-integrated tools (i.e., Systems Analysis and Sefaira).
- In BIM-integrated BEM category, Systems Analysis was more accurate than Sefaira in simulating annual gas consumption.

- Altogether, BEM tools indicated a lower absolute value of deviation in electricity use, compared to gas use data.

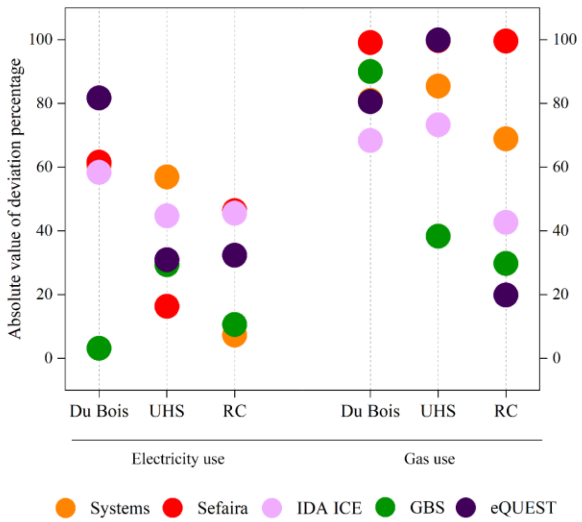

Figure 17 Absolute value of annual energy use deviations.

In Figures 18 to 20, annual end-use data for all the case study buildings, and their end-use deviation from the baseline data are shown. Deviation percentages of the end-use data from the baseline indicated that BIM-integrated BEM tools (i.e., Systems Analysis and Sefaira) and a BIM-interoperable BEM tool (i.e., GBS) had the lowest deviations from the baseline in the lighting and equipment load predictions. On the other hand, a BIM-separated BEM tool (i.e., eQUEST) and a BIM-interoperable BEM tool (i.e., IDA ICE) indicated the highest percentage of deviation in lighting and equipment load simulation. For fans and pumps load prediction, GBS and Sefaira were still among the lowest deviations, while Systems Analysis for Du Bois Library and UHS case study buildings had the highest percentage of deviation. In this category of end-use data, IDA ICE and eQUEST presented medium to maximum deviations from the baseline.

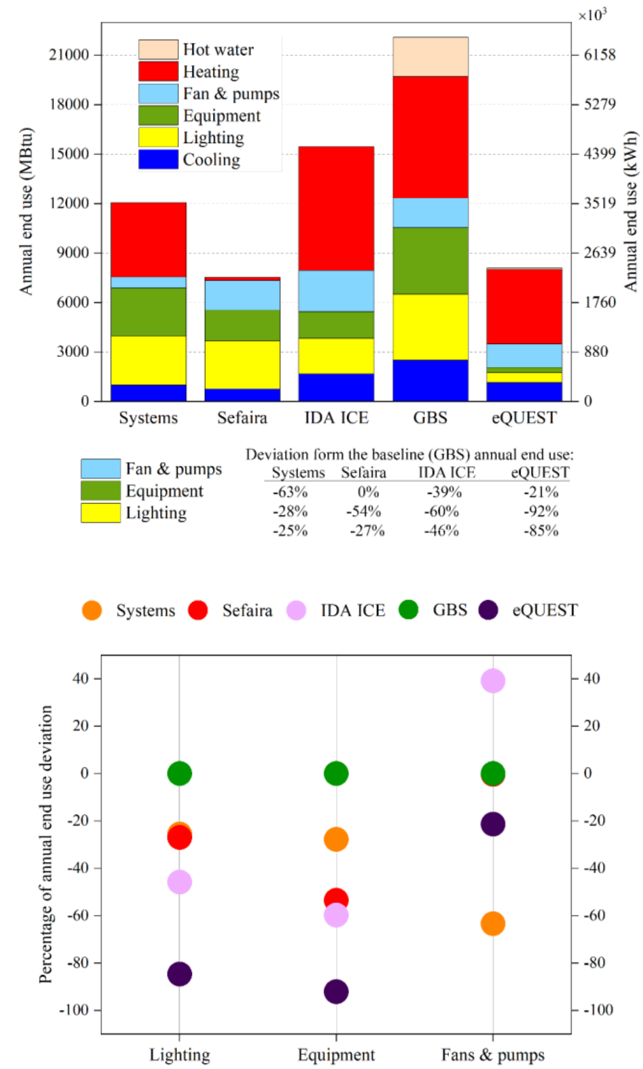

Figure 18 Annual end-use deviations in Du Bois library.

