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Understanding the Integration of Building Energy Modeling into the Building Design Process: Insights from Two Collaborative Construction Projects

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Abstract: This research investigates the integration of building energy modeling (BEM) within collaborative construction projects to inform design decisions for achieving high-energy performance goals. The study aims to understand current practices, benefits, and challenges associated with this integration. Using an ethnographic case study approach focused on two high-energy performance social housing projects with integrated project delivery and integrated design processes, data were collected through direct observations, document analysis, and interviews with project team members. Design process modeling was utilized to dissect current practices, followed by a hybrid inductive and deductive thematic analysis to find challenges related to energy performance design in collaborative projects. Findings from this research revealed that BEM experts often operate in isolation, with late integration of energy models into design decisions. Compliance-centric BEM usage and challenges related to interoperability of design and BEM tools further compound the issue of seamless collaboration. However, the study highlights that early collaboration among project stakeholders emerges as a pivotal factor in informed design decisions, bridging the gap between energy modeling and design. This research provides valuable insights for practitioners seeking to optimize BEM in their design process, and offers support to policymakers aiming to enhance the role of BEM in projects.

Keywords: building energy modeling; design decision-making; energy performance gap; sustainable building design; integrated design process; integrated project delivery; collaborative design

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1. Introduction

The building sector is responsible for almost 30–39% of global energy consumption and 27–38% of global greenhouse gas (GHG) emissions [1,2]. This is while there is an urgent need for new energy efficient buildings as the world's population and urbanization continue to grow [3]. Therefore, there is a significant urgency and at the same time opportunity to enhance energy efficiency and lower GHG emissions in the building sector. In response to this demand, various policies, standards, and certifications have been developed to set targets for energy consumption during the design of new buildings to promote building energy efficiency [4,5]. However, energy performance gaps (EPGs) by the time buildings reach the operations phase show that achieving high levels of energy efficiency in buildings is often challenging [5–8]. The EPG represents the difference between the designed building energy performance and the actual energy consumption of the building when it is in operation. According to several studies [5,9–11], this gap can reach two-to-five times the designed energy performance, impeding the achievement of energy efficiency goals. Understanding EPG is crucial to ensuring that buildings contribute meaningfully to global climate targets.

Mitigating EPG offers environmental and economic benefits by providing a realistic perspective on energy reduction potential, improving energy efficiency, and ultimately reducing emissions and operational costs. It is crucial to give careful consideration to the design phase to effectively address the EPG root causes, as the foundation of the entire project is formed in the design phase [5]. More particularly during the design phase, according to several studies [5,12–14], ineffective communication and collaboration among building energy modeling (BEM) experts and other stakeholders on energy performance design decision-making is the most important root cause of EPG. Ineffective communication and collaboration can lead to additional causes of EPG including inaccurate assumptions, oversimplification of the energy model, inadequately defined design constraints, and incomplete data. BEM, essential for predicting a building's energy performance, relies on accurate information and well-defined parameters, which can be compromised by these issues. Therefore, effective stakeholder communication and collaboration are critical, as their outcomes directly inform BEM inputs, impacting the reliability of performance predictions and the ability to achieve optimized energy efficiency.

One of the most effective strategies to address such ineffective communication and collaboration among BEM experts and key stakeholders during the design phase is adopting collaborative design and delivery methods [8,15–17]. However, such strategies are not tailored to specifically improve the collaboration among BEM experts and other stakeholders [15,16] to better mitigate EPG during the design phase.

The main research objective of this study is to better understand the energy performance design practices in collaborative projects, with a specific emphasis on the integration of BEM to attain high-energy performance goals. More specifically, this research aims to:

- Investigate the processes of the current energy performance design practices in collaborative projects, and to better understand the role of BEM activities within design activities, tools used in different activities, and interactions among BEM experts and other stakeholders.
- Identify the benefits and challenges of energy performance design practices in collaborative projects, with a particular focus on the integration of BEM during the design phase to achieve high-energy performance goals.

To address the research objective, the researchers adopted an ethnographic case study research methodology to investigate two social housing projects, one applying the integrated project delivery (IPD) method, and the other applying the integrated design process (IDP) with high-energy performance goals. One of them adheres to the Passive House (PH) standard, while the other aligns with the British Columbia (BC) Energy Step Code, a regional standard specific to BC. This ethnographic study was conducted by attending and observing the project meetings and reviewing project-related documents, such as energy modeling reports, technical drawings and specifications, and meeting minutes. Initially, the researchers used design process modeling to uncover activities and their sequences, design changes, stakeholder interaction and tool utilization. This modeling revealed information gaps, prompting additional data collection via semi-structured interviews with the project design team. These interviews offered deeper insights into the design process models. Finally, all the collected data were subjected to a hybrid approach of inductive and deductive thematic analysis. This comprehensive analysis led to the benefits and challenges inherent in decision-making practices related to energy performance design within collaborative construction projects striving for high-energy performance. Researchers compared findings with existing literature, thereby adding an additional layer of validation.

This study presents a unique opportunity for conducting an ethnographic study, allowing the collection of data from ongoing projects for in-depth analysis. It provides a distinctive chance to investigate design process models, specifically focusing on BEM integration within collaborative construction projects. Moreover, this ethnographic study contributes to identifying genuine challenges faced within the construction industry, particularly in the context of BEM integration into the design process. Additionally, it contributes to investigating communication and collaboration in integrating BEM into the design process within collaborative projects. Ultimately, this research seeks to gain insights into whether there is a tendency among stakeholders to optimize the energy performance of buildings.

Section 2 presents the literature review. The methodology used in this research is described in Section 3. Design process models of the two case studies are outlined in Section 4, and the benefits and challenges are introduced in Section 5. The conclusion and possible future work are presented in Section 6.

2. Literature Review

During the design phase, BEM serves the purpose of predicting the energy consumption of a building during its operational phase. Its primary objective is to assess whether the design complies with energy performance goals and design objectives, enabling the identification of potential areas for improvement. The energy performance goals and design objectives for projects are sometimes not aligned with the actual performance of a building after occupancy. Salehi et al.'s investigation [18] on the Centre for Interactive Research on Sustainability (CIRS) building at the University of British Columbia (UBC) in Canada is a prime example of this gap. The CIRS building was awarded LEED Platinum certification, but during its initial year of operation, it utilized about 60% more energy than what the energy model had anticipated during the design phase. There were some issues that contributed to the EPG of CIRS building, with one of them being the failure of its heat exchange system. This system was a key component of the CIRS energy performance strategy, designed to transfer heat to an adjacent building. The failure was primarily attributed to poor communication and collaboration during decision-making in the design process [19]. Making more informed design decisions needs the effective integration of BEM and project stakeholders during the decision-making process. High levels of contribution require working with collaborative methods while having high-energy performance goals. Improving the performance-driven design process in collaborative construction projects entails understanding the current process and its benefits and challenges. Since collaborative methods are relatively new, there is not much literature about them. Therefore, researchers included all challenges in integrating BEM during the design phase and challenges that hinder the realization of energy efficiency goals, irrespective of the delivery methods. Challenges can be categorized into three main themes as adapted from the work of Staub-French and Khanzode [20]: process-related, tools-related, and organization-related challenges. These three themes are interconnected and impact the effectiveness and efficiency of the overall process. Each of these areas is discussed below.

Process-related challenges in BEM: The accuracy and reliability of information can be compromised during the process of gathering, transferring, and assimilating information [6,21]. Even with advancements in information technology, achieving complete information integrity is challenging due to difficulties in collecting complete information [6], incomplete design details [22], and lack of key energy performance information from manufacturers [23]. Poor communication and collaboration can further impact information integrity, leading to building EPGs [6].

Poor communication has been mentioned as one of the most important causes of EPG [5]. Xu et al. [24] indicated the potential of collaboration to fix building energy performance issues by the most critical stakeholders, including designers, commissioning agents, and manufacturers, through a social network model. To increase collaboration, they suggested five strategies, such as increasing awareness of the role of collaboration in building energy management and providing collaboration subsidies. Zou and Alam [8] proposed a framework to close the EPG through collaboration among key energy stakeholders. To effectively implement this framework, they recommended: all stakeholders must have the motivation to participate in closing EPG; consistent terminology should be used in the prediction model and building management system; prediction models should be regularly updated; and knowledge should be seamlessly transferred between stakeholders.

Zou et al. [25] showed the dynamics of collaboration between designers and contractors through evolutionary game theory. The findings indicate that the most effective approach to encourage collaboration is by simultaneously reducing the costs associated with collaboration, increasing the benefits of collaboration, and minimizing the losses resulting from a lack of collaboration. Echeverria-Valiente et al. [15] examined the effect of improving collaboration through integrated design strategies on anticipated energy demand. They identified seven features of energy-efficient buildings and evaluated their implementation in two case studies in south-central Chile. The integrated design strategies resulted in over 50% reduction in energy demand.

Terim Cavka et al. [19] specifically investigated how decisions made during the design phase of a project can contribute to the EPG. Their analysis showed that the poor performance of the heat recovery system for the CIRS building was related to inaccurate assumptions of neighboring building performance for design decision-making. The study highlighted the effect of decision-making during the design phase on actual building performance. According to previous research, three things are important to investigate in order to close the EPG at the design phase: (1) methods that can improve communication among stakeholders; (2) effective tools that can promote collaboration; and (3) impacts of communication and tools on EPG. Understanding the current decision-making criteria and stakeholder interactions [5,13,26] and determining communication breakdowns would help shape the required collaboration to close the EPG [27].

Tool (energy simulation)-related challenges in BEM: There are two types of energy-consumption analysis techniques: forward modeling, which uses algorithms to estimate the impact of selected systems on the building's energy use, and inverse modeling, which uses data-driven methods relying on detailed metering and monitoring data of the building. Regarding forward modeling, there are three factors that may contribute to a performance gap in energy modeling: capabilities and limitations of building energy analysis tools [28], the use of realistic weather [29,30] and occupancy data [22,31], and the level of detail in the model's information [32]. In general, regarding capabilities and limitations of BEM tools, there are three approaches to computing energy usage: dynamic, steady-state, and quasi steady-state. The steady-state and quasi steady-state methods calculate the heat balance over a sufficiently long period (like a month or year) while disregarding stored and released heat. Meanwhile, any dynamic effects are accounted for by using empirically determined gains and loss utilization factors [33]. According to Kotarela et al. [34], the quasi steady-state methods tend to overestimate the energy consumption of buildings when compared to dynamic methods. In terms of detail, experience can improve the level of detail in the model, but time is limited in the design process. To make the energy modeling process more efficient, it is recommended that modelers use existing embedded information in the design authoring process instead of developing new models. However, there is a current gap in information-communication technology support for energy-efficient design due to the lack of interoperability between energy analysis and building design tools [35,36], which directs attention to the BIM–BEM research area.

Energy simulation tools are not user-friendly for architects and are overly complicated for them to use [37,38]. Academic tools are often more specialized in terms of data transfer and optimization, whereas commercial tools are better integrated and have a user-friendly interface that allows for visualization of building geometries, design options, and analysis results, but may have limitations in certain decision support functions like uncertainty analysis. Collaboration between academia and technology providers is crucial to develop user-friendly tools that can effectively support decision-making processes in industry [39].

Recent studies have proposed using data-driven methods to create more robust and precise models for predicting building energy consumption [40–42]. However, creating predictive models is challenging due to the need for sufficient historical operational building data, which can be difficult to collect due to time and measurement device limitations [43].

Organization-related challenges in BEM: The unclear responsibility among project stakeholders is one of the most impactful issues contributing to EPG of buildings [17]. A survey carried out in Australia, India, the US, and the UK, showed that the majority of architects did not view building performance simulation as their responsibility [44]. Insurance limitations, fee structures, and contractual constraints are some of the obstacles that may impede architects from fully assuming such responsibilities in an architectural practice [45].

Another aspect of organization-related matters is policies, guidelines and standards. While building energy efficiency standards that only consider building design have limitations in promising energy savings, an outcome-based compliance path can be added to the existing standards to ensure actual energy savings [46,47]. This approach addresses the issue of not knowing whether design decisions result in energy savings once a building is occupied. Moreover, policymakers are advised to take into account the actual energy usage of buildings while setting targets, as this will increase the likelihood of the measures implemented to achieve the targets being successful [48].

