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THE BIM AND BEM INTEGRATION – OPPORTUNITIES, LIMITATIONS, AND INFLUENCE ON BUILDING DESIGN

INTEGRACIJA BIM IN ENERGIJSKEGA MODELIRANJA STAVB - PRILOŽNOSTI, OMEJITVE IN VPLIV NA NAČRTOVALSKI PROCES

BIM A+ European Master in Building Information Modelling

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Assoc. Prof. Mitja Košir, PhD.

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BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK

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Izvleček:

Zanimanje gradbene industrije za energijsko modeliranje stavb ni novo saj le-to predstavlja močno orodje za določitev energijske učinkovitosti stavb. Takšno modeliranje je v pomoč načrtovalcem, lastnikom in upravljalcem stavb pri doseganju njihovih trajnostnih ciljev, omejitvi rabe energije in stroškov projekta. Energijsko modeliranje stavb je možno integrirati v načrtovalski proces na različnih stopnjah načrtovanja, od konceptualne zasnove pa vse do izvedbe ter kasneje tudi v procesu upravljanja stavb. V pričujoči nalogi se posvečamo integraciji BIM in energijskega modeliranja stavb v zgodnji fazi načrtovanja. Glavni poudarek predlagane naloge je raziskati stanje tehnike na področju integracije BIM in energijskega modeliranja stavb ter izpostaviti priložnosti in omejitve takšne integracije z vidika načrtovalca stavb. Posebej zanimiva je identifikacija (i) prednosti v primerjavi s pomanjkljivostmi, (ii) vplivov na potek dela in (iii) potenciala za povečanje učinkovitosti končnega projekta. Pregled literature je razkril pomanjkanje raziskav o procesnih zemljevidih v korist tehničnih vidikov integracije energijskega modeliranja z BIM. Sočasno je bila identificirana tudi potreba po izboljšanju standardov, povezanih z energijskim modeliranjem stavb. Rezultati praktičnega primera so pokazali, da je za zagotovitev brezhibnega delotoka integracije potreben zemljevid procesa, slednji pa mora biti pripravljen za specifično programsko opremo. Upoštevanje jasnega in celovitega procesnega načrta, prilagojenega zgodnji fazi načrtovanja, poveča učinkovitost delotoka, koordinacijo in produktivnost. Prav tako pomaga načrtovalcu pri raziskovanju nabora projektnih rešitev v razmeroma kratkem času, s čimer se posledično izboljša kakovost projekta z gledišča trajnostnih ciljev.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

The interest of the AEC industry in building energy modelling is not new. BEM is a powerful tool to assess and control the building's energy performance. It assists both AEC professionals and building owners in reaching their sustainability goals and limits energy consumption and the project's cost. BEM can be integrated at different design stages, from the concept design to construction and management. This work is interested in the BIM-BEM integration at the early design stage. The main focus of the proposed thesis is to investigate the state-of-the-art in the field of BIM and BEM integration. In particular, to highlight opportunities and limitations of integrating the energy performance evaluation of buildings with BIM models from the point of view of the building designer. Of particular interest is the identification of (i) benefits vs drawbacks, (ii) impacts on the workflow, and (iii) potential for increasing the final design's performance. The literature review revealed the lack of research about process maps favouring technical aspects and the need to improve BEM-related standards. The results of the practical case demonstrated that a software-specific process map is needed to ensure a seamless BIM-BEM integration workflow. The respect of a clear and comprehensive process map adapted to an early design stage increases the efficiency of the workflow, coordination, and productivity. It also assists the designer with exploring more design options in a relatively short time, improving the design in respect of sustainability goals.

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Last but not the least, I heartily express my gratitude to my family, my pillar who was always supportive and encouraged me to widen my knowledge and achieve my ambitions. Nothing would have been possible without my parents and my sister who despite the distance supported me unconditionally.

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AEC	Architecture Engineering Construction
HPG	High-Performance Green Building
ES	Energy Simulation
BIM	Building Information Modeling
BEM	Building Energy Modeling
IR	Information Requirements
LOD	Level Of Development
LEED	Leadership in Energy and Environmental Design
USGBC	U.S. Green Building Council
IFC	Industry Foundation Classes
gbXML	Green Building eXtensible Markup Language
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers and
HVAC	Heating Ventilation and Air Conditioning
IEEE SD	The Institute of Electrical and Electronics Engineers Standards Association
EUI	Energy Use Intensity
WWR	Window-to-Wall Ratio
UC	Utility Cost
WUI	Indoor Water Use Intensity
NECB	National Energy Code for Buildings
sDA	Spatial Daylight Autonomy
ASE	Annual Sunlight Exposure

1 INTRODUCTION

1.1 General outline

The world is witnessing dramatic growth in population, economy, and living standards. These have led to an increase in the energy consumption of buildings. The exponential growth in AEC (Architecture Engineering Construction) and built infrastructure have led to an urge to implement energy-saving strategies. According to a recent report from the Intergovernmental Panel on Climate (IPCC, 2018), the built environment is responsible for:

• the use of 40% of global energy, 40% of global resources, 25% of global water, and approximately 33% of GHG emissions and

• over 30% of landfill waste (for the entire construction sector).

The construction sector in Europe has recently been labelled the poorest regarding productivity, and many difficulties have been identified in terms of digital innovations. Therefore, there is a need for the AEC industry to reconsider the efficiency of the buildings and reform the current processes (Elagiry et al., 2019)

Nevertheless, significant savings could be achieved with the proper use of technology and some energy-saving strategies. ‘A high-performance green (HPG) building has energy, economic, and environmental performance that is substantially better than the standard practice (U.S. Dept. of Energy DOE, 2003). HPG buildings are more energy efficient. They economize natural resources and save money. They also provide a healthy and comfortable living space for the occupants with a low environmental impact. According to Riley et al. (2004), High-Performance Green buildings minimise resource consumption from the design phase to the construction and all over the building lifecycle. In addition, it offers a comfortable, healthy, and productive environment for its users while applying “green” and “sustainable” strategies (Riley et al., 2004). “The return on investment for HPG facilities is realized through reduced operating costs, occupant satisfaction, reduced absenteeism, and increased performance” (Kobet et al. 1999).

HPG Buildings' design is characterised by using simulation tools to assess, compare and validate the design scenarios. These tools offer different abilities to support the design's modification and estimate its energy consumption. Some tools were used to better understand and control the energy performance of buildings through Energy Simulations (ES). The use of Building Information Modeling (BIM) and Building Energy Modeling (BEM) methodologies becomes an essential part of it. Elnabawi (2020) has admitted that BEM is necessary for the energy consumption estimation of a building as it assists designers, facility managers, and owners in assessing the building’s energy consumption to determine its energy performance during the design phase (Elnabawi, 2020). It has also been said that 80% of the building's energy performance is decided within the first 20% of the design process (Lack and Butler, 2019). Therefore, the architectural model must be shared in the early design stages to create the building energy model and then run the energy simulation to reduce the risks of model divergence and avoid errors, and misunderstandings (Klitgaard, Kirkegaard, & Mullins, 2006).

1.2 Research Aims and Objectives

This research aims to experiment with the BIM-BEM integration process and evaluate the challenges that arise while performing an energy simulation during the early stage of the design phase. The ES is a decisive tool when choosing between design options and optimising the solutions. It is thus necessary to understand the extent of the support that BEM offers designers and the challenges they might face during the process of using it. The main question is, what opportunities do BIM-BEM offer to designers and what limitations do they face in the process? Would using BEM at the early design stage bring more opportunities than challenges? Would it contribute to the efficiency of the design workflow and contribute to efficiency in the design? Furthermore, how would it affect the design process as a whole?