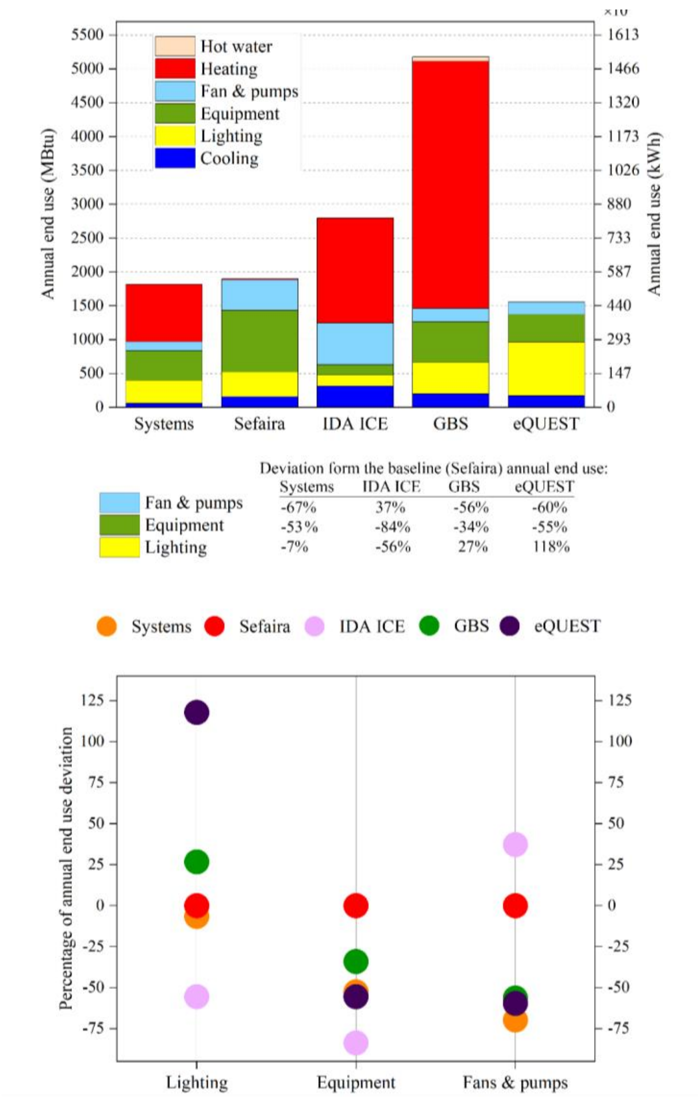

Figure 19 Annual end-use deviations in UHS building.