Lack of knowledge and experience is one of the EPG causes [24,49] which can lead to unsound design choices [50]. Imam et al. [51] introduced the modelling literacy of design teams as a contributor to the EPG in building design. The study found that a significant proportion of building modelers lacked modeling literacy, leading to suboptimal design choices, and suggested a need for improved building physics education in both industry and universities to close the performance gap.

In many challenges, there is a clear lack of effective communication and collaboration between energy modelers and other stakeholders.

3. Methodology

To better understand how BEM is integrated in current energy performance design practices in collaborative and high-energy performance projects, the research team used long-term ethnographic case studies of design phases of two complex social housing projects. Figure 1 shows the research approach conducted in this study. Researchers conducted a comprehensive literature review to identify the scope of the study and research area, as well as to develop a research design, develop a code manual for thematic analysis and validate findings. Two housing projects that were in the design phase were selected as case studies based on the identified research area. To gather data, an ethnographic qualitative study method was chosen, which involved direct observation of bi-weekly project consultant meetings. Additionally, the collected data were enriched through a thorough review of relevant project documents. Data collected through observation and document analysis were analyzed through the design process modeling. The process models helped to understand the current practice including the role of BEM activity within design activities, tools used in different activities, and interactions among BEM experts and other stakeholders. By analyzing the process models, researchers identified areas with information gaps that necessitated further data collection. These insights informed the development of interview questions for conducting semi-structured interviews with the project design team. Semi-structured interviews helped researchers to understand design process models. Then, all the collected data, including approach to literature review, ethnographic data, transcribed semi-structured interviews, and the understanding of current practice of integrating BEM into the design process were subjected to a hybrid approach of inductive and deductive thematic analysis to further identify the benefits and challenges associated with the current practice of integrating BEM in the design process. Finally, the findings were verified through semi-structured interviews with the project design team and through existing literature.

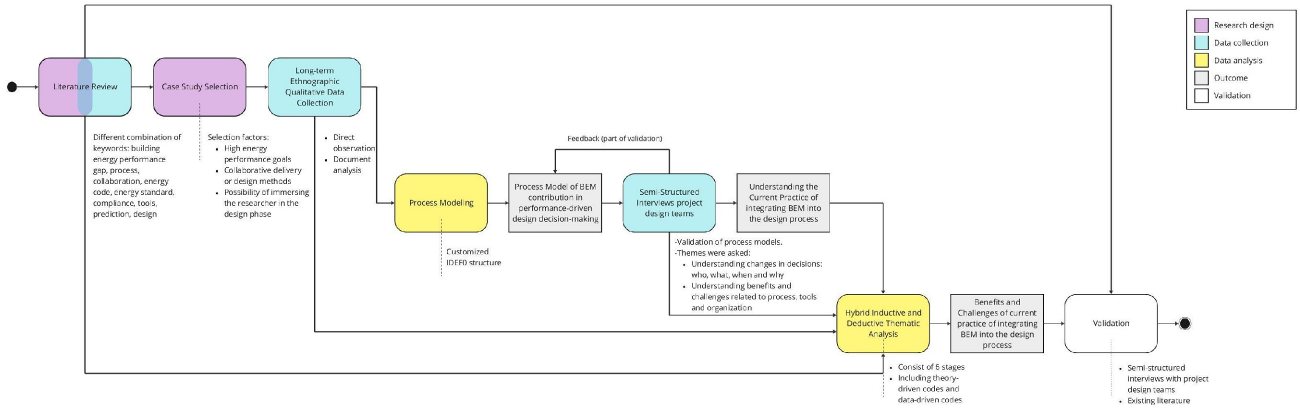


Figure 1. Research approach to conduct the study.

3.1. Approach to Literature Review

The literature review was used for identifying research areas, developing research questions, establishing an appropriate research methodology, extracting theory-driven codes and validation. To review the literature, researchers searched keywords through article titles, abstracts and keywords in Scopus, Google Scholar and Web of Science. Different combinations of following keywords were utilized: building EPG, process, collaboration, energy code, energy standard, compliance, tools, prediction and design. Afterward, the search results were refined to include only articles written in English and 429 results were found. Irrelevant articles were excluded from the analysis by carefully reviewing the abstracts to ensure their alignment with the research topic. Finally, 48 articles were chosen. Researchers reviewed problem statements, research objectives, background, methodologies, results and discussions of these selected articles to design the research. And they took notes from the background, results and discussion parts of selected articles to further develop a code manual for thematic analysis.

After conducting a thematic analysis, some of the findings were validated through the examination of those 48 selected articles. However, due to the emergence of new themes, researchers conducted additional searches using the mentioned search engines and specific keywords associated with each benefit and challenge. This led researchers to include 11 more relevant articles in the study for validation.

3.2. Case Study Selection

To effectively attain the research objective, the selection of appropriate case studies necessitated careful consideration of four key selection factors:

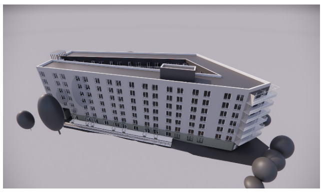
Selection Factor 1. Having high-energy performance goals;
Selection Factor 2. Applying collaborative methods during the design phase;
Selection Factor 3. Having an opportunity for ethnographic study during the design phase;
Selection Factor 4. Being large-scale, as larger-scale projects tend to foster a greater degree of stakeholder interaction to ensure an in-depth exploration of stakeholder interactions.

In addition to the above-mentioned selection factors, there are two common approaches towards achieving energy-efficient buildings: (1) pursuing specific energy performance certifications; and (2) complying with international or regional building energy codes and standards. Therefore, to gain a better understanding of the current practices related to the integration of BEM in the design process, the research team selected two different case study projects to cover both mentioned approaches, with one case study representing each approach.

Both projects placed a significant emphasis on building energy efficiency goals during the planning phase, and in their request for proposals, leading them to adopt collaborative methods during the design phase. Table 1 describes features of these case studies, named the

"Vienna House" project and the "1st and Clark" project. The energy performance goals of the two projects differ, with the Vienna House pursuing PH Classic Certification and the 1st and Clark Project adhering to the BC Energy Step Code 4, representing distinct approaches to achieving high-energy performance. Furthermore, the projects adopt different delivery models, with the Vienna House utilizing the CM-IDP model and the 1st and Clark Project employing the IPD model, thereby illustrating variations in collaborative processes. Both projects offer opportunities for ethnographic study, facilitating direct observation of design decision-making. As large-scale projects, the Vienna House has a treated floor area of 7591.3 m², while the 1st and Clark Project encompasses 13,643 m². These factors were pivotal in selecting appropriate case studies for examining how BEM is integrated into the design process in collaborative projects. The general information and modeled design process of each case study are investigated in the following subsections.

Table 1. Features of case studies based on selection factors.

Case Study Name / **Selection Factor**	 **Vienna House Project Location: Vancouver, Canada Design Phase Starting Date: September 2021**	 **1st and Clark Project Location: Vancouver, Canada Design Phase Starting Date: March 2018**
Selection factor 1: Energy Performance Goal	Pursuing PH Classic Certification	Complying with BC Energy Step Code 4
Selection factor 2: Delivery Model	CM-IDP	IPD
Selection factor 3: Opportunity for Ethnographic Study	Yes	Yes
Selection factor 4: Treated Floor Area (m^2)	7591.3	13,643

3.2.1. Case Study 1: The Vienna House Project

The first case study, the "Vienna House" project, is a six-story affordable social housing project located in Vancouver, Canada, with a treated floor area of 7591.3 m^2. The project's design phase began in September 2021 using a combination of the Construction Management (CM) and IDP delivery model. Figure 2 illustrates the collaborative project environment, with the design team actively addressing design issues. Aiming to achieve PH building certification, project stakeholders initially discussed various options for setting energy efficiency goals in IDP Workshops, including PH certification, PH-like, and Step 4 of the BC Energy Step Code. PH-like did not offer a significant enough improvement to justify additional costs, while Step 4 was not as rigorous as PH. PH offers greater energy savings and environmental benefits. Finally, the project aimed to obtain PH Classic certification, and one of the IDP design workshops specifically focused on PH design considerations to help project stakeholders understand the high-level engineering concepts and building system design for PH. The PH Planning Package (PHPP), an Excel-based quasi-steady-state energy analysis tool, was used for BEM. Figure 3 shows the PHPP interface for the Vienna House project, highlighting key areas for inputs, outputs, and the overall PHPP environment layout, with numerous cells requiring manual entry. Space heating and cooling demands, frequency of overheating, airtightness, primary energy renewable demand, and non-renewable primary energy are the key design metrics for PH certification. Throughout the project, these metrics were used to ensure that the design aligned with the project's energy efficiency goals. The mechanical consultant company was responsible for managing the PHPP and energy modeling.

Figure 2. Collaborative design issue resolution by the Vienna House project team, with Revit model (red), collaborators (blue), collaboration environment (gray), and design issues (light blue) highlighted.

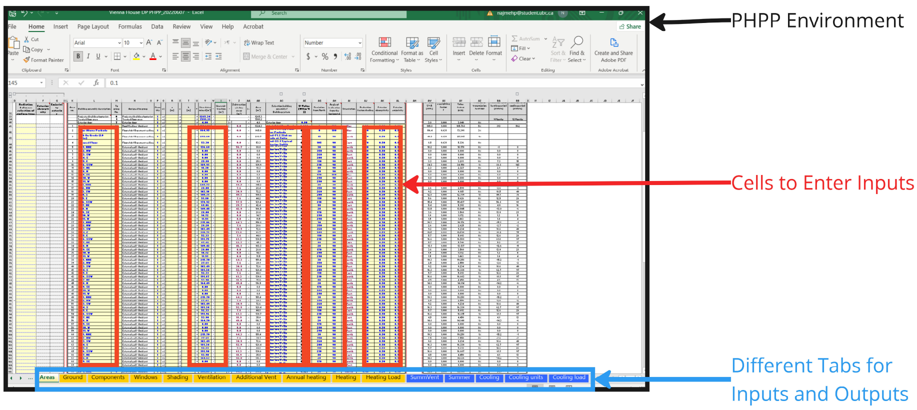


Figure 3. Interface for PHPP: Snapshot of the 'Area' tab in the PHPP for the Vienna House project, illustrating the PHPP environment (black), with input cells highlighted in red and tabs for inputs and outputs in blue.

3.2.2. Case Study 2: The 1st and Clark Project

The second case study, the "1st and Clark" project, is a 10-story mixed-use residential/clinic building project located in Vancouver, Canada, with a treated floor area of 13,643 m^2. The project's design phase began in March 2018, and it employed the IPD method. Figure 4 depicts a collaborative project environment, where the design team and trades collectively address design and scheduling issues. The project's objective was to achieve Step 4 of the BC energy step code (only for residential units), which consists of five steps for simple projects and four steps for complex projects (such as 1st and Clark), with the fifth step being equivalent to zero-energy buildings. For BEM, the project uses Integrated Environmental Solutions Virtual Environment (IES VE), a dynamic energy analysis tool. Figure 5 shows the interface for IES VE. The essential design metrics for meeting the BC Energy Step Code requirements on this project included total energy use intensity (TEUI), thermal energy demand intensity (TEDI), frequency of overheating, and airtightness. The BEM expert was a third-party company.