1.3 Main Hypothesis

With the development and continuous research on ES and BEM tools, we believe that we have reached an advanced stage that using BEM for BIM at the design phase could contribute positively to the design development. We believe that the use of proper ES tools and a straightforward workflow would indeed contribute to a more efficient workflow. It might affect the design as some recent tools provide real-time simulation, which could eventually cut the rework time, and allow the simulation of more design options and the optimization of the selected design strategy without needing a detailed model and specialized professionals.

2 METHODOLOGY

To validate our hypothesis, this research was divided into two main parts.

As a first step, a comprehensive survey on BIM-BEM integration studies was conducted in order to understand the current level of BIM-BEM implementation. This survey aims to:

- Explore The theoretical frame of the BIM-BEM implementation, the level of the integration of energy analysis and the development of research in this field, the main flowcharts, and prerequisites to assure the energy analysis.
- The gaps in the BIM-BEM process and the limitations as identified by previous researchers.

After the identification of knowledge gaps based on the studied literature, we focused on two main aspects of the BIM-BEM integration.

- Identifying a comprehensive data workflow in the early design process.
- Identifying design aspects (activities and requirements) that limit the needed rework in the BIM-BEM workflow.

In the second part, a practical case study was investigated to implement integration strategies highlighting the issues evoked in previous studies. The process map implemented was inspired by previous research works and adapted to the early design stage. The pre-processing step included identifying the project goals and aspirations, IRs (Information requirements) and LOD (Level of development). Afterwards, we proceeded with setting the project location and building the BIM model on the authoring tool and then transfer it to the BEM tool for energy analysis. In chapter 3, we identified and compared some widely used BEM tools, and we chose the adequate tool to suit our purpose of performing the energy simulation at an early design stage. Our choice was based on the design phase we are investigating and the capacity of a designer to use the tool with ease. After identifying the tool, we created a second BEM tool-specific process map to guide us through the integration process. The energy analysis comprises a series of simulations and comparisons of different design options and optimisation processes.

2.1 BEM Opportunities

Figure 1: BIM dimensions (Biblus)

Figure 1 represents the seven dimensions of BIM, with BEM falling under sustainability, the sixth dimension. It is used in two main areas. At the design stage, it is used for the evaluation of design and estimation of the energy consumption of different design options and checking compliance with legislation requirements and building rating systems and their goals and prerequisites. For this purpose, BEM could be used at different stages of the design, from concept design to detailed design, as elaborated in figure 2.

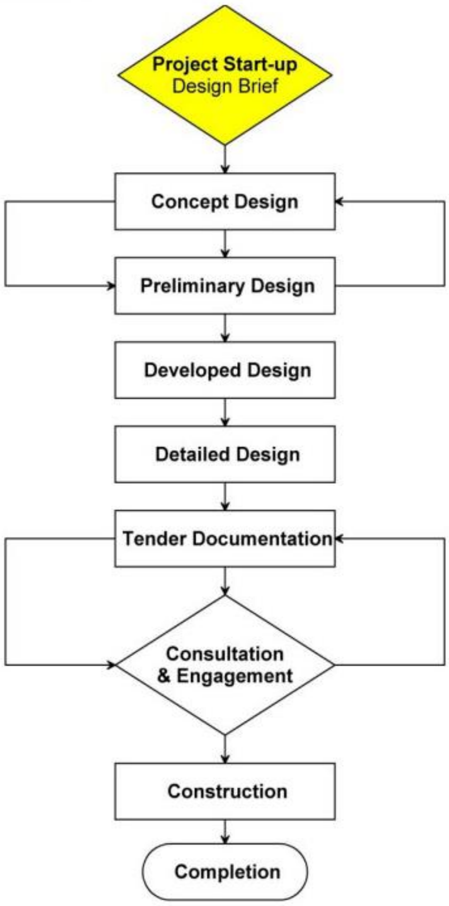


Figure 2: The conventional design process (MinistryfortheEnvironment2008)

Navigant Research (2018) report stated that energy simulation results are valuable in comparing design options in the conceptual design phase and the modelling control of the building during the operation and maintenance phase. In facilities management, BEM can be used to identify potential improvements in system levels to reduce energy consumption and to monitor and control the building's energy consumption (Reeves and Olbina, 2012). It offers numerous benefits to each intervenient of the sector. Figure 3 summarizes the main goals and benefits of using BEM. It shows that BEM offers equal opportunities to designers, building owners and future occupants as it aims to provide a healthy and sustainable environment. It assists designers through all design phases to focus their time effectively and reach their goals. It also creates new technical expertise opportunities for professionals. As for building owners, the main advantage is reducing the costs of construction, operations, and maintenance.

Broad Energy Modeling Goals and Benefits

	CONCEPT DESIGN	SCHEMATIC DESIGN	DESIGN DEVELOPMENT	CONSTRUCTION DOCUMENTS	CONSTRUCTION/ POST-OCCUPANCY
TEAM GOALS	Use early Design Performance Modeling to help define the goals of the project (NOTE: Design Performance modeling could be with either component modeling tools or a basic building energy model, but should at this stage address other performance param-eters in addition to energy.) Define the project requirements, as informed by modeling results	Review financial and performance energy information from model to guide design decisions	Review design alternatives based on initial goals, as informed by modeling results Create baseline and alternatives to choose from	Create documentation needed to accompany energy model results for code compliance Create documentation needed to accompany energy model results for commissioning and metering/ monitoring validation	Use results of the as-built model for commissioning Compare results of the as-built model against metered data to look for operating problems
ENERGY MODELING GOALS	Experiment with building siting and orientation Determine effective envelope constructions Assess the effects of daylighting and other passive strategies Explore ways to reduce loads	Create a rough baseline energy model Test energy efficiency measures to determine the lowest possible energy use Set up thermal zones and HVAC options	Create proposed models with system alternatives to choose from Refine, add detail, and modify the models, as needed Provide annual energy use charts and other performance metrics for baseline vs proposed Evaluate specific products for project Test control strategies Do quality control check on the models	Complete the final design model Do quality control check on the models Create final results documentation needed to submit for code compliance	Complete the as-built model with installed component cut-sheet performance values Collect metered operating data to create a calibrated model to share with outcome-based database
BENEFITS TO CLIENT	Get entire design team united around project goals Use modeling results to make design decisions informed by integrated system performance	Test different options before implementing them Determine the most efficient and cost effective solutions	Determine the most efficient and cost effective solutions Size mechanical equipment correctly	Use energy model as part of LEED or other sustainable design certification application Provide ability to better predict energy use in the building	Provide ability to refine operations to meet reduced energy use goals in the built project

Figure 3: Energy Modelling goals and benefits (AIA 2012)

Furthermore, energy performance analysis and simulations are necessary for various building sustainability rating systems, such as the U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) certificate (Kim and Anderson, 2013). Energy simulation is becoming an integrated part of architectural services and part of client requests for these sustainability certifications. Table 1 summarizes the main rating systems in different countries and regions.