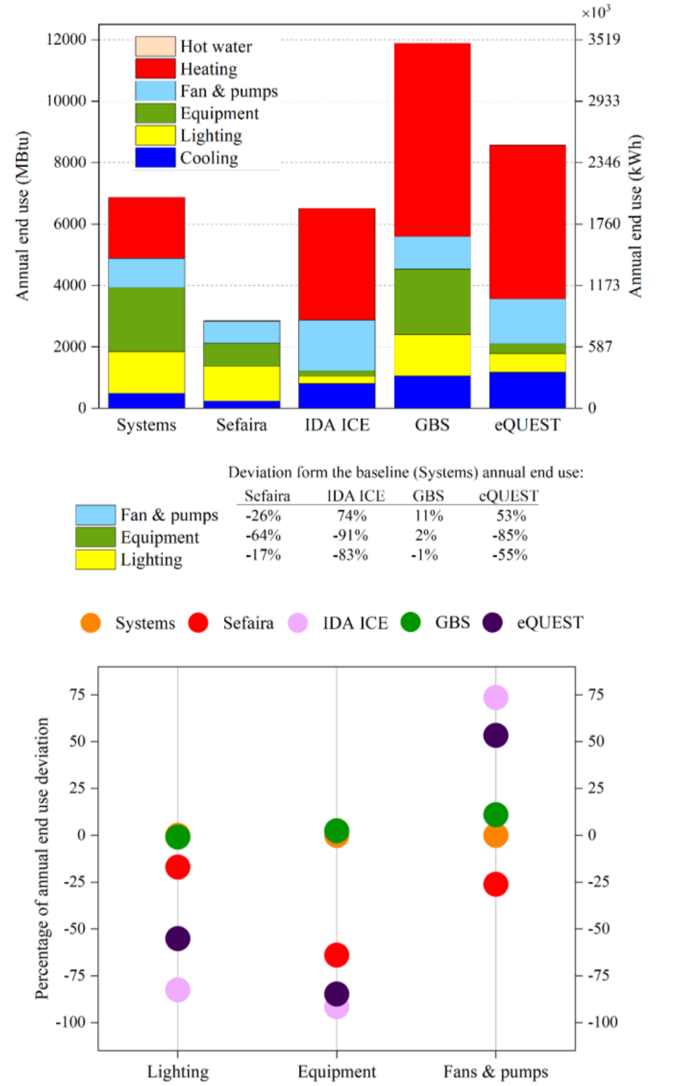

Figure 20 Annual end-use deviations in RC building.

In Figure 21, the absolute value of annual end-use deviation for all the case study buildings are shown.

These values are presented in absolute values to visualize how accurate were the BEM tools in simulating/predicting end-use data, and where results were clustered and/or scattered. Based on the absolute value of deviations, concluding remarks are as follows:

- In the category of electricity-based end-use data, BIM-integrated BEM tools (i.e., Systems Analysis and Sefaira) and BIM-interoperable BEM (i.e., GBS) were more clustered and less deviated, compared to BIM-separated and

BIM-interoperable (i.e., eQUEST and IDA ICE, respectively) that were more scattered and deviated.

- In the category of gas-based end-use data, a BIM-interoperable BEM tool (IDA ICE) presented less deviated and more scattered end-use data, specifically for heating loads. It is then followed by BIM-integrated BEM (Systems Analysis), which had the second lowest deviation in gas-based end-use data for two of the case study buildings.

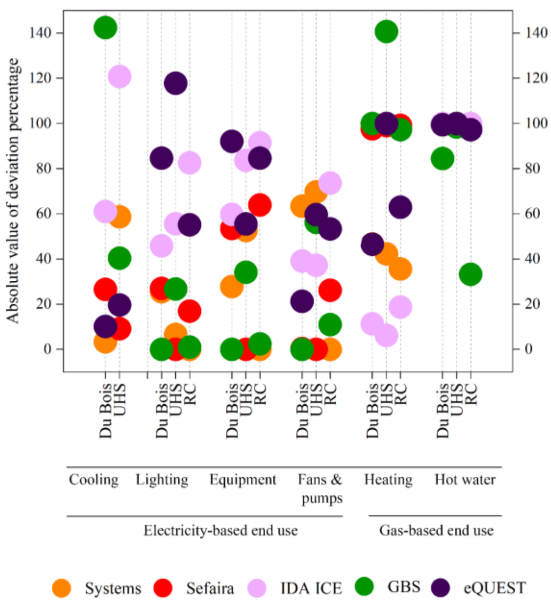

Figure 21 Absolute value of annual end-use deviations in all the case study buildings.