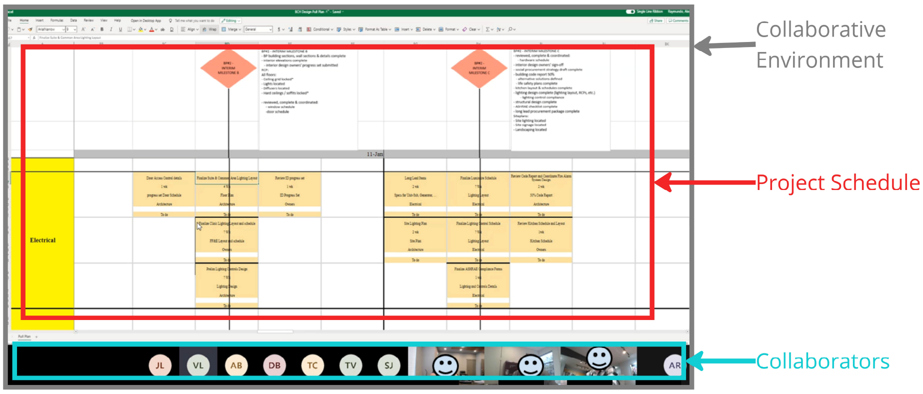


Figure 4. Collaborative resolution of design and scheduling issues by the 1st and Clark project design team and trades, with the collaborative environment, project schedule, and collaborators highlighted.

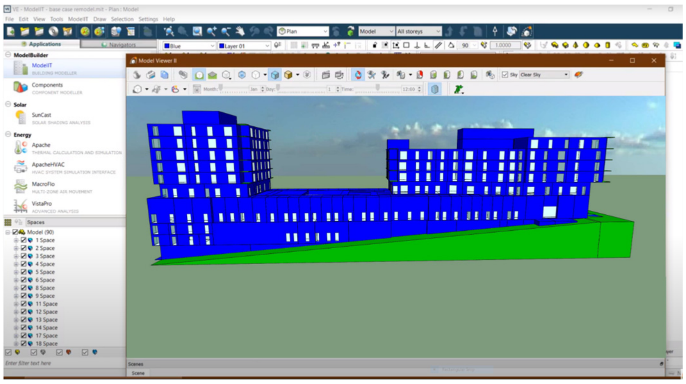


Figure 5. IESVE interface and its energy model view for 1st and Clark project.

3.3. Data Collection

Researchers applied three ways of data collection including literature review, ethnographic data collection, and semi-structured interviews. The literature review was discussed in Section 3.1, and notes taken from selected articles were used to develop a code manual for thematic analysis. The other two ways are discussed below.

3.3.1. Ethnographic Data Collection

To gain a comprehensive understanding of the design process including the integration of BEM and project stakeholders in decision-making, it is crucial to recognize collaboration and interaction among BEM experts and other stakeholders in selected case study projects. Ethnographic study is a qualitative research method to study social interactions, behaviors, and perceptions that occur within groups, teams, organizations, and communities [52]. It provides researchers with valuable access to hard-to-obtain data, allowing them to uncover the true dynamics and inner workings of organizations [53] and in-depth insights and understanding of a topic [54].

The main data collection method in ethnography is direct participant observation, often supplemented by other methods to enrich findings. An ethnographic approach was chosen for this study because it captures the complexity of interactions and decision-making in collaborative environments. While data collection approaches such as surveys and interviews provide insights into participants' views and experiences, they lack the ability to observe real-time interactions and contextual dynamics [53]. In contrast, the ethnographic approach enables direct observation of behaviors and interactions, making it ideal for studying how BEM is integrated into design activities and stakeholder collaboration.

For this study, a long-term ethnographic approach, defined as more than six months of observation [55], was employed. Document analysis was used as a supplementary method to enrich the findings. Researchers participated in bi-weekly project consultant and progress meetings, where designers and other stakeholders (depending on the meeting topic) discussed various aspects of the project. During these meetings, researchers took detailed notes on the topics of discussion, design changes, participant roles in decision-making, interactions between disciplines, and how decisions were reached. They also recorded who participated in the discussions, what questions were asked, and the reasoning behind those questions. These observations provided crucial insights into the dynamics of decision-making, including how agreements were reached and the factors that influenced discussions. Such details are often forgotten or overlooked when design teams progress to the next stage, particularly if interviews, surveys, or project documents are the only sources of information.

Researchers documented the notes taken during these meetings and cross-checked them with the meeting minutes provided by the design teams. While the design teams prepared minutes summarizing final decisions and follow-up questions, these documents often lacked details on interactions and decision-making dynamics, such as negotiation processes or the roles played by different stakeholders. This gap in documentation is why ethnography was chosen as the primary method, as it allowed researchers to capture these critical, yet often undocumented, aspects of the design process. In a few meetings, such as project steering committee meetings where researchers were not allowed to participate or observe, meeting minutes prepared by the design teams were reviewed. When clarifications were needed, researchers followed up with emails to address any questions or uncertainties.

3.3.2. Document Analysis

For document analysis, researchers carefully analyzed project meeting minutes, design drawings and energy reports. In their review of project meeting minutes, their focus was on pinpointing the decisions made, recording the decision dates, and identifying the roles of the individuals involved in making these decisions. Similarly, they conducted a detailed review of design progress drawings, aiming to uncover any changes made during the design phase, along with their respective dates. Additionally, the researchers conducted a comparative analysis of the inputs and outputs within energy reports to detect alterations and discern the design decisions that informed each report.

In both projects, multiple researchers were involved, each conducting their own studies and interviews with design teams on specific research topics. For this study, researchers reviewed transcripts of other researchers' interviews that were relevant to process, sustainability, and resilience aspects, such as IPD impacts, BIM co-ordination, innovations, and climate change.

3.3.3. Semi-Structured Interviews

After conducting design process modeling, researchers identified certain gaps in data collection that required further investigation, such as understanding the reasoning behind specific decisions and the experience of design teams regarding collaboration and the integration of BEM within the design process. To address these gaps and collect additional data, two semi-structured interviews were conducted with the architect of the Vienna House project and the BEM expert of the 1st and Clark project, as they were more closely involved with BEM and its related decisions. The primary purpose of these interviews was to collect data, and the process models were used as a tool to visualize where more information was needed, helping the interviewees better understand the context of the questions and how they related to the overall design process.

Firstly, the model was presented to the project teams during the interviews to verify data collected through direct observations and document analysis. Secondly, questions were asked based on two themes: (1) understanding the process of design decision-making, with a particular focus on decision changes by exploring the who, what, when, and why aspects; and (2) understanding the participants' experiences in the case studies, specifically regarding the benefits and challenges encountered in terms of process, tools, and organizational aspects. Afterward, the interviews were transcribed and analyzed to bridge the information gaps, enhancing understanding of the design process and identifying additional themes related to benefits and challenges.

3.4. Data Analysis

3.4.1. Modeling the Design Process

Modeling the design process for case studies offers valuable insights into understanding current energy performance design practices in collaborative high-energy performance projects. This includes understanding the role of BEM in design activities, the tools used in different activities, interactions among BEM experts and other stakeholders, various BEM and design activities, and identifying inefficiencies in the practice. Process modeling can help to understand decision-making activities and interactions among stakeholders and different activities as well as identify inefficiencies and areas of improvement [56]. For design process modeling in this study, Integrated Definition for Function Modeling 0 (IDEF0) was utilized because it is helpful to model decisions and activities of an organization or system [57]. Figure 6a depicts the structure of IDEF0 for design process modeling. IDEF0 structure comprises a box representing an activity, with four arrows illustrating its inputs, outputs, controls, and mechanisms. Additionally, the activity number is indicated in the bottom right corner.

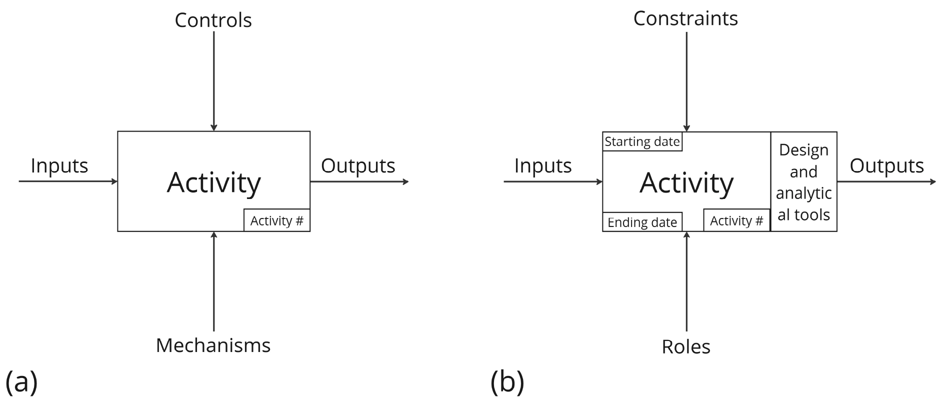


Figure 6. (**a**) Structure of IDEF0. (**b**) Customized IDEF0 structure for this study.

To highlight the key aspects of PTO lenses and sequence of activities, a customized structure of IDEF0 (shown in Figure 6b) was employed in this study to model the design process. In this customized IDEF0, each activity box features three small boxes: one on the right side to represent the design and analytical tools that were used, one at the top left corner to indicate the activity's starting date, and one at the bottom left corner to indicate the activity's ending date. In this study, activities are categorized into two groups: design decision-making and energy modeling, to provide a clearer understanding of BEM integration within the design process. Design decision-making activities are denoted by a 'D' prefix preceding their activity number, while energy modeling activities are identified with an 'E' prefix. The input arrow in the IDEF0 structure represents the documents, information, or decisions necessary for a specific activity, while the output arrow signifies the final decision or outcome generated from that activity, which can be in the form of a document, information, or decision. Mechanisms refer to physical aspects of the activity such as people, machines, and tools. While tools can be categorized as mechanisms, this study opted to refer to mechanisms as roles to emphasize the importance of interactions and collaboration in decision-making concerning building energy performance. The width of the role arrow corresponds to the number of roles participating in a particular activity. Controls can include standards, plans, templates, and checklists or any inputs that direct the activity. Differentiating between inputs and controls in the IDEF0 structure can occasionally introduce uncertainty. Inputs undergo transformation or modification to create the desired outputs, whereas controls rarely undergo changes. Controls in the customized IDEF0 refer to strong constraints associated with building energy performance for decision-making. Design process modeling using the customized IDEF0 facilitates the identification of areas that require enhanced collaboration and interactions among stakeholders, revealing isolated stakeholders and delineating the transitions between different design stages. Additionally, it aids in understanding whether decisions are made or used at the right time during the design phase. Furthermore, the model was presented to project teams through semi-structured interviews to verify data collected through direct observations and document analysis.

3.4.2. Hybrid Inductive and Deductive Thematic Analysis

To identify the benefits and challenges of current practices of integrating BEM in the design process in collaborative construction projects with high-energy performance goals, researchers needed to categorize data collected from direct observation, document analysis, and semi-structured interviews systematically. Thematic analysis involves identifying significant themes that emerge and contribute to describing the phenomenon [58]. The procedure entails identifying themes through "careful reading and re-reading of the data" [59]. Themes are used to categorize collected data for analysis. It is important to note that researchers opted not to use content analysis since they treated each individual comment, note or interpretation as equally important, regardless of whether it was repeated in the collected data. Two coding approaches can be used in thematic analysis:

- Deductive approach: a deductive approach is a top-down approach, where researchers begin the analysis by creating a code manual with their initial set of codes based on theory or existing knowledge. It is called theory-driven coding which is described by [60].
- Inductive approach: An inductive approach, also known as a bottom-up approach, refers to a method wherein themes are determined by the data themselves. It is called data-driven coding which is described by [61].

A hybrid approach of inductive and deductive thematic analysis was used in this study, with the aim of leveraging the benefits of both. This hybrid approach provides greater rigor for qualitative studies [62] and it allows for triangulation of findings [63]. It is a flexible and iterative approach that allows for a better understanding of phenomena. It analyzes the study within a predefined and acceptable framework, yet it remains open to the emergence of new themes. As this approach is a recent development by Fereday and Muir-Cochrane [62], and it has been predominantly used in social and nursing research, its application in the construction industry research remains relatively limited. While hybrid deductive and inductive research designs are prevalent among some construction industry researchers [64], there are few instances of coupling them with coding, particularly in content analysis (e.g., [65–68]) and rarely in thematic analysis (e.g., [69]). This study follows the six stages of the hybrid inductive and deductive thematic analysis approach developed by Fereday and Muir-Cochrane [62], which utilized the coding stages from studies [60,61]. Figure 7 shows the six stages undertaken to code data.