Table 1 Sustainability rating systems

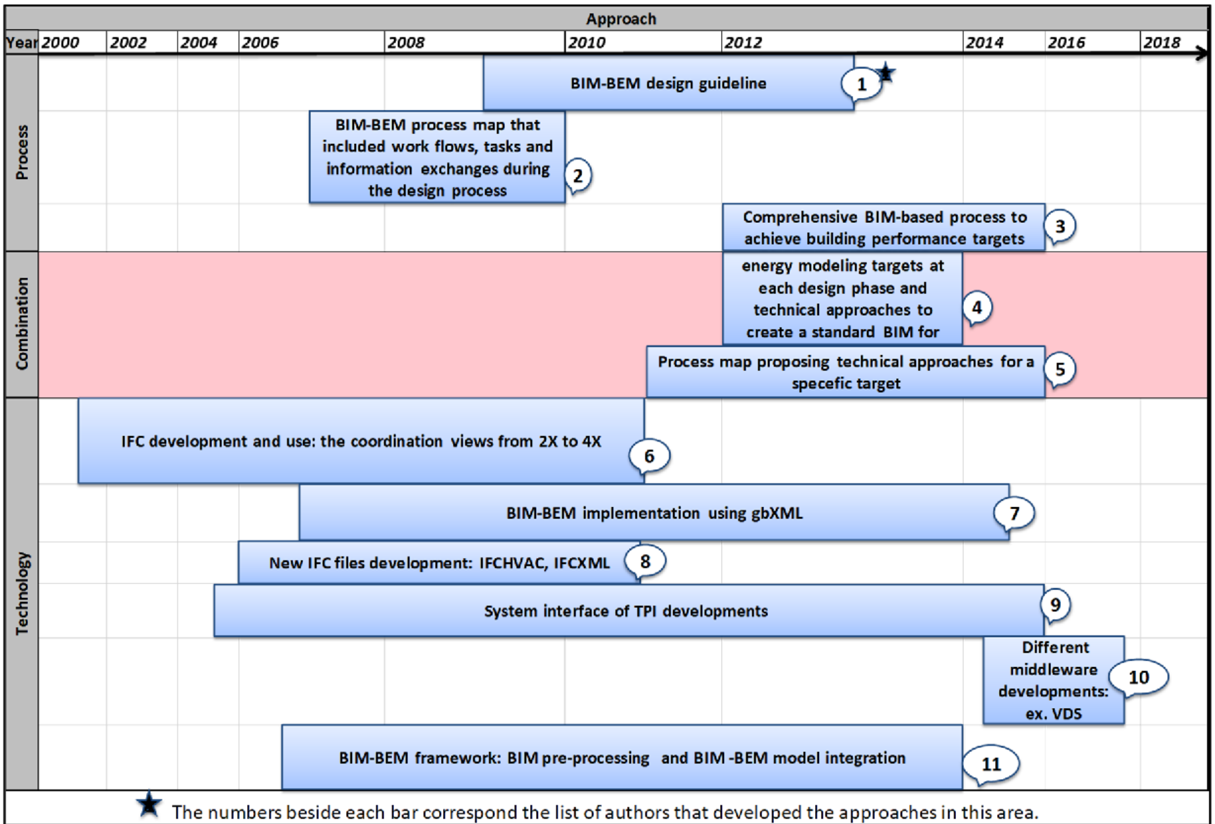
Rating system	Origin
LEED (Leadership in Energy and Environmental Design)	United States of America 2000
WELL (International WELL Building Institute) Living Building Challenge	2014
Green Globes	2000
Fitwel	2015
TRUE	2017
ENERGY STAR	1992
EDGE	2013
Green Star	Australia 2003
NABERS	1998

BREEAM (Building Research Establishment Environmental Assessment Method)	The United Kingdom 1990
DGNB	Germany 2007
Protocollo Itaca and Green Building Council Italia	Italy 2000
BCA Green Mark Scheme	Singapore 2005
Estidama	United Arab Emirates 2010
Green Globes	Canada and the USA

2.2 Literature review

Few studies were carried out on the BIM-BEM integration and management for the design process. Most of the studies on the BIM-BEM design process for disregard the identification and implementation of the required technological approaches to complete the energy simulation. In the research survey, Farzaneh (2019) stated that around one-third of the research covered the design process, and two-thirds covered technological approaches. In contrast, 15% of the surveyed research discussed both aspects (Farzaneh, 2019).

In their review on using ‘Building Information Modelling for building energy modelling during the design process’, the authors summarized the existing studies on BIM-BEM from 2001 to 2018. It is necessary to study where the industry stands in terms of technological progress and identify the gaps and have an insight into future works. The authors’ summary referenced in figure 4 divides the past research into three categories, process, technology, and a combination of both. They also organized them chronologically, and we can notice that more recent research is interested in the technology of BEM rather than the integration process. Therefore, some of the implemented processes may not be fully developed or are outdated. This lack of research offers a chance for new studies to develop and adapt previous studies to the new standards and push for more elaborated solutions and process maps.



Authors	
1	Bloomberg, Burney et Resnick (2012); CIC (2011); Eastman et al. (2009); Solnosky (2013); STAM (2016).
2	Koppinen et Kiviniemi (2007); Korkmaz et al. (2010).
3	Attia, Walter et Andersen (2013); Lee (2016); Tuomas Laine (2012); Wong et Fan (2013).
4	AIA (2012); D. Rovas (2017); GSA (2012); SALD (2016); Scherer (2017).
5	Arayici et al. (2018); Ilhan et Yaman (2016); Stumpf, Kim et Jenicek (2011); Wu et Issa (2014); Zanni, Soetanto et Ruikar
6	Bazjanac (2001; 2004; 2008); Bazjanac et Kiviniemi (2007); Bazjanac et Maile (2004); Hetherington et al. (2011); Maile, Fischer et Bazjanac (2007); O'Sullivan et Keane (2005); Plume et Mitchell (2007).
7	Azhar, Brown et Farooqui (2009); Ham et Golparvar-Fard (2015); Maile, Fischer et Bazjanac (2007); Osello et al. (2011).
8	Bazjanac et Maile (2004); Kim et Anderson (2011); Yi et al. (2007).
9	Jeong et al. (2014; 2016); O'Sullivan et Keane (2005); Sanguinetti et al. (2012); Yan et al. (2013).
10	Jabi (2014; 2015).
11	Bazjanac (2008); Bazjanac et Kiviniemi (2007); Hitchcock et Wong (2011); Maile, Fischer et Bazjanac (2007); Miller (2010); O'Donnell (2014); Osello et al. (2011).

Figure 4: BIM-BEM Research summary (Farzaneh, 2019)

2.2.1 BIM-BEM integration

BIM-BEM integration's main step is properly translating the BIM model into the energy simulation tool. Negendahl (2015) detailed three model integration approaches (Figure 5):

•Combined approach: where the simulation is performed in the same BIM tool that designs and calculates.

•Central approach: the model is built in one tool and then centralized into a data schema (such as Industry Foundation Classes (IFC) or Green Building eXtensible Markup Language (gbXML) then transferred to the simulation tool.

•Distributed approach: a middleware is used to modify and enhance the model in real-time so that the information is successfully interpreted between the design and the simulation tool.