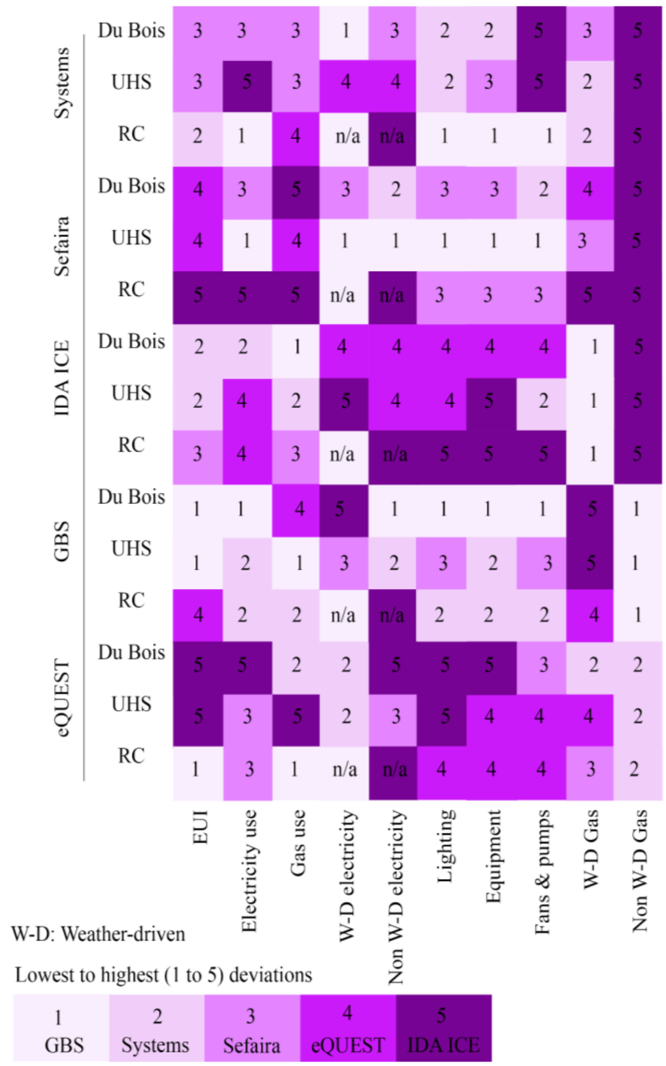

Figure 22 BEM tools deviation rating in a 3-layer structure (EUI, energy and end-use).

In Figure 22, BEM tools are rated from 1 to 5, based on their deviations from the baseline data. Here, a three-layered structure of energy data assessment is utilized, including EUI, energy, and end-use. As shown, BIM-interoperable BEM tools were on the opposite sides of the spectrum, where GBS was rated with the lowest and IDA ICE with the highest overall deviations, considering all layers of the energy consumption information. BIM-integrated BEM tools (i.e., Systems Analysis and Sefaira) were respectively rated the second and third, followed by a BIM-separated BEM tool (i.e., eQUEST) rated the fourth.

BIM and BEM Workflows

BIM to BEM workflows discussion is divided into six categories, based on the type of BEM tools. In each category, the workflow that was implemented/encountered in the energy performance analysis of all the case study buildings is discussed. BIM to BEM workflows indicated both similarities and uniqueness, depending on the case study buildings' characteristics (i.e., typology and geometry). Additionally, BEM tools' capability/limitation to (i) provide the users with a list of building functionality to choose from and (ii) interpret the BIM-models to create the analytical surfaces and spaces are discussed.

BIM to Systems Analysis Workflow

Systems Analysis, as a BIM built-in application, allows users to utilize the BIM/Revit environment to create a BEM-model. The BEM-model that is generated using Systems-Analysis includes: (i) analytical spaces (i.e., discrete volumes of air that gain/lose heat from/to one another), and (ii) analytical surfaces (i.e., the path of heat transfer between the analytical spaces). The steps are to specify the geographic location of the building, and other parameters that were used to create the BEM-model (i.e., building type, schedule, etc.). Next, areas of the building that will be served by a specific HVAC system are defined using "System-Zone".

One capability of Systems Analysis BEM tool is that it allows users to define more than one mechanical system, which for Du Bois Library case study building was beneficial. Here, both systems (i.e., air handling unit with a variable air volume system, and a fan coil for the induction unit) were defined as building equipment.

Systems Analysis was not able to read and properly interpret Du Bois Library's BIM-model when it included a basement courtyard. And, without providing an error message, it terminated the analysis, and no report was generated. Here, after applying iterative changes to the BIM-model's geometry, and running the simulation after each change, it was found out that the basement courtyard was the issue. Therefore, the entire basement level was excluded from the Du Bois Library's BIM-model and BEM-models.

Another consideration for Systems Analysis was its capability to read the spaces within the BIM-models. As such, building area of all the case study buildings' BEM-model was smaller than that of their BIM-model. As previously shown in Figures 13 to 15, BEM-models of Du Bois Library, UHS, and RC were respectively 29%, 28%, and 20% smaller than their BIM-models. Additionally, an outpatient building was not provided as a typology in Systems Analysis. In the case of the library and gymnasium buildings (Du Bois Library and RC), it was not an issue. However, for UHS case study building, since outpatient building typology was not an option, the closest one (i.e., Office building) was assigned to the BEM-model. Both area calculation and building typology have an impact on building energy consumption, and therefore they can skew the predicted results if not appropriately defined in the simulations.