Stage 1: Developing the Code Manual

Selecting a code manual was a crucial decision for the study, as it functioned as a data management tool, aiding in the organization of text segments with similar or related content to facilitate interpretation [60]. This stage incorporates the study's credibility. In this study, researchers chose a conceptual framework developed by Staub-French and Khanzode [20] which views construction industry topics in three lenses of process, tools, and organization. The term "process" in this study refers to all aspects related to the procedural steps and collaborative efforts during the design decision-making, specifically related to BEM. "Tools" encompass any analytical instruments or software used during the design decision-making, specifically related to BEM. "Organization" refers to the organizational structure, policies, standards, guidelines, and people involved in design decision-making, specifically related to BEM. These three lenses were considered broad code categories to form the code manual. Afterward, through an analysis of notes gathered from a systematic literature review, six codes were identified as sub-codes for the three lenses. Table 2 shows the code manual including theory-driven codes for this study.

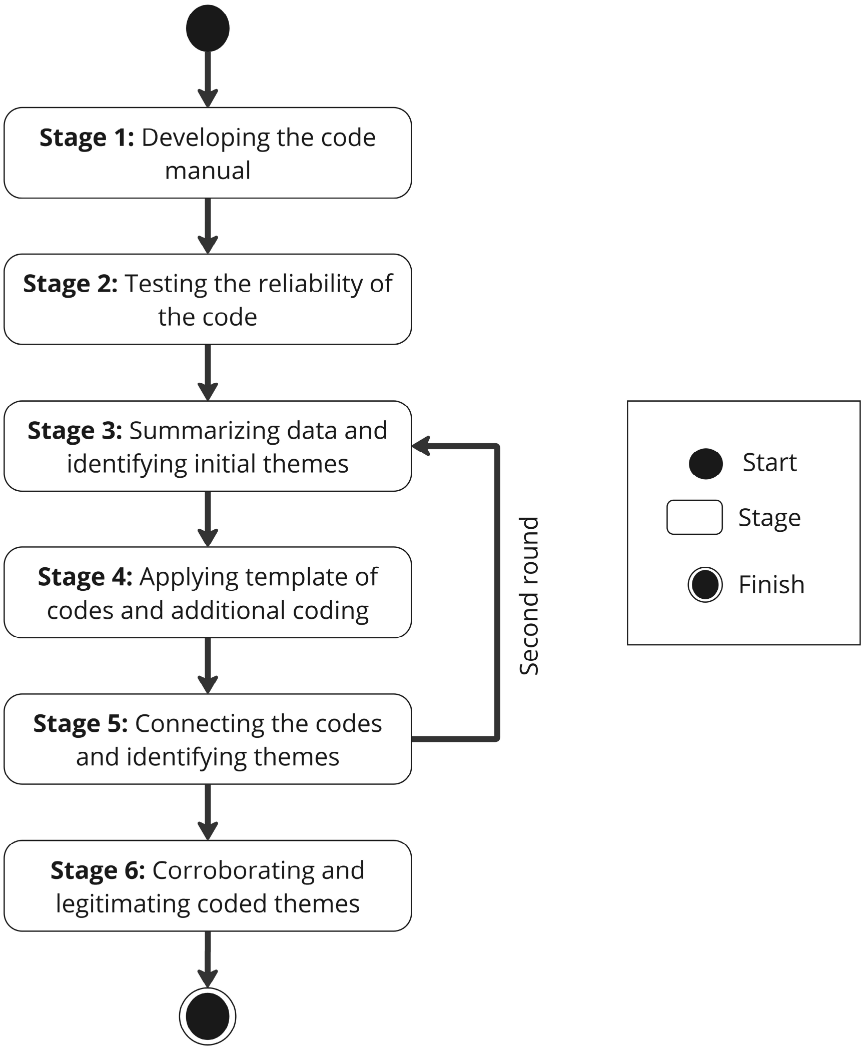


Figure 7. Six stages of coding data in hybrid deductive and inductive thematic analysis [62].

It includes broad codes—Process, Tools, and Organization—and their corresponding sub-codes. Under the Process category, the sub-codes are "Collaboration", which refers to the interaction and exchange of ideas between BEM experts and other stakeholders during design decision-making, and "Information Integrity", which addresses the accuracy and reliability of information. The Tools category includes the sub-code "Capability", representing the ability of BEM tools to perform various functions and support design workflows. Finally, the Organization category contains three sub-codes: "Rules and Guidelines", referring to the principles, standards, and regulations governing energy performance in buildings; "Knowledge and Experience", which relates to the expertise and insights of stakeholders; and "Accountability", which captures the responsibility stakeholders hold during the design process. These codes and sub-codes form the foundation for analyzing how BEM is integrated into collaborative design decision-making.

Table 2. Theory-driven codes and sub-codes (code manual) for the study.

Broad Code	Sub-Code	Definition
Process	Collaboration	Interaction and sharing of ideas between BEM expert and other stakeholders to have informed design decisions.
	Information integrity	The accuracy and reliability of information which is a fundamental aspect of data quality.
Tool	Capability	Capacity to perform various functions, support diverse workflows, and provide valuable resources to users.
Organization	Rules and guidelines	A set of established principles, standards, codes, regulations and guidelines that govern the energy efficiency and performance requirements for buildings.
	Knowledge and experience	The information, expertise, skills, and insights possessed by stakeholders who are responsible for making design decisions.
	Accountability	Responsibility and answerability of stakeholders for any specific activity during the design process.

Stage 2: Testing the Reliability of the Code

Two documents, one master thesis and one project report related to the CIRS energy performance story, were chosen as sample documents for coding. They were coded by the researchers based on the code manual. A comparison of the results revealed that no adjustments to the code manual were required.

Stage 3: Summarizing Data and Identifying Initial Themes

Researchers summarized the collected data by addressing two questions below:

- What was the design evolution story through various stages of the design process: conceptual design, schematic design, and design development?
- What were the benefits and challenges associated with integrating BEM in the design process?

Meanwhile, notes were taken from potential themes as additional codes to the code manual.

Stage 4: Applying the Template of Codes and Additional Coding

Researchers applied codes from the code manual to collected data to extract insights from data collected concerning benefits and challenges in current practices of integrating BEM in the design decision-making process. This phase was conducted on a Miro Board using sticky notes instead of N-Vivo, as the data volume was manageable, and the Miro Board facilitated the process. The text analysis during this stage was guided by, yet not limited to, the initial codes. Throughout coding, inductive codes were applied to data describing new themes. During the coding of transcripts, inductive codes were assigned to segments of data that described a new theme. These emerging themes were either distinct from the pre-defined codes or extended existing codes outlined in the code manual.

Stage 5: Connecting the Codes and Identifying Themes

Researchers identified both similarities and differences among codes, leading to the emergence of underlying themes within the data. In this process, similar codes were combined to create new themes. These emerging themes were then organized and refined to reveal deeper insights within the data.

Stage 6: Corroborating and Legitimating Coded Themes

To corroborate the results, researchers repeated stages two to five, ensuring a thorough validation process. Additionally, findings were shared with project stakeholders, who provided feedback. The details of this stakeholder engagement to validate results were described in Section 3.4.

3.5. Validation

To validate the accuracy and reliability of the collected data and analyses, two methods were used: (1) expert interviews and (2) data and methodological triangulations. These methods were chosen specifically to confirm that the data accurately captured the realities of BEM integration, while also minimizing potential biases.

As for domain expert validation, a total of four interviews were conducted: two with individual experts from within the projects and two with external specialists. The interviews with experts from within the projects were conducted in two rounds with the architect of the Vienna House project and the BEM expert of the 1st and Clark project. The first round focused on validating the collected data by presenting it to these key stakeholders. Their feedback helped confirm the accuracy of the data and ensured it reflected actual design practices and decisions. In the second round, the same individuals were consulted to validate the preliminary analysis. This step ensured that the identified benefits and challenges aligned with real-world experiences in similar projects.

Two additional interviews were conducted with architects who have over eight years of experience in BEM but were not involved in the case studies. These external experts reviewed the research findings and approach, providing feedback based on their independent professional experience. This step added an extra layer of validation, reducing bias by incorporating perspectives from professionals outside the studied projects. The feedback from all interviews was carefully considered, and adjustments were made to the design process models if needed. This combination of internal and external validation ensured that the findings accurately represented BEM integration while minimizing potential biases.

Additionally, researchers sent a document detailing the identified benefits and challenges to the principal BEM expert of the 1st and Clark project for verification via email, as they were unavailable for an interview at the time. The feedback received from the principal BEM expert indicated that no changes were necessary for design process models and the identified benefits and challenges. Furthermore, the benefits and challenges were assessed by comparing them with the existing literature to identify those that had already been addressed in prior papers. The challenges that have been previously mentioned in the literature were cited throughout Section 5 of the text. This approach helps mitigate research bias.

Moreover, researchers used triangulation methods to mitigate any bias [70] as another layer of validation. Using the triangle analogy, triangulation involves examining a single point from three distinct and independent sources. It was initially applied in military and navigation sciences [71]. In the context of research, triangulation refers to the utilization of multiple methodological resources or practices [72,73]. There are four types of triangulations in qualitative research [72]: data triangulation, methodological triangulation, investigator triangulation, and theory triangulation. In this study, researchers used data and methodological triangulations. Data triangulation means using multiple data sources which can be different in time periods, locations, or perspectives. To avoid confusion between a data source and data collection (which is part of methodological triangulation), Denzin [72] defined a concept of three data points (methods to generate data), which can be likened to time, space, and people. In this study, in terms of data triangulation, two different case studies were studied which included different spaces. This involved analyzing two distinct case studies: the Vienna House project and the 1st and Clark project. These case studies provided varying locations (space data point), insights from different project teams (people data point), and data collected across different design stages (time data point).

Methodological triangulation refers to multiple data collection or data analysis methods [63]. In this study, data were collected through direct observation, document analysis and semi-structured interviews. For methodological triangulation in data analysis, qualitative researchers frequently adopt both inductive and deductive approaches to data analysis [63], where they extract findings and concepts from the data while also using the data to test existing theories and concepts. In this study, a hybrid method including inductive and deductive thematic analysis was used to analyze the same data.

4. Design Process Models for Case Studies

4.1. Design Process Model for Case Study 1: The Vienna House Project

The Vienna House design process and integration of BEM during the process, shown in Figure 8, consists of the schematic design, and design development stages. As depicted in Figure 6b, the activities are represented by boxes, while the inputs and outputs are denoted by horizontal arrows. Additionally, constraints and the roles involved in each activity are depicted by vertical arrows. Since the study wants to investigate how BEM is integrated in the design process, activities can be grouped into two streams depending on their types: the ones related to design decisions are shown in blue, while the activities focused on energy modeling are represented in purple.

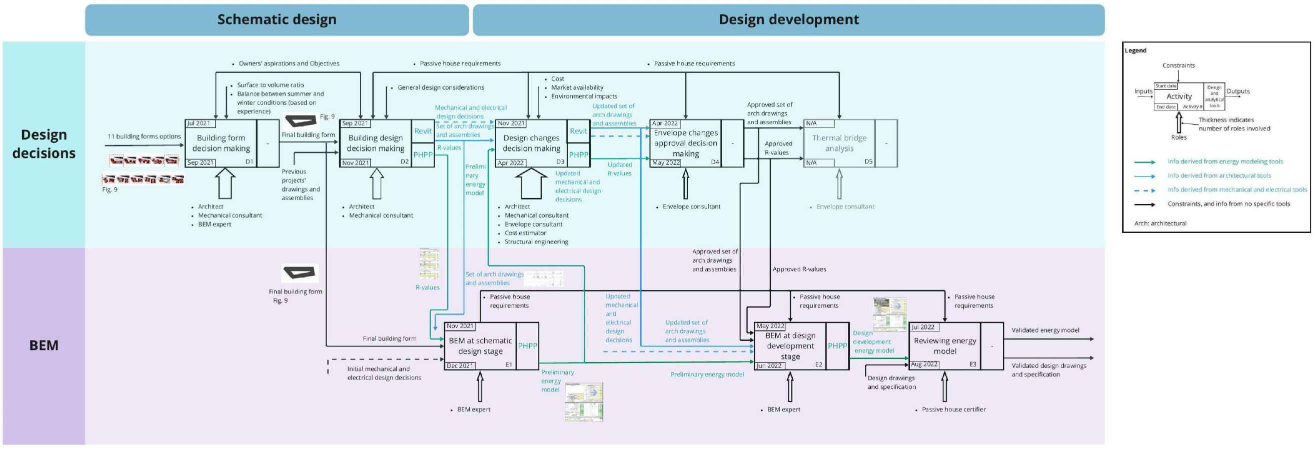


Figure 8. Design process model of Vienna House and the integration of BEM during the process.