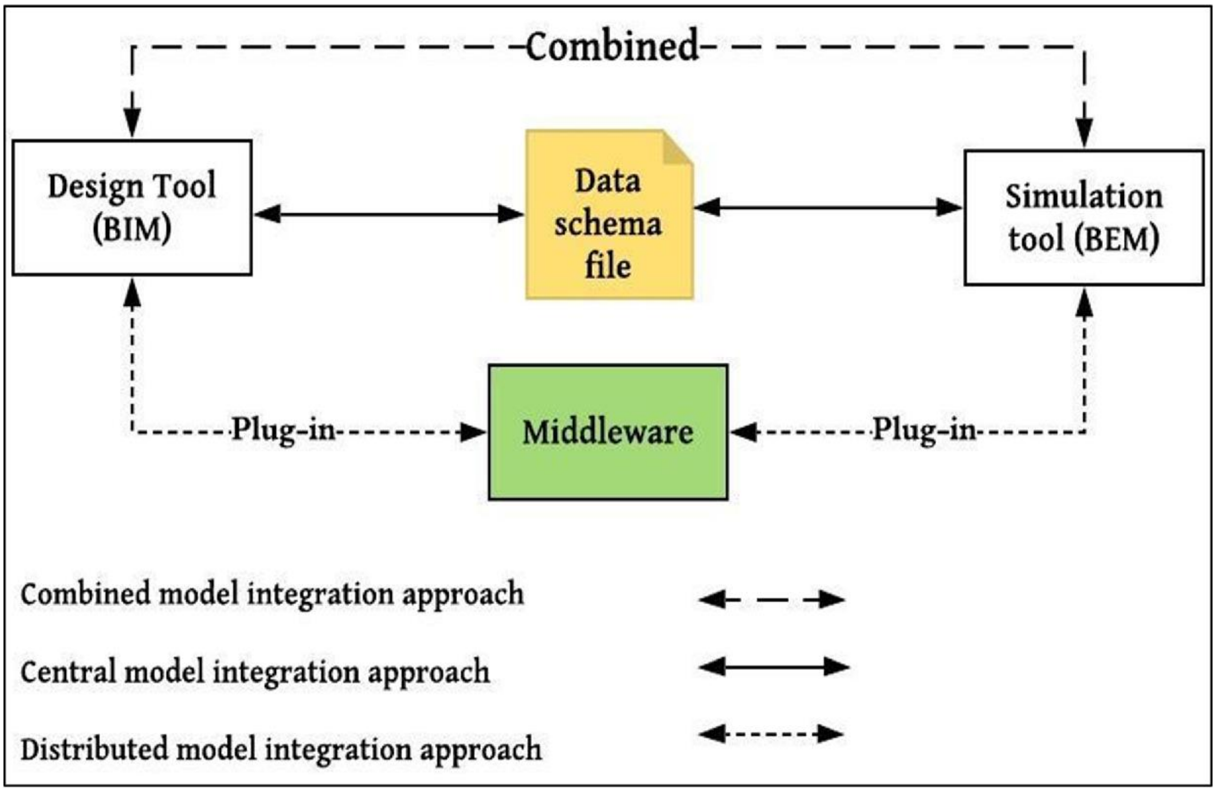


Figure 5: Model integration approaches (Farzaneh, 2019)

According to the literature, the most common approach for BEM is the central model integration. Therefore, data schema and interoperability play a major role in implementing this approach successfully.

2.2.2 BIM-BEM workflow

Numerous other research (Negendahl, 2015; Wu et Issa, 2016; Zanni, Soetanto et Ruika, 2017; Aida et al., 2019; Jorge González et al., 2021) have been conducted on the BEM in BIM and many of them propose some frameworks and workflows to achieve a successful integration.

Mohajer and Aksammija (2019) proposed the following workflow for their research (Figure 6).

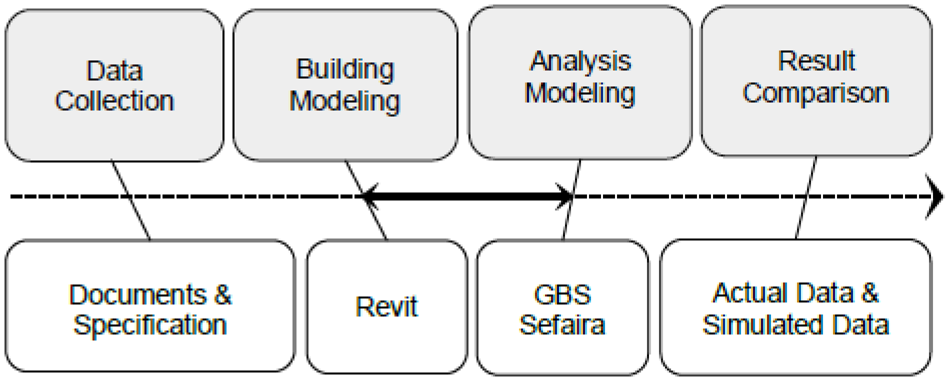


Figure 6: Research Workflow(Mohajer and Aksammija, 2019)

This workflow is based on comparing two BEM tools (GBS and Sefaira) compatible with Revit. They aimed to compare the built-in tool and the plug-in application of each tool in terms of results and input parameters. These parameters were collected from building standard codes. Although they opted for the same workflow, they found discrepancies in the results, and the built-in tool did not provide valid simulation results. Their workflow did not provide detailed information regarding the IRs. However, their research detailed the glazing type, and building materials whose parameters were based on The American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE90.1 and Heating Ventilation and Air Conditioning (HVAC) parameters.

González et al. (2021) on the other hand, studied the effects of manipulating lighting, plug load efficiencies and HVAC systems on the energy performance of a building and for this purpose, they proposed a methodology flowchart for energy simulation at the detailed design stage as well as a BIM-BEM integration flowchart for optimum interoperability.

As shown in the flowchart (Figure 7), their methodology is based on defining spaces and energy attributes. Only thermal and visual variables were considered in their research (temperature, humidity, air velocity, airflow, and illuminance). Those parameters were selected to guarantee a comfortable indoor environment. The model is based on building the model and then populating it with data as things progress. The model contains all data related to geometry and components and their properties then the location and weather data are added. The next step is adding energy-related data and then running the first stimulation. Afterwards, standards are implemented to adjust the comfort level, and the following steps help optimize and upgrade the energy model. The integration elements are detailed in figure 8.

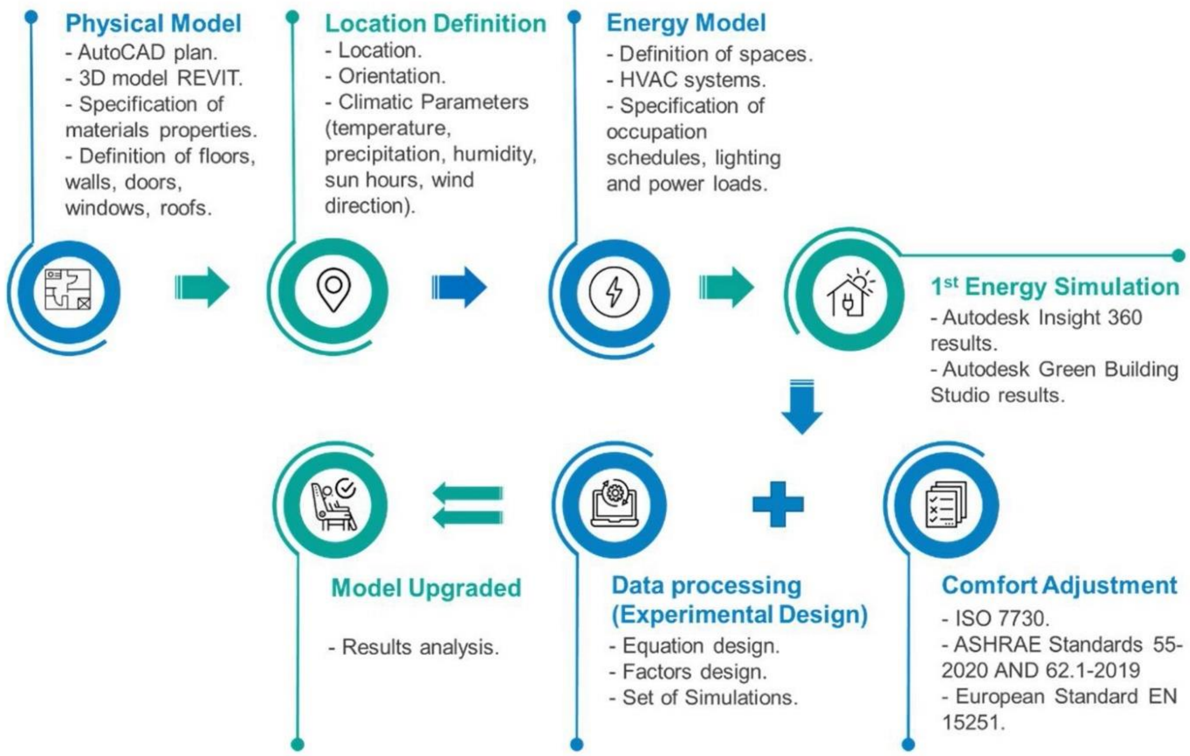


Figure 7: BIM-BEM Flowchart (González et al., 2021)