BIM to Sefaira Workflow

Sefaira allows users to run the analysis both internally, within the BIM/Revit environment, and externally. If used internally within Revit, it only allows users to adjust the BEM inputs through a "Real Time Analysis" slider, where no specific values can be assigned. For the purpose of this study, Sefaira's web application, as an external platform, was utilized to assign certain input values.

One consideration for Sefaira is its capability to read the spaces within the BIM-model. As such, building area of BEM-models was either bigger or smaller than that of the BIM-models in all the case study buildings. As previously illustrated in Figures 13 to 15, the area of Du Bois Library, UHS, and RC's BEM-model was respectively -23%, +3%, and -12% deviated from that of their BIM-model. Furthermore, Sefaira provided a limited list of building/zone typologies. For instance, since Library was not available, for Du Bois Library case study building Office was selected. Similarly, in RC case study building, instead of the gymnasium, School was selected, as the closest option that was available.

For UHS case study building, Sefaira was not able to appropriately interpret building geometry on the second and third floors, where flooring in the BIM-model included both exterior and interior surfaces. Sefaira assigned both flooring systems as interior surfaces on different levels, rather than interior and exterior floors on the same level.

BIM to Insight Workflow

BIM to Insight did not provide detailed information that can be used for the purpose of workflow assessment. Therefore, in this study, only the predicted EUI that was presented within an EUI range was used for the comparative analysis of the energy data.

BIM to IDA ICE Workflow

IDA ICE uses IFC input data to create BEM-models by converting BIM spaces to IDA ICE zones. In Du Bois Library, UHS, and RC case study buildings, IFC data sharing format transferred both building zones and envelope properties. However, it did not transfer information pertaining to glazing, opening, and shading surfaces, which were later added to the BEM-model within the IDA ICE environment. Since IDA ICE is an object-oriented BEM tool, it allows users to simultaneously monitor the changes in real-time, while adding the glazing systems/openings to the model.

One consideration for IDA ICE is that with complicated building geometries it cannot identify exterior and interior surfaces. Therefore, "Building Body", which should represent exterior surfaces of the building model, may mistakenly consider exterior surfaces as interior ones. In Du Bois Library, due to the simple and cubic building geometry, the "Building Body" was correctly interpreted by IDA ICE. However, in UHS and RC case study buildings some portions of the buildings that are exterior surfaces were assigned as interior ones, because they were inside the "Building Body".

One capability of IDA ICE is that it allows users to define properties of the thermal zone, pertaining to their internal loads and HVAC systems, rather than providing a list of building typologies. Therefore, for Du Bois Library case study building, it was possible to represent its two mechanical systems (i.e., air handling unit and induction unit). Building area deviation between the BEM-models and BIM-models, for Du Bois Library, UHS, and RC case study buildings were -22%, 5%, and 2%, respectively, as shown in Figures 13 to 15. The negative deviation in the case of Du Bois Library indicates that IFC data transfer did not accurately share information pertaining to building spaces/zones. However, for UHS and RC case study buildings, since building geometries were more complicated and IDA ICE assigned a larger "Building Body" to the BEM-models, the area deviations were less and positive.

BIM to GBS Workflow

GBS provided smooth gbXML data transfer from the BIM-models to GBS web application. It also provided a comprehensive list of building typologies, from which Library, Healthcare Clinic, and Gymnasium were selected respectively for Du Bois Library, UHS, and RC case study buildings. Within the GBS web application, there are two platforms to access the simulation results: Classic and Project Solon. In the Classic view, GBS does not provide monthly energy data in the generated BEM report. Rather, it indicates what percentage of the annual energy use is used for various end-use sectors. In the Project Solon view, there are Widgets that can be used to access more detailed information, such as monthly heating and cooling loads.

The area of BEM-models in GBS were smaller than that of the BIM-models. As previously shown in Figures 13 to 15, BEM-models of Du Bois Library, UHS, and RC were respectively -30%, -28%, and -17% deviated from the baseline area.