Prior to commencing the design process, the project team conducted five integrated design workshops. These workshops aimed to showcase the team's prior project experience, propose potential design solutions, and enhance the understanding of project objectives among all stakeholders. Since those workshops were primarily intended for information sharing rather than decision-making, they have not been included in the design process model.

4.1.1. Schematic Design Phase of the Vienna House Project

The project team made significant design decisions at the start of the design phase before having an energy model in place. As shown in Figure 8, the first activity during the schematic design phase was activity D1, building form decision-making, ending in September 2021, which was critical and time-consuming, requiring numerous meetings among the architect, mechanical consultant, and BEM expert. The architect proposed 11 distinct building form options, each of which was analyzed and compared across various criteria. In Figure 9, columns represent different building form options, while rows depict comparison criteria: zoning/planning, pro forma, PH, and livability. For zoning and planning, quantifiable factors include gross floor area, lot coverage, floor plate area, façade length, solar access to the north, and floor space ratio. For pro forma, factors include total unit count, core quantity, and studio units. Livability considerations quantify dual-aspect units, units with a single aspect facing SkyTrain, daylight in public corridors, and east-facing daylight access. PH criteria include gross surface area, surface area-to-floor area ratio, and number of exterior corners.

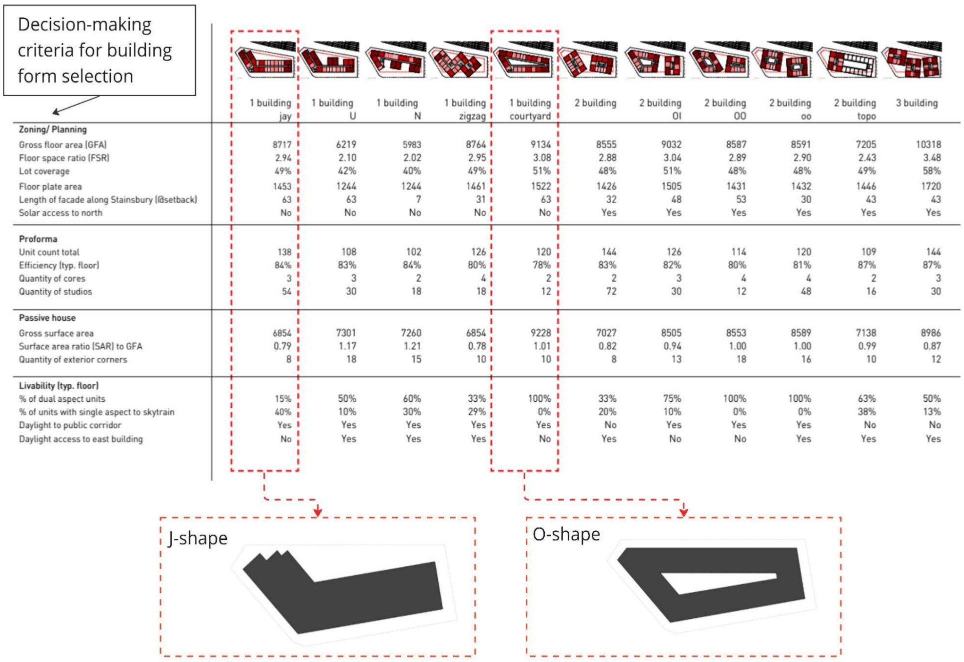


Figure 9. Building form options for Vienna House project (adapted from [74,75]).

Among the factors mentioned, the surface-to-floor area ratio has emerged as a particularly important consideration for the architect. They tracked the surface-to-floor area ratio of each mass in a crude way by measuring the ratio of exterior surface area to gross floor area for the heated envelope. They aimed to achieve a ratio of less than two, meaning that the surface area of the building would be less than twice the floor area. This would make the building compact enough to not present an obstacle to PH standards, even though it may not be completely optimized. It was possible to make an extremely compact building, but this might have required full air conditioning during summer, which was expensive, considering the size of the project which was larger than typical for a multifamily project that led to high internal heat gain.

The two highest ranking schemes, option 'O' and option 'J' (shown in Figure 9), were shortlisted for further development and costing. The team relied on the experience-based guidance of the mechanical consultant to determine the impact of the surface-to-floor ratio on energy consumption and PH certification. This guidance informed the decision to choose a courtyard form over a more compact building form focused on reducing heating demand. The courtyard form was an O-shape surrounding a central courtyard, with all units having dual exposure, allowing for a higher surface-to-floor ratio while balancing between summer and winter heat and daylighting. Although the O scheme costs were modestly higher, the courtyard scheme provided solar access, ample natural ventilation, and passive cooling compared to other options. The team added an extra story to the building, which proportionately added a significant amount of floor area and made the building efficient enough to move forward with the chosen scheme.

After activity D1, the architect and mechanical consultant started activity D2, envelope, and building system design. Owners' aspirations and objectives, general design considerations and PH requirements were constraints for the decisions. A set of drawings and R-values for envelope (calculated by PHPP) were sent to the BEM expert and activity E1, energy modeling at schematic design stage, started when design decisions were made. At this stage, the design team was required to demonstrate that they had engaged a certified PH consultant. The results were not as unfavorable as initially feared despite having to add one more storey. The results of activity E1 were received by the design team after the design development stage and specifically, activity D3, design changes decision-making, had already started. This overlap means that the activity E1 results did not effectively influence the design decisions for the schematic design stage as it should be. In other words, activity E1 was primarily completed to check whether the project could meet PH certification requirements, and not used to further optimize the design.

4.1.2. Design Development Phase of the Vienna House Project

During the design development phase, in activity D3, which is design changes and decision-making, more constraints and roles were involved. More collaboration occurred through the involvement of the architect, cost estimator, and envelope, mechanical, electrical and structural consultant. Two notable changes during activity D3 were exterior wall and heat recovery ventilator changes. Figure 10 shows a decision activity for exterior wall change with a timeline of the decision-making events and their description. In the initial document published for assemblies, the only option for the exterior wall was a site-built wall, including one layer of drywall, two layers of Rockwool insulations and one layer of plywood sheathing. However, in an updated document, an alternative option of a prefabricated panelized system was added. When the Class C cost estimation document was reviewed, it showed no significant cost difference between the site-built wall and the prefabricated panelized system. During activity D3, the decision was made to choose the prefabricated panelized system over the site-built wall. The changes in exterior wall layers by switching to prefabricated panelized system were a 51-mm reduction in the thickness of the first rockwool layer, newly added 15-mm oriented strand board (OSB) sheathing, and replacement of the second layer of rockwool with dense packed cellulose insulation. As a result, the overall exterior wall thickness increased by 77 mm and the R-value increased by four units. The prefabricated panelized system, despite being thicker compared to the site-built option, offered environmentally friendly and factory-fabricated benefits and slightly better thermal performance. The panels were taped and made airtight in the factory, resulting in accuracy and scheduling benefits. This shift to a prefabricated wall had sustainability advantages in terms of materials and construction efficiency.

Figure 11 shows a decision activity for the heat recovery ventilator (HRV) change (within activity D3) with a timeline of the decision-making events and their description. During the schematic design stage, Mitsubishi HRV was chosen for activity E1, but an alternative option of Sanden CO_2, during the design development stage, was raised due to cost considerations. Sanden CO_2 was found to be approximately CAD 100,000 cheaper, and the performance differences between the two options were negligible. Because these collaborations (Figures 10 and 11) occurred during the design phase and before activity E2, these key decisions were able to be represented in the energy model. If this decision had happened later, it would not have been captured in the energy model, and this would have contributed to an EPG. It is important to note that for these decisions no energy models were created to see impacts of changes on energy demands and overheating hours.

According to Figure 8, after activity D3, updated drawings, assemblies, and envelope R-values needed the envelope consultant's approval. The process of determining the R-values involved the architect sending the values to the envelope consultant, who needed to review the architectural drawing set before approving the R-values. Once approved, the BEM expert used this information directly in the model. Activity E2 began at the end of the design development stage. The sequencing and outcomes for activity E2 were the same as activity E1, such that the results did not lead to design changes during the design development stage. At the end, the energy model of the design development stage was reviewed by a PH certifier and validated energy performance results and design drawings were sent to the construction documentation stage.

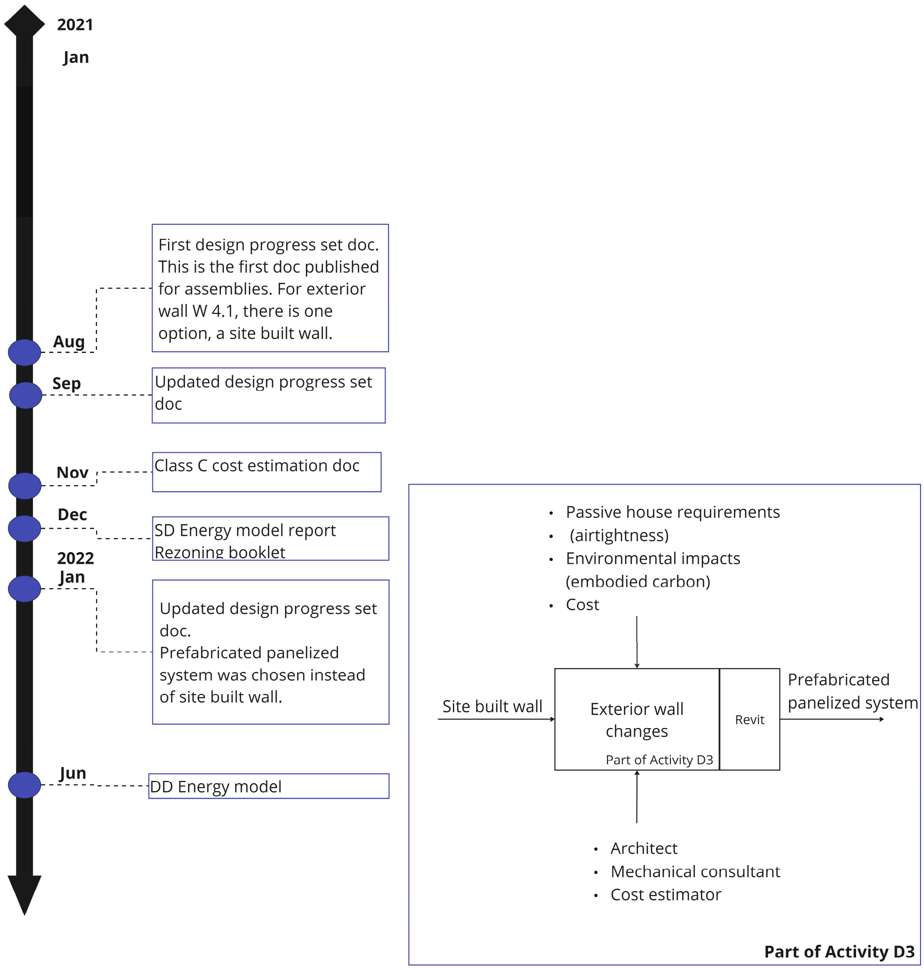


Figure 10. Decision-making activity for exterior wall change within activity D3, with timeline of evidence (**left**) and decision-making activity (**right**).