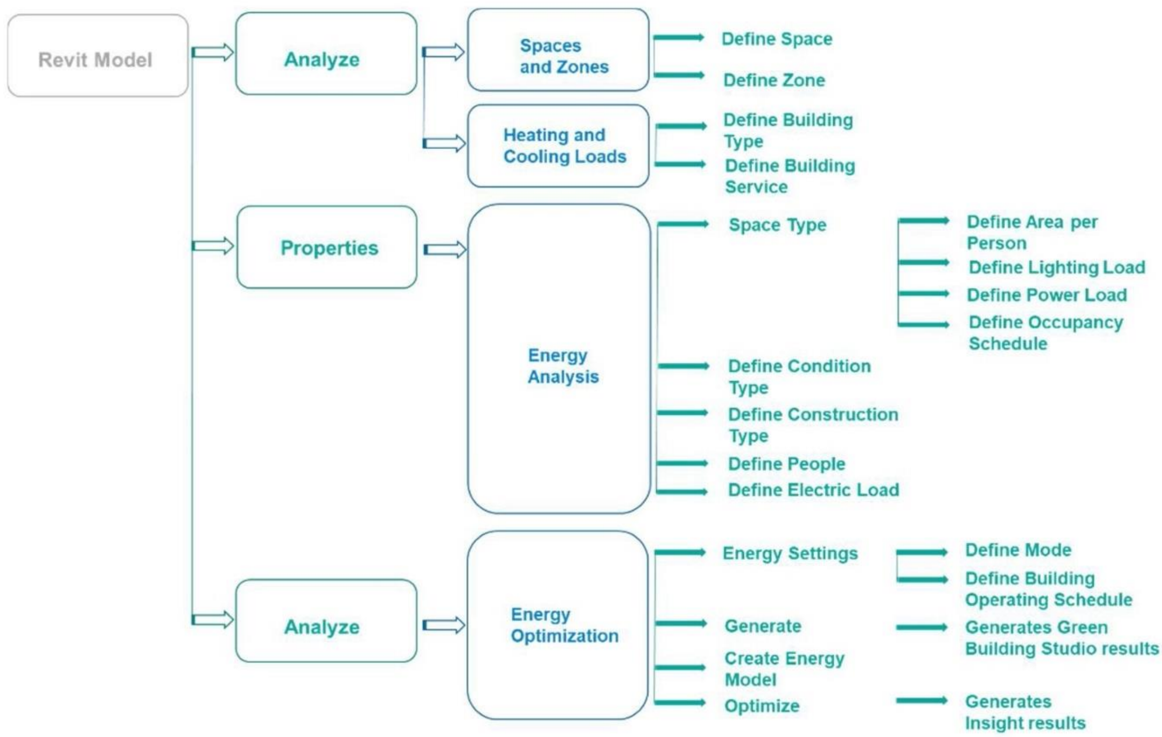


Figure 8: BIM-BEM integration flowchart (González et al., 2021)

One of the issues identified during the literature mapping was that numerous research that was either software-based or sustainability certification based – i.e., no generic workflows were identified. For instance, Wu and Issa (2014) developed a process map specific to LEED Certification, and it is considered among the most comprehensive maps of BIM-based sustainable design. Their process map guides the designer from the concept design phase to the construction and post-construction phase. The limitations of this map are the disregard of other design steps, the work of details regarding the work and data flow concerning BIM and BEM, and the lack of integration process and LOD specification.

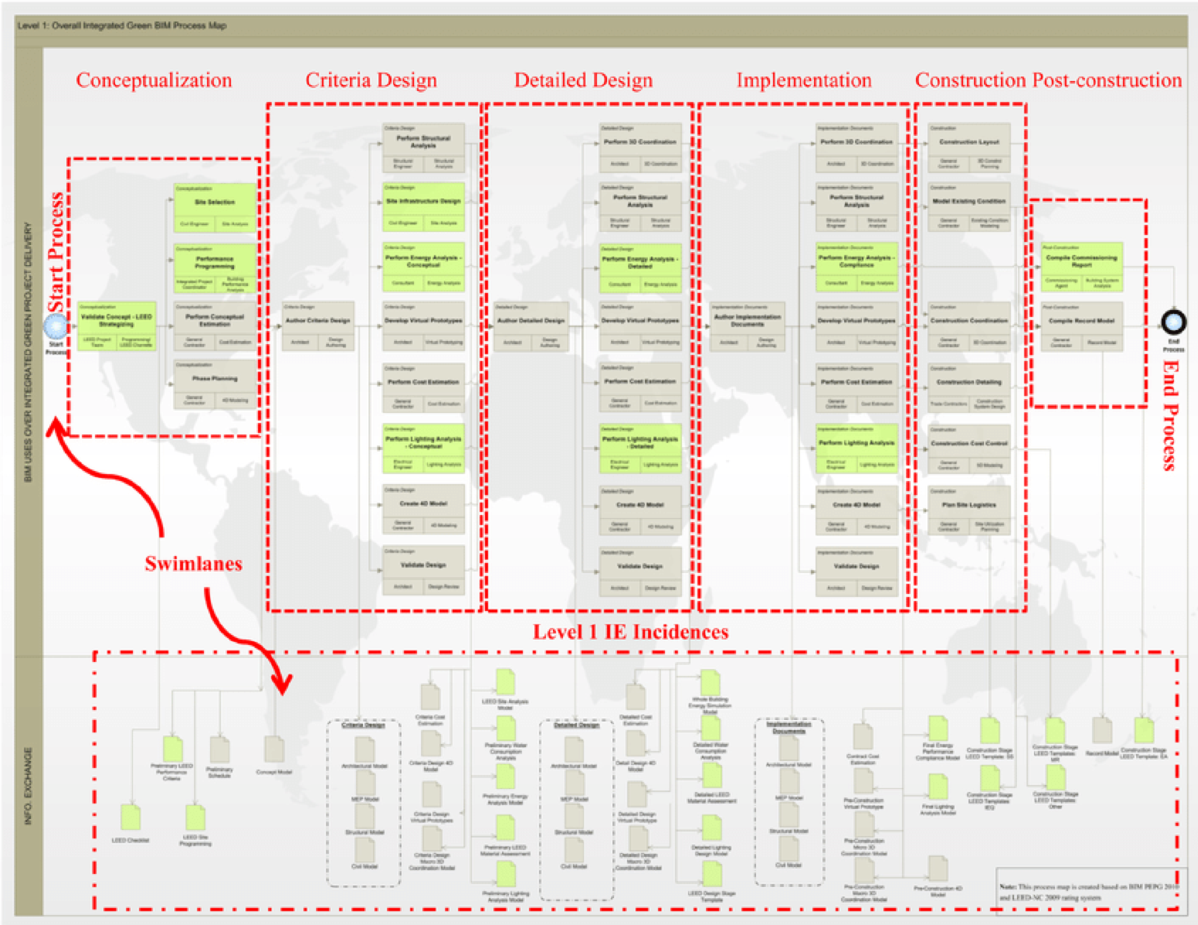


Figure 9: Overall Integrated BEM process map developed by Wu and Issa (Wu and Issa, 2014)