BIM to eQUEST Workflow

eQUEST BEM-model development procedure, compared to the other five BEM tools, was more tedious. Here, building geometry is directly developed in eQUEST, which for the RC case study building with a more complicated and curved geometry was more time-consuming. Additionally, eQUEST is not an object-oriented tool, where changes in the wizard can automatically reflect on the BEM-model. Therefore, it requires users to click a few times (minimum of three times) to close the wizard windows and give the software some time to process until the changes are incorporated into the model. If additional changes and edits are needed, this process will be repeated, until the BEM-model's geometry is satisfying.

eQUEST provides the users with a relatively comprehensive list of building typologies. However, the Library type of building is not included in that list. Therefore, for Du Bois Library case study building the closest option (School/College) was selected. UHS and RC case study buildings were assigned as Health/Medical Clinic and Health/Fitness Center, respectively.

Conclusion

Interoperability between BIM to BEM has substantially improved in the last decade. These developments have enabled users to define more parameters within BIM that impact building energy performance. However, further developments are needed to continue improving interoperability and workflows between BIM and BEM tools. These future developments should address the following issues:

- Space and zone types data within the BIM-model should be automatically transferred to the BEM-models, rather than requiring manual input of data or assignment of one thermal zone per space.
- Interoperability schemas need to be developed to store and transfer all the details incorporated in the BIM-model, such as shading and glazing information.
- Various building typologies should be incorporated into the list of buildings and/or space functionalities to resemble buildings' internal loads and space more closely.
- Simulation procedures and calculation algorithms of all the BEM tools should be further developed to capture and predict energy performance of the buildings more accurately.
- BEM tools' capabilities should be extended, enabling them to model complex building geometries, as building form influences buildings' area and performance simulation/prediction. Additionally, the need

for manual repair of the BEM-model after BIM to BEM data transfer should be eliminated.

- BEM tools should be object-oriented to help decrease the modeling and processing times.
- Possibility of integrating Algorithm-Aided Design (ADD) to improve modeling capabilities.

References

Bazjanac, Vladimir, and Drury B. Crawley. 1997. The Implementation of Industry Foundation Classes, Simulation Tools for the Building Industry, Lawrence Berkeley National Laboratory.

Dong, Bing, Khee Poh Lam, Y.C. Huang, and G.M. Dobbs. 2007. A Comparative Study of the IFC and gbXML Informational Infrastructures for Data Exchange, Computational Design Support Environments. Tenth International IBPSA Conference 3: 1530–37.

Farid Mohajer, Mahsa, and Ajla Aksamija. 2021a. "Comparison of Energy Usage Intensity in Higher-Education Buildings: Benchmarking Actual Case Study Buildings vs. CBECS Baselines." Architectural Research Center Consortium Conference Proceeding: 119-126.

Farid Mohajer, Mahsa, and Ajla Aksamija. 2021b. "Impacts of Building Function on Normalized-Steam Consumption: Analysis of Floor Area Normalization vs. Linear Regression on Heating Degree-Days in Heating-Dominated Climate." Journal of Green Building: 73-85.

Gao, Hao, Christian Koch, and Yupeng Wu. 2019. Building Information Modelling Based Building Energy Modelling: A Review. Applied Energy 238 (September 2018): 320–43. https://doi.org/10.1016/j.apenergy.2019.01.032.

Gourlis, Georgios, and Iva Kovacic. 2017. Building Information Modelling for Analysis of Energy Ef Fi Cient Industrial Buildings – A Case Study. Renewable and Sustainable Energy Reviews 68: 953–63. https://doi.org/10.1016/j.rser.2016.02.009.

Hitchcock, Robert J., and Justin Wong. 2011. Transforming IFC Architectural View BIMs for Energy Simulation. Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association: 1089–95.

Pinheiro, Sergio V., James; O'Donnell, Reinhard Wimmer, Vladimir Bazjanac, Sergej Muhic, Tobias Maile, Jerome Frisch, and Christoph van Treeck. 2016. Model View Definition for Advanced Building Energy Performance Simulation, CESBP/BauSIM 2016 Conference: 383–90.

Steel, Jim, Robin Drogemuller, and Bianca Toth. 2012. Model Interoperability in Building Information Modelling. Software and Systems Modeling 11 (1): 99–109. https://doi.org/10.1007/s10270-010-0178-4.