In a relatively complex building, the thermal bridging analysis would be lagging behind the modeling of mechanical components and system performance in the energy model as the architect said. As a result, a buffer was kept for thermal bridging to ensure that the heating demand was met. This buffer was about two units of the heating demand target of 15 kilowatt hours per square meter per year. The development of details for the thermal bridge analysis took time, and as a result, the team was held onto the buffer while waiting for the detailed analysis to be completed. In Figure 8, activity D4, thermal bridge analysis, is in gray because, at the time of this research, it was pending and had not yet been received by the project team. When the design team received feedback on their first review of the PHPP, there were not many issues with the building systems, but mainly issues with thermal bridging that have not yet been resolved. Based on the architect's input, the thermal bridging details will be finalized during the preparation of Construction Documents and prefabrication drawings.

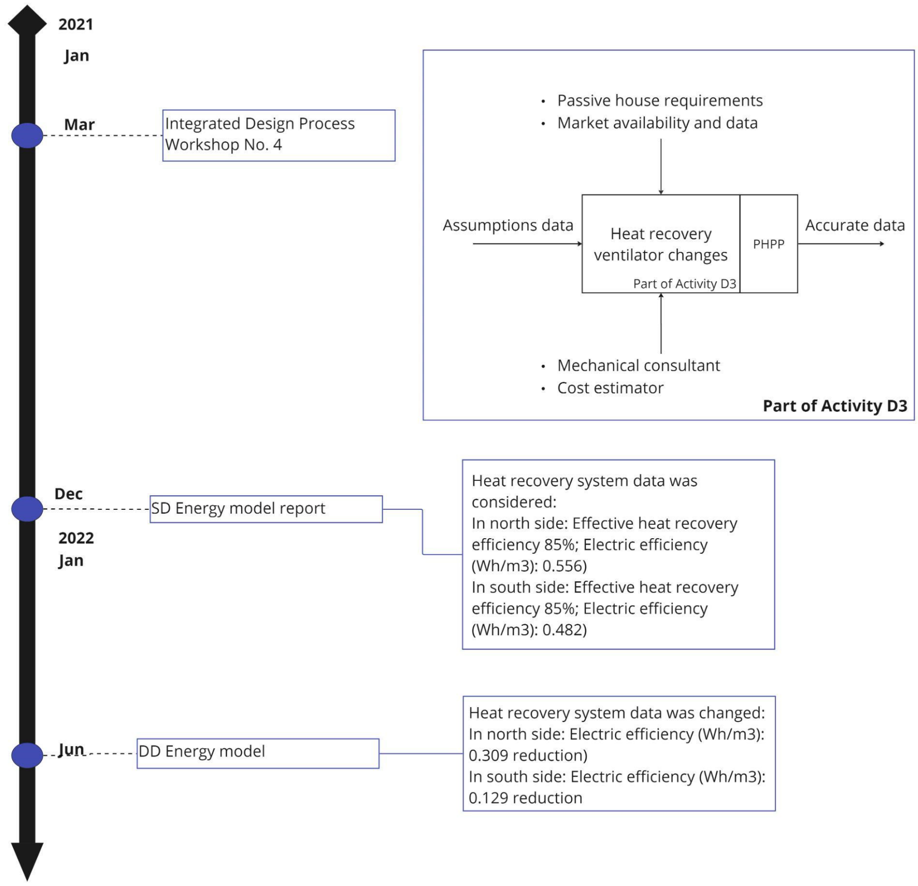


Figure 11. Decision-making activity for HRV change within activity D3, with timeline of evidence (**left**) and decision-making activity (**right**).

4.1.3. Communication Frequency and Key Insights in the Design Process of the Vienna House Project

Regarding the frequency of communication, the architect had frequent meetings and communication with the mechanical and electrical consultant. However, their interactions with the BEM expert were less frequent, and they relied on the mechanical and electrical consultant to ensure the accuracy of information in the energy model. There was some back and forth via email with the BEM expert before key submission milestones. The envelope consultant was not required to attend all of the consultant meetings and was met less frequently than other consultants. The certifier was not typically involved in project meetings and is mainly paid for periodic reviews of the energy models. The certifier could also provide design assistance if difficult conditions in the building needed to be modeled. The unusual building form design of Vienna House made it challenging to verify airtightness, so the certifier will need to mediate between the project team and the PH Institute to determine an acceptable protocol for testing.

The key insights derived from the process modeling highlight that BEM results are not timely received by the design team to effectively guide design decisions. One significant advantage of making changes early is the opportunity to incorporate them into subsequent energy models to assess their effects. Notably, communication frequencies among team members varied, revealing a pattern where the architect interacted more frequently with the mechanical and electrical consultant than with the BEM expert. The observations described in this subsection are used for analyses in Section 5.

4.2. Design Process Model for Case Study 2: The 1st and Clark Project

Figure 12 shows the 1st and Clark design process and the contribution of BEM during the process. Boxes indicate activities, horizontal arrows are inputs and outputs, and vertical arrows are constraints and roles involved in a specific activity (as shown in Figure 6b). The design process consists of conceptual design, schematic design, and design development stages. Since this study intends to investigate how BEM is integrated into the design process, the activities can be categorized into two streams based on their types: the design decision activities, highlighted in blue, and the BEM activities, which are marked in purple. Three energy models were made throughout the design process, including one model at each stage.

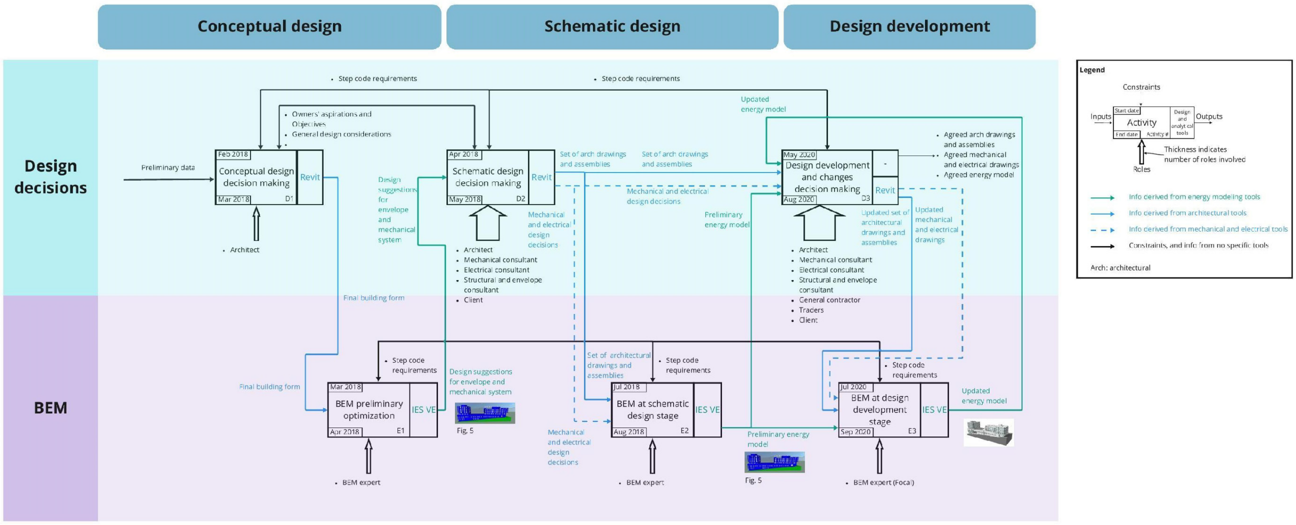


Figure 12. Design process of 1st and Clark project and the integration of BEM during the process.

4.2.1. Conceptual Design Phase of the 1st and Clark Project

As shown in Figure 12, activity E1 was conducted at the end of activity D1, conceptual design decision-making, and was used to optimize the design for the next stage. At activity D1, the architect provided a design with a basic floor layout and was the key player. Constraints were owners' aspirations and objectives, general design considerations and BC energy step code requirements. The BEM expert suggested some design scenarios through activity E1 to the designers (based on the basic floor layout) to apply in schematic design decisions. The initial model was to ensure at a high level that the inputs were roughly aligned with the desired energy targets. Activity E1 focused strongly on designing the envelope for optimal assembly performance, and on determining the construction techniques necessary to achieve the desired results. At this stage, the BEM expert had a basic floor layout design with elevations from the architect. To assess the impact of different features on TEDI, the BEM expert conducted a sensitivity analysis. For this purpose the BEM expert selected key features to consider for the TEDI requirement and iterated simulations. Wall performance, ventilation rates, and heat recovery efficiency were among the key features selected to achieve the desired TEDI results. The BEM expert also evaluated the impact of electric baseboards and lighting on TEDI, as the latter affects the building's heat balance even though it is not considered heating equipment. Although other metrics such as energy use were also important, meeting TEDI usually guaranteed meeting TEUI based on BEM expert experiences. By analyzing the sensitivity of these different features, the designers gained an understanding of the importance and impacts of the selected features on the building's overall performance. The reason for sensitivity analysis was as the design progresses through multiple stages, the modeler will not necessarily conduct energy modeling for every change. However, by conducting sensitivity analyses and establishing an initial performance benchmark, the designers could focus on the most impactful features and guide the design toward meeting the desired energy targets in subsequent stages. For the conceptual design stage, a mechanical engineer was not involved in the project yet, so the BEM expert made standard assumptions for mechanical systems and leaned on the conservative side to avoid surprises later.

4.2.2. Schematic Design Phase of the 1st and Clark Project

The client, structural and envelope consultant, mechanical consultant and electrical consultant were added to the design decision-making team at activity D2, at the schematic design stage, and the constraints were the same as activity D1. At activity D2, an initial set of drawings and assemblies, mechanical and electrical specifications were discussed. In the middle of the schematic design stage, the BEM expert participated in design coordination meetings every other week. The BEM expert did not update the model at every meeting but instead provided feedback on how the design changes may impact the energy model and energy efficiency goals. The architects provided actual assembly descriptions for activity E2 which was done at the end of schematic design decision-making. The purpose of activity E2 was to define feasible mechanical systems and their size constraints in order to find equipment that meets desired efficiency requirements. The BEM expert only presented numerical values for energy-related assumptions without any suggestions on how to achieve those numbers, such as the specific types of insulation and their respective thicknesses. It was not their responsibility to determine the methods of reaching those targets. Lighting is an important input for energy modeling, and LED lighting is commonly used in BC. Typically, a full lighting design with specified fixtures and powers is not available during the schematic stage (as in this project), so the modeler used lighting power densities from established standards such as NECB and ASHRAE 90.1 to estimate the lighting power for a given space use type. Communication about electrical assumptions was typically done via email and about mechanical assumptions was via phone call and email. The outputs of activity E2 entered the next stage. Hence, activity E2 did not influence schematic design decision-making and was used only for checking requirements for the BC energy step code.

4.2.3. Design Development Phase of the 1st and Clark Project

In this project, the detailed design stage started with a delay. The activity E3 started during activity D3, detailed design decision-making. BEM was created using drawings of all components, including architectural, mechanical, and electrical systems. Then, it was sent to project stakeholders, such as designers and the trades to review, as is necessary on an IPD project. The stakeholders discussed the energy model assumptions in two meetings and asked the BEM expert to revise the model. Therefore, activity E3 output arrow went back as an input for activity D3 and two energy models were created at this stage. In other words, activity E3 influenced design decision-making at the detailed design stage. BEM was based on consultant review comments. Two notable changes were added: Innova PTHP in suites; and modifying podium glazing from USI 1.4 to USI 2.27. Figure 13 represents the decision-making activity for glazing changes within activity D3. Activity E3 was initially created using inputs for activity E2, assuming that all glazing (both residential and commercial) had a U-value of 2 W/m2K. In activity E3, the U-value for all glazing was reduced to 1.4 W/m2K, with a maximum Solar Heat Gain Coefficient (SHGC) of 0.350 to meet BC Housing Construction Guidelines. However, during an Architectural PIT meeting, it was determined that using commercial windows with a U-value of 1.4 W/m2K would be too expensive and they are not easily available in the BC market, based on information from the glazing trade. As a result, the U-value only for commercial glazing was increased to 2.27 W/m2K, leading to a nearly 20% increase in the TEDI.