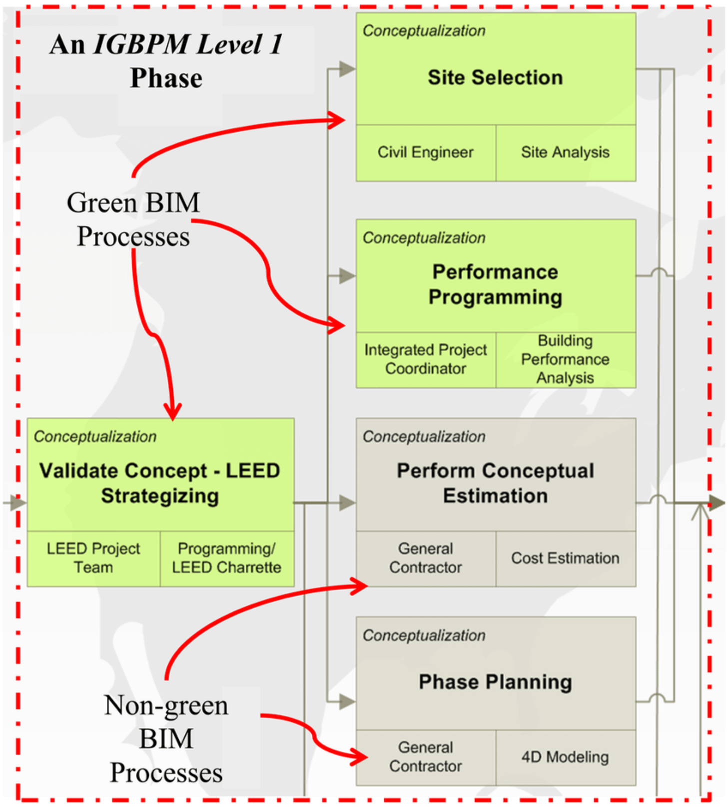


Figure 10: Level 1 of Wu and Issa's process map (Wu and Issa, 2014)

Zanni et al. (2016) developed a map describing the procedure for using BIM for sustainable design. The map (Figure11) is divided into levels, each describing different briefing stages: strategic, initial and final. Within the levels, level 1 corresponds to high -level IDEF0 process model. Levels 2 and 3 (IDEF3) provide granularity detailing the functions and missions of each role, parallel activities, and soft-gates. As a matter of fact, their BIM-enabled SBD process framework (Figure 12) details the roles, tasks, deliverables, and decision points of the BEM-based design. The authors emphasise the importance of setting roles and responsibilities given the multidisciplinary collaboration needed for sustainable-based design. Their research nevertheless did not describe the design activities at each of the three levels of their process map. Additionally, although the LOD was introduced, it was disregarded in the energy simulation part.

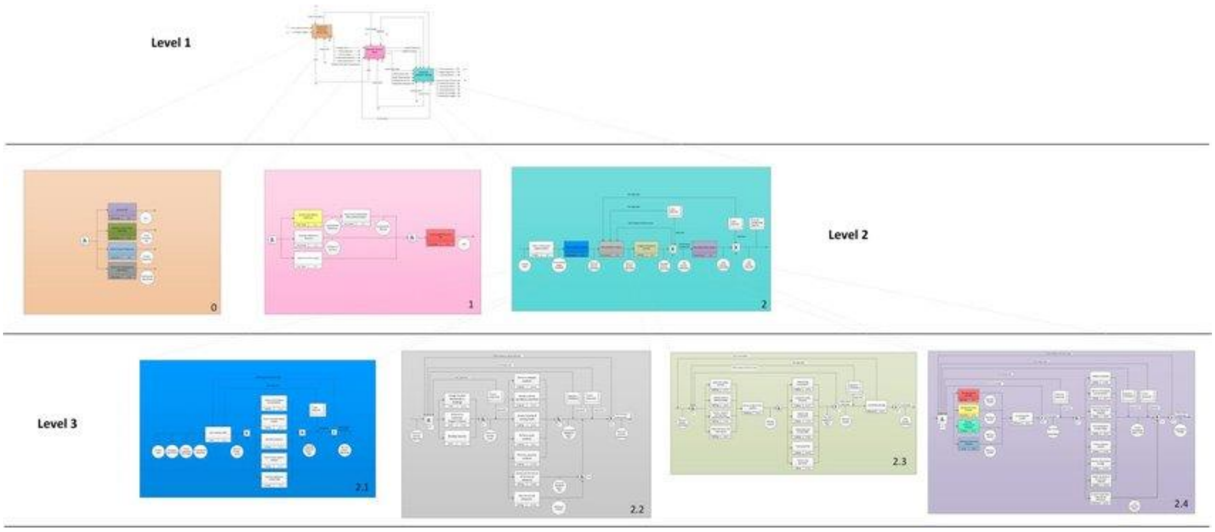


Figure 11: IDEF process model master-map showing hierarchical relationships between processes and sub-processes (Zanni, Soetanto and Ruikar, 2016)

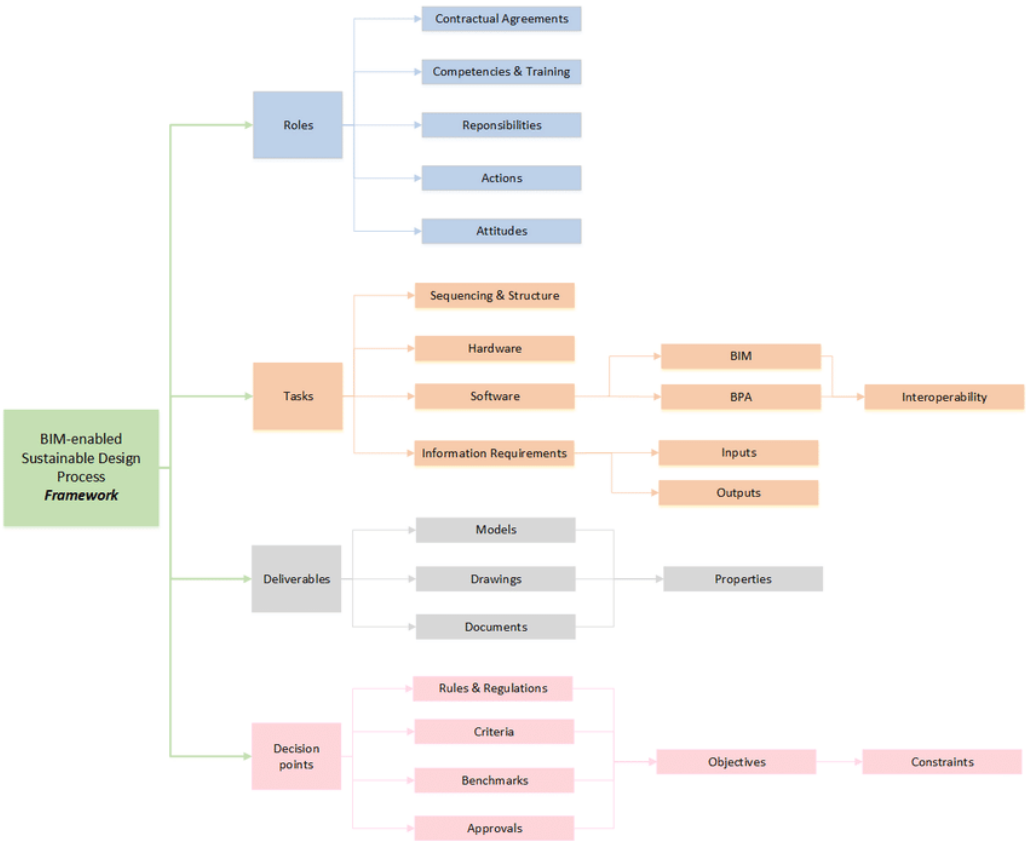


Figure 12: BIM-enabled SBD process framework (Zanni, Soetanto and Ruikar, 2016)

Farzaneh (2019), proposed a more detailed framework for their research. Their proposed process map is more holistic and is not a certificate or software specific. A comprehensive framework that defines technical approaches is needed to lead a successful BIM-BEM. They emphasized the importance of two main pillars: the process and the technology. Furthermore, “This can be realized by proposing the proper techniques for all of the design phases and embedding the technical approaches within the design process." (Farzaneh, Monfet and Forgues, 2019). The framework should define the target of the ES, the design procedures, the data flow, the modelling techniques, the IRs and the LOD. The previously proposed frameworks are software specific. Thus, there is a need for a general framework. In their process map illustrated in figure 12, they developed the information protocol needed to meet each design step's scope from pre-processing to design revision. In each phase they propose the activities and IRs necessary for the creation of the BIM model and the BEM model with exchange and decision-making steps between each phase. In addition, they detail exchange data and formats that allow the translation of the model from BIM to BEM. This proposed framework is easy to follow, as stated by the authors. It contains the essential details and the accurate and proper information requirements with classified and detailed LOD proper to energy simulation. This work is the most comprehensive up-to-date BIM-BEM map.

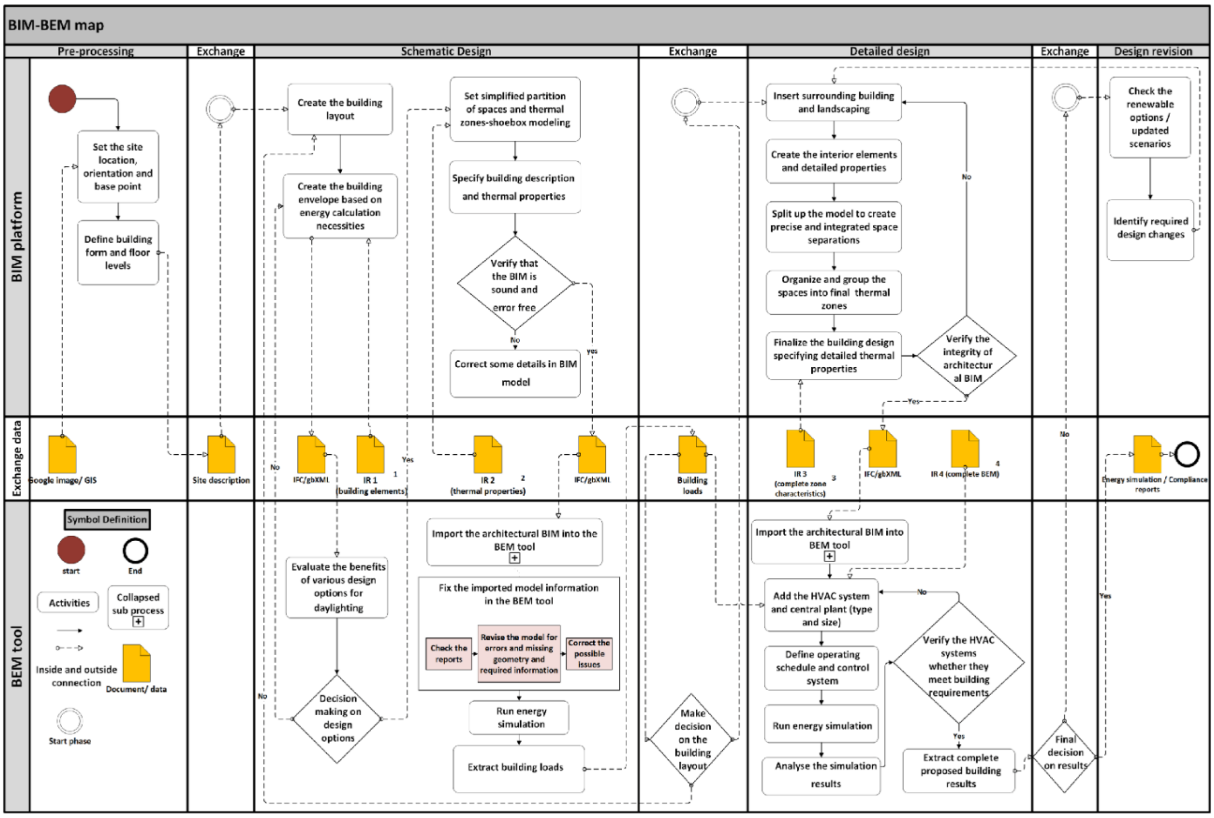


Figure 13: BIM-BEM process map proposed by Farzaneh (Farzaneh, 2019)

2.2.3 LOD and IR

Choi et al. (2016) stated that a BIM model contains most of the information required for the energy simulation tool's energy analysis model. The model that Tuomas Laine (2012) represented includes weather conditions, building geometry and information, spaces and thermal zones, internal loads, and HVAC systems. Nevertheless, the transfer of this type of data from BIM to BEM faces some interoperability issues for mechanical systems information, which makes it impossible, according to O'Sullivan (2005).

Correct data definitions are essential to provide a true data exchange for BEM, and therefore, the BIM model should contain all the relevant and accurate IRs (Latiffi et al, 2015). In the BIM-BEM process, the IRs' categories, types, and ranges of units are essential to understand and differentiate at different modelling steps. Furthermore, this is based on the project's scope and design activities (Fox and Hietanen, 2007).

Designers face inconsistent, unclear, and incomplete data sources through the BIM-BEM process. The model is not built based on an accurate IR at each design and modelling step without an integration protocol. Furthermore, the model is shared at an inappropriate unacceptable level during the design phase (Wu and Issa, 2014). This leads to more change and a need to review the model in further steps. The change in the level of modelling refers to the LOD. According to Farzaneh (2019) the LOD "allows relying on specific information in the imported model, enabling consistency in communication and execution. Thus, modelling with accurate IR and sharing at the proper LOD is required."(Farzaneh, 2019). Nevertheless, the LOD for energy simulation is dependent on the design scope and activities at each phase.

One of the BEM objectives is to provide an optimal design solution from the point of energy performance. For this end, a collaboration at an early design stage between architects and engineers is essential. Traditionally, energy use decisions are not considered during the early design stage. The analysis of the energy performance of a building at a later design stage leads to inefficient changes and/or considerable design rework (GSA05, 2012). In this regard, Azari, and Kim (2015) recommend starting the BIM-BEM process at the project front-end. Architects and engineers should make decisions together and collaborate based on correct and accurate data. Consequently, this saves time, increases the value to owners, and optimizes the whole building's life cycle efficiency.

In figure 14, Farzaneh (2019) places all the energy simulation requirements in the preliminary design phase. And in figure 15 she attributed different LODs to different design phases, considering the IRs at each phase and graphical and non-graphical modelling elements.

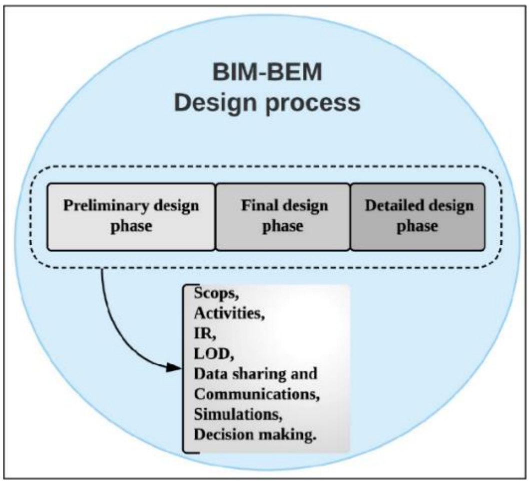


Figure 14: BIM-BEM design process (Farzaneh, 2019)