Figure 14 shows decision-making activity for cooling system changes within activity D3. In activity E2, the energy model used passive cooling with a limitation of 200 h for overheating. However, later, an amendment to the city of Vancouver (CoV) energy modeling guideline recommended that for buildings with vulnerable groups, the maximum allowable overheating hours should be 20 instead of 200, even for passive cooling. In response, activity E3 was designed to meet the new overheating requirement of 20 h. However, the model did not initially meet the requirement, and the mechanical consultant suggested adding Innova PTHP in suites to comply. As a result, in the revised BEM in activity E3, Innova PTHP was added to the suites to meet the new overheating requirement as an active cooling system.

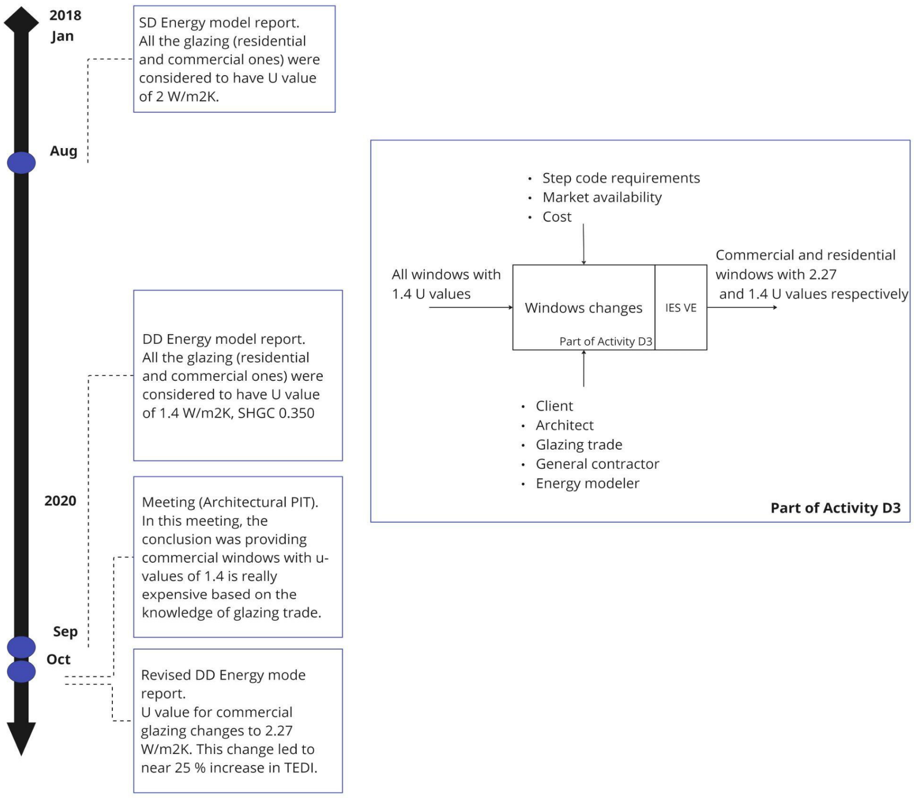


Figure 13. Decision-making activity for windows change within activity D3, showing timeline of evidence (**left**) and decision-making activity (**right**).

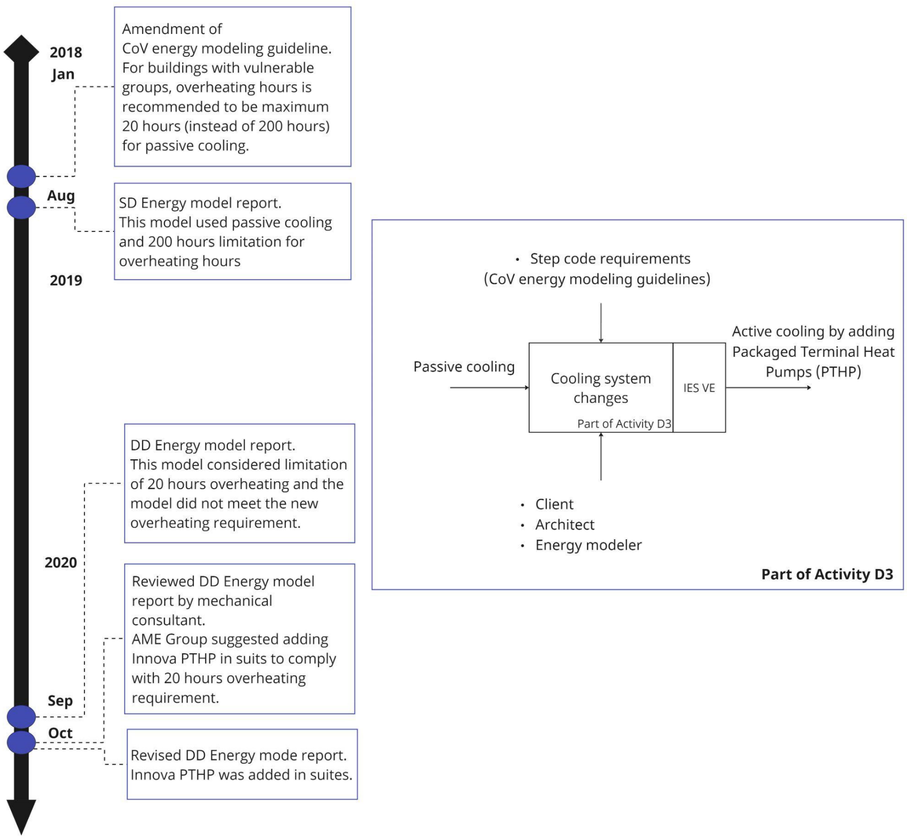


Figure 14. Decision-making activity for cooling system change within activity D3, showing timeline of evidence (**left**) and decision-making activity (**right**).

4.2.4. Communication Frequency and Key Insights in the Design Process of the 1st and Clark Project

The key insights derived from the process modeling emphasize the need for timely incorporation of BEM results into the design process to inform design decisions. While there was increased engagement from the BEM expert in this project compared to the other case study, the overall trend revealed the architect's frequent interaction with the mechanical and electrical consultant rather than with the BEM expert. Some back-and-forth communication occurred between the BEM expert and the design team, illustrating how BEM influences decision-making. The observations outlined in this subsection will be utilized for analyses in Section 5.

5. Observed Benefits and Challenges

The extensive data analysis of the two ethnographic case study projects through hybrid inductive and deductive thematic analysis led to the emergence of observed benefits and challenges of current practices of integrating BEM in the design process in collaborative construction projects with high-energy performance goals. The identified themes are presented within three categories of process, tools, and organization, as organized below.

5.1. Observed Benefits

5.1.1. Process-Related Benefits

More collaboration, better assumptions: Collaboration between stakeholders in collaborative project delivery methods helps the design team better understand their design's impact on building performance and the constructability of different design options. This enables the design team to refine the energy model to make it closer to what will happen in the construction and operation phases. In other words, it can improve information integrity. For example, in the 1st and Clark IPD project, after reviewing the energy model by the project stakeholders, the design team decided to change the window design to a higher U-value because the glazing trade argued that the previous higher performance options were unavailable based on market analysis. This change was applied to the energy model, and as a result, the projected TEDI increased by 20%. In the Vienna House IDP project, integrated design workshops helped owners and the design team to be on the same page regarding energy performance goals of the building and the design team gained an understanding of the design options available in each discipline. Additionally, the engagement of the cost estimator in detailed design-decision making changed the exterior wall's R-value which affected the energy model. This finding aligns with the study by [19], which identified a correlation between suboptimal system performance during operations and design decisions lacking accurate contextual information. Evidence from the Vienna House and 1st and Clark projects underscores the importance of early, informed collaboration to ensure the consideration of accurate and sufficient data in mitigating EPG and shows that ineffective communication and collaboration can still occur, even in projects with collaborative delivery models.

IDP and IPD methods are time-consuming but effective: During IDP and IPD, the involvement of the project teams in meetings was time-consuming, particularly for making critical decisions. But, in some cases, the project teams admitted that these collaborations were effective, such as decisions regarding the building form in Vienna House. A few articles emphasized the significant role of collaborative delivery methods in facilitating better-informed assumptions and decision-making processes [15,19,24]. Nonetheless, the Vienna House project reveals that, from the stakeholders' perspective, such an approach can require substantial time investment.

Benefits of sensitivity analysis at the conceptual design: It is important to conduct sensitivity analysis early on. Through sensitivity analysis, designers and BEM experts can gain valuable insights into the potential impacts of changes to various building components or systems on overall energy performance. This can help identify areas where improvements can be made and facilitate informed decision-making throughout the design process. "The design team expected standard R 22 in the walls instead of high-density R 24. And because we've done the sensitivity analysis earlier, we can say, okay, that's not a big deal, because we know the relative impact that R-values will have on the overall building performance" (Project's BEM expert, Interview, February, 2023). The application of sensitivity analysis during the initial design stage was discussed by several studies [76–78]. However, this study on the 1st and Clark project provides new insights by documenting the practical application of sensitivity analysis in a real project. The findings demonstrate that early sensitivity analysis can enable the design team to make informed decisions based on practical constraints, offering a clear understanding of performance trade-offs.

Benefits of early involvement of builders: Involving construction managers in the design process can provide valuable feedback on the buildability and cost of design decisions. For example, they can provide insight on the practicality of different window types and insulation options, which can help the design team make more informed decisions earlier in the process. In the 1st and Clark project, evidence showed that early engagement of builders could provide feedback on the availability of products and the compatibility of assumptions in the energy model with real-world market conditions. This can avoid costly revisions later in the process. However, in the Vienna House project, despite the construction manager's enthusiasm to be involved in the design process earlier, the design team only asked the construction manager for feedback on economic aspects of the electrical design. This missed an opportunity to gather valuable input on other aspects of the design, such as insulation and window types.

Easy co-ordination while having a BEM expert in the design team: "It has worked quite well to have the energy modeler as part of the mechanical and electrical team, ideally within the same company. This is because the architect has to do less co-ordination for the energy model, and only needs to co-ordinate with the envelope consultant" (Project's Architect, Interview, October, 2022). While architects are experts in building design, they may not have the same level of knowledge about mechanical systems and energy modeling. As a result, they may not feel confident in the accuracy of energy model results. However, by including a BEM expert on the design team, the modeling process can be improved. The BEM expert can work closely with the mechanical and electrical team to ensure that the building systems are optimized for energy efficiency and their specifications are correctly entered into the model leading to more accurate and effective modeling results. Furthermore, having the BEM expert on the team can free up the architect to focus on other aspects of the design, knowing that the energy model is being expertly handled by the BEM expert. Based on the opinion of the Vienna House architect, having the BEM expert within the same company as the mechanical designers can also reduce co-ordination challenges, as the team is already familiar with each other's work and can communicate more easily. This can help ensure that the energy model is integrated with the overall building design, resulting in a more effective and energy-efficient building.

Benefits of early engagement of mechanical consultants: Early engagement of mechanical consultants in energy modeling can bring various benefits to a building project. Mechanical consultants can provide valuable input in terms of the most efficient and effective HVAC system design, which can result in a reduction of energy consumption and a more accurate energy model. Mechanical consultants can provide insights into the interaction between the HVAC system and the building envelope as well. "It is important to try to get a decision as early as possible on the mechanical design, such as what type of ventilation system is going to be used, because the difference in putting a HRV in every suite versus using a central system is a pretty large impact to the energy model" (Project's BEM expert, Interview, February, 2023).

5.1.2. Tool-Related Benefits

BEM tools have been instrumental in securing funding from various sources for both projects by demonstrating energy consumption reductions. Additionally, they play a crucial role in obtaining certifications and demonstrating compliance with codes and standards.

5.1.3. Organization-Related Benefits

Organizational familiarity with performance targets: Establishing organizational familiarity with performance targets is crucial for successful project outcomes. In the context of the IPD project, 1st and Clark, the project team ensured that all stakeholders possessed a clear understanding of the specific performance objectives being pursued. As a result of this concerted effort, the project team was able to minimize significant deviations from the targeted R values for assemblies. "Everyone was on board with what sort of performance we were targeting. Construction assemblies reflected on that" (Project's BEM expert, Interview, February, 2023).

5.2. Observed Challenges

5.2.1. Process-Related Challenges

Considerable distance between design decision-making and energy modeling: One challenge during the design process is that sometimes BEM or discussions around energy modeling take place later in the project, when the project has already moved into the next stage and outcomes from the BEM are not able to be successfully integrated into the decision-making process. "There is a big gap where the project team is not really doing another iteration of the energy model. And the distance between design decision-making and energy modeling is something quite hard to close. And it can be quite slow feedback due to the difficulty of creating energy models. So by the time you get your energy results back, you've already kind of moved on to different details and to building different issues" (Project's Architect, Interview, October, 2022).

Late thermal bridge analysis: In complex building design projects, it is highly advisable to conduct thermal bridge analysis early on and ensure alignment with the overall design process. This approach can greatly improve confidence in energy performance results and help avoid the need for overly conservative allowances.

Unified language between envelope consultant and BEM expert: Challenges may arise when stakeholders are using different units of measurement or terminologies, leading to potential errors and misinterpretations. In the Vienna House project, for instance, there was a lack of unified language between the envelope consultant and BEM expert, which resulted in co-ordination difficulties. The BEM expert utilized metric measurements while the envelope consultant used imperial measurements, making it challenging to reconcile inputs and outputs.

5.2.2. Tool-Related Challenges

Interoperability issues and lack of flexibility in Revit: Interviewees mentioned that BEM is a complicated process and one issue is the interoperability between design and energy modeling tools, particularly for large buildings. It is difficult to automatically obtain reliable energy performance results when design changes are suggested or applied by the design team. As a result, the project team is not eager to model more options and instead creates one energy model for each stage throughout the entire design process. As interviewees argued, Revit, one of the most used building information modeling (BIM) tools, needs to be more flexible to provide an automated and accurate energy model easily. The larger the project size, the more complex the integration. "In case of passive house design, if you're designing a very small building, you can model it in SketchUp, and use the plug-in SketchUp to test things quite quickly in PHPP. But once you start modeling a big building in Revit, and your systems get more complicated, it often involves a manual process for the energy modeler to capture the information from the drawing set, and put it into the PHPP, which is in Excel sheets" (Project's Architect, Interview, October, 2023). Because of difficulties of importing models from Revit, BEM experts usually work with PDF or CAD files of drawings. "It is faster to draw geometry directly in IES VE rather than import it from Revit. And another reason for not using Revit is different zoning in energy models" (Project's BEM expert, Interview, Feb, 2023).

BIM–BEM interoperability issue was also mentioned in several studies [79–81]. This study on the Vienna House and 1st and Clark projects shows that interoperability challenges created reluctance among the project team to perform iterative BEM and provide frequent feedback to the BIM process, causing the project team to prefer manual input methods.

Lack of automatic LCA: "Frequent LCA is useful but it is challenging to have it automatically" (Project's Architect, Interview, October, 2022). Life Cycle Assessment (LCA) is a valuable tool for assessing the environmental impacts of buildings during the early design phase [82]. However, conducting frequent LCA analyses can be challenging, especially when it comes to automating the process. Additionally, the availability and quality of data and the complexity of the building systems and materials can also affect the accuracy of the results. Therefore, finding ways to automate LCA analyses while ensuring their accuracy and reliability remains a significant challenge for building design and construction professionals. This challenge was also mentioned in several studies [83–85].

Complexity of some of the energy analysis and thermal bridge tools: In the PHPP used in Vienna House, evaluating various design options for energy efficiency was a challenging and time-consuming process. This difficulty limited iterations for energy models and trying more design options. Thermal bridge analysis requires drawing a lot of details in thermal bridge software. To account for the complex details involved in thermal bridge analysis, the preparation of the necessary drawings and results can be a time-consuming process, as was the case in the Vienna House project. This challenge was also mentioned in several studies [86–90]. However, the Vienna House project illustrates how late this analysis reached the designers, by which time most design work had already been completed. It highlights the benefits of initial discussions on thermal bridging considerations and emphasizes the importance of determining, at an early stage, the optimal timing for conducting thermal bridge analysis within the design process.

5.2.3. Organization-Related Challenges

Clarity of space usage at the early design stage: It is important to define how a space will be used when designing the building systems, particularly for larger spaces. For example, an office space will have different energy needs and requirements for set points and ventilation than a lounge area. Understanding the intended use of the space early in the design process can help to avoid major specification changes related to space application, resulting in energy and cost savings during the design process.

Lack of LCA consultant and thermal bridge expertise within the design team: One of the challenges encountered in the Vienna House project was the lack of available data or analysis on the embodied carbon of certain building components, such as the wall assembly. Although the architect had an intuition that prefabricated walls had less embodied carbon compared to site-built walls, no concrete data or analysis was readily available to justify this change. Additionally, early engagement of thermal bridge expertise was limited in this project, as the analysis was to be performed by a third party, which resulted in delays and a slower decision-making process.

Difficulty in defining correct requirements: Given the various occupancy classes and stakeholders involved in a project, it can be challenging to ensure that all requirements are met to avoid any surprises down the line. In particular, the 1st and Clark project, BC Housing, CMHC, and the CoV all had different energy requirements that had to be considered. This means that the energy requirements needed for the building permit application may not be the same as those required for the conceptual phase and rezoning requirements. This is where early energy modeling and analysis can be especially important, as it allows the project team to identify and address any potential conflicts or issues that may arise. By identifying overlapping and separate energy requirements, the project team can work to optimize the design and decide how to proceed with requirements while ensuring that all stakeholders' needs are met. Although this challenge was also mentioned in [91], the 1st and Clark project indicates that early energy modeling and discussions between BEM experts and other stakeholders can help prioritize and reconcile diverse requirements across stakeholders from the outset.

Confusion because of changes in energy codes: Because of the long duration of the 1st and Clark project, there was a significant time gap of two years between the initial conceptual design and the subsequent design stages. During this period, there were changes in the energy code regulations that were in effect. As a result, these code revisions caused confusion and uncertainty when it came to moving forward with meeting the performance requirements of the project. "Changing in codes makes it confusing to know whether the project will be grandfathered into the original requirement" (Project's BEM Expert, interview, February, 2023). This could have resulted in delays or additional costs if the design team had to go back and make significant revisions to their plans in order to comply with the updated energy codes.

Complexity of the energy codes: It was noted that energy standards and codes are poorly structured or disorganized, with complex and hard-to-follow requirements. They could make it difficult for designers and builders to understand and comply with energy efficiency standards and codes. One of the interviewees used the term "code spaghetti" for this challenge. "This is my favorite term for the multiple different requirements, code spaghetti... Step code alone refers to NECB and CoV EMG, then there are different versions of NECB, etc....!" (Project's BEM Expert, interview, February, 2023).

Compliance vs. Optimization: BEM is mainly used to comply with building energy performance codes and certifications. Improving the accuracy of BEM inputs, obtaining more accurate results, and optimizing the design are less of a priority. In other words, there are fewer incentives in current practices for designers to optimize the energy performance design. Therefore, there is an opportunity lost to reduce the EPG and design buildings with better energy performance.

6. Conclusions and Outlook

This research paper delved into the critical issue of ineffective communication and collaboration among project stakeholders in the context of energy-efficient design decision-making practices. To investigate this, two case studies were conducted, chosen for their emphasis on high-energy performance goals, use of collaborative methods, and substantial project scale. Qualitative data were collected through an ethnographic approach including direct observations, combined with project document analysis, and semi-structured interviews with project team members. Design process modeling was conducted using a customized IDEF0 structure, resulting in design process models that provided a tangible visualization for understanding BEM engagement within the design process in collaborative construction projects. This was followed by a hybrid inductive and deductive analysis to dissect the intricacies of current practice, highlighting both the benefits and challenges that exist within the three categories of process, tools, and organization.

It was observed in this research that BEM experts often are isolated from the design process, and this isolation is further compounded by the late integration of energy modeling outcomes into the design decision-making. Moreover, this study underscores the critical importance of early collaboration among different project stakeholders. Early engagement, including peripheral roles like cost estimators and tradespeople, can enrich the integrity of both energy models and design decisions, fostering a holistic approach. Policies supporting such early involvement could further institutionalize design practices that integrate energy efficiency from the outset. In addition to the early-stage engagement of project stakeholders, it is imperative to have clear project requirements and ensure alignment among all stakeholders from different disciplines at early stages. This clarity can put BEM experts aligned with the design process and can promote collaboration across diverse disciplines. Furthermore, it is important for BEM experts to have a grasp of both architectural and mechanical aspects of the design. This interdisciplinary comprehension can enhance the design team's confidence in the energy modeling outcomes. A concerning aspect for BEM experts is the intricate nature of energy codes, often characterized by cross-references between different codes and various versions of codes, causing potential confusion and complexity.

Moreover, as this research highlights, energy modeling requirements are generally limited to checklist-based regulatory compliance rather than leveraging BEM as a robust tool for optimizing energy performance in the design of a building. A lack of incentives for iterative BEM applications also contributes to this underutilization of BEM for energy performance optimization. These findings highlight the need for policies that encourage iterative, performance-based BEM applications to better support energy performance optimization. This research also demonstrates challenges related to the interoperability of BEM 2023 software with other tools especially with BIM platforms and the complexity of BEM software themself for conducting detailed energy modeling. As a result, this research shows that design teams tend to rely more on qualitative insights from energy experts rather than conducting comprehensive BEM analyses, limiting the use of quantitative energy performance outcomes in design decisions.

The findings from this study offer practitioners valuable insights on effectively incorporating BEM into their design process to make informed design decisions. By addressing challenges within their scope, practitioners can optimize the benefits of BEM and collaborative efforts. Furthermore, these findings can provide valuable support to policy makers in developing strategies to enhance the role of BEM in projects and promote performance-driven compliance requirements. Effective policy frameworks that focus on performance-based requirements, rather than solely prescriptive standards, could facilitate more meaningful contributions from BEM to the energy efficiency of building designs and serve as incentives for iterative BEM applications.

In future endeavors, both researchers and industry partners are encouraged to collaborate on the following areas:

- Enhancing collaboration and bridging gaps between BEM and design decision-making: There is a need to bridge the gap between BEM and design decision-making activities. This could be achieved by developing novel procedures that promote effective integration of BEM into the design process. This integration can be achieved through the characterization of energy performance design decision-making and BEM. Additionally, the creation of user-friendly tools for iterative and easier energy modeling should be explored.
- Quantifying early engagement impact: Future research should aim to assess the influence of early engagement of project stakeholders during the design phase of real projects, both qualitatively and quantitatively, compared to scenarios where such engagement is lacking. This would shed light on the true impact of early involvement.
- Assessing BEM expert knowledge impact: The effects of BEM experts' familiarity with architectural and mechanical aspects of energy modeling, as well as their comprehension of energy codes, should be qualitatively and quantitatively investigated. Understanding how these factors influence modeling outcomes is crucial.
- Simplifying energy code utilization: Efforts should be made to reduce the complexity of using energy codes. This could involve the development of tools that streamline the code navigation process.
- Investigating collaboration during operation phase: Benefits and challenges of current practice regarding collaboration during operation phase in order to enhance building performance should be identified. Additionally, the impact of collaborative design decisions on actual building performance needs to be assessed. This can provide insights into effective strategies for the design phase that can contribute to narrowing the EPG during the operation phase. Specifically, identifying key requirements for a successful handover in terms of bridging the performance gap during the operation phase can be helpful.

This study offers an in-depth examination of BEM integration in two collaborative design projects. The study's findings highlight the importance of collaboration and frequent data exchange between BEM experts and other stakeholders. Moreover, it demonstrates that the presence of a collaborative contract model alone does not ensure the integration of critical roles, especially from an energy performance perspective. This research provides actionable insights that can guide practitioners in optimizing BEM usage and serve as a basis for policymakers aiming to promote performance-driven requirements in building codes. Additionally, this research opens avenues for future studies to quantify the impact of early stage collaboration on energy performance outcomes.

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