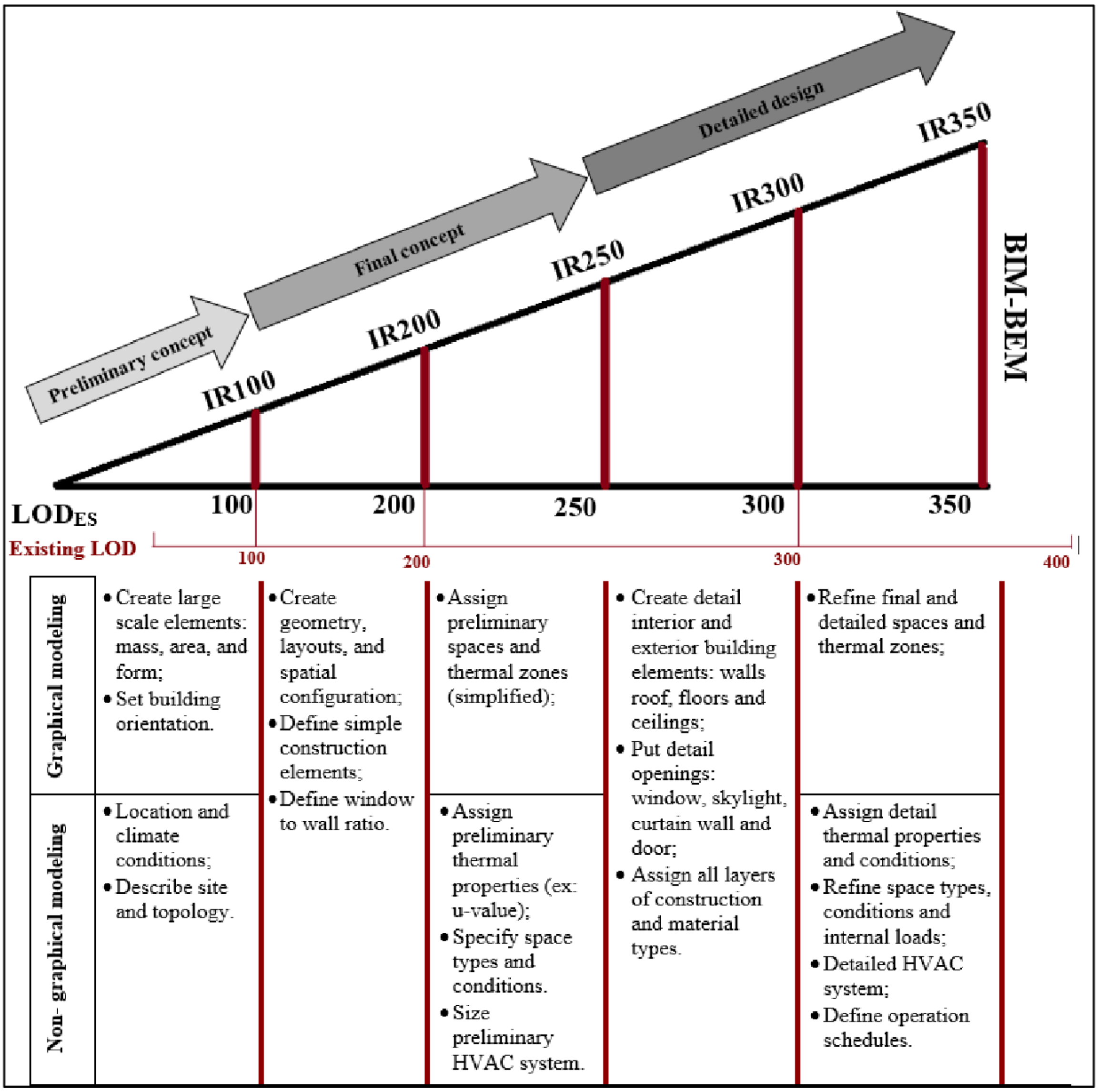


Figure 15: BIM-BEM information protocol (Farzaneh, 2019)

2.2.4 Energy Simulation and BEM tools

Energy simulation tools serve to predict the energy performance of a building design. They have been widely used for the past six decades to cover parts of the building performance assessment.

Based on energy simulations, designers can assess and predict energy consumption, annual energy costs, and annual carbon emissions, compare the effectiveness of different efficiency measures and realize cost savings. The simulation requires a set of data, including the weather data, the building geometry, building envelope composition and characteristics and the usage pattern of the building. The ES aims to lower energy consumption while preserving or increasing the comfort level of the building users.

The primary benefit of energy simulation is the capacity to compare design options. Design alternatives are assessed for energy use and thermal comfort (Maile et al., 2007). Additionally, BEM tools could be used for:

(1) Building Energy Prediction & Estimation,

(2) Building Energy Consumption,

(3) Building Energy Design Optimization,

(4) Building Energy Evaluation,

(5) Building Energy Efficiency,

(6) Building Energy Management, and

(7) Building Energy Optimization

In the design phase, BEM is used as a comparison and optimization tool to compare design iterations. Meanwhile, in the facility management phase, it serves as a measurement tool, predicting the energy use of a building (Reeves and Olbina, 2012).

Some of the predominant energy simulation tools are RIUSKA, GBS, eQuest, and Design Builder (Kim and Anderson 2013). BEM tools use specific parameters to process their calculation whether they are integrated with BIM tools or used as an external tool. In most cases, the data received will come from a BIM tool:

• The building envelope, zones, and rooms

• The building structures

• The equipment

• The control scenarios

Dong et al. (2007) classified major BEM tools into two main groups. Some of them use DOE or EnergyPlus calculation engine developed by the US Department of Energy (eQUEST, DesignBuilder, GBS, etc.…) and the others like TRACE 700, IES-VE (IES Virtual Environment) and IDA-ICE, use their own imbed calculation engine.

The AIA Architect’s Guide to Integrating Energy Modeling in the Design Process (AIA 2012) defines 5 desired characteristics of an efficient simulation tool:

- Easy and seamless Data transfer
- Building systems defaults
- Robust engine
- Comprehensive Resource Analysis
- Clear Graphic Output
- Real-World Accuracy

In table 2 we compared the BEM tools used for the early design stage as recommended by AIA (2012). These tools are targeted at architects or are intuitive for architects to use, and they are also among the widely used tools on the market.

Table 2: Major BEM tools

Design Stage	Early-Stage Simulation			Whole Building Energy Modeling		
Tool	**Sefeira Concept**	**GBS**	**Cove.tool**	**IES-VE**	**Design Builder**	**Open Studio**
Calculation Engine	Sefaira	DOE-2.2	Ray Trace	Apache	Energy Plus	Energy Plus
Application Type	Web-based and plug-in	Web-based and plug-in	Web-based and plug-in	Stand alone	Stand alone	Stand alone
Graphic Results	yes	yes	Yes	Yes	Limited	Yes
Approved for Code Compliance	No	No	Yes	Yes	Yes	Yes
Freeware	No	No	No	No	No	Yes
Advantages	User-friendly Is a whole-building model	Cloud-Based Large computing capacity	Cloud Hosting and Computing	Accuracy Possibility to import 3D models and stay in the BIM	A simple interface At the moment the most	Freeware and open-source Includes easy-to-apply

	Allows multiple comparisons side-by-side		Data Visualization AI, Automation, and Machine Learning APIs and Data Exchanges	environment to set Thermal characteristics and run the energy analysis.	intuitive interface out there for EnergyPlus.	templates containing construction and building activity data. Support for LEED reporting and performance-path code compliance.
Disadvantages	Not free invalidated by ASHRAE	Not free The "web-service automatically generated detail" doesn't always is not satisfactory to architects or energy modellers' desire for detailed manipulation of building components past the schematic design phase.	Could not be used off-line Disregards material properties introduced in Revit. The location setting is not very accurate	Not suitable for architects to use at the early design stages. The help manuals and calculation methodologies still reflect IES's initial development for European standards and design practices	Not free No import function Limited ability with complex systems	Not a commercial product can be "rough around the edges" in places. Currently offers graphic access to only the most common EnergyPlus features

2.2.5 Interoperability and exchange formats

According to The Institute of Electrical and Electronics Engineers Standards Association (IEEE STD) 610.12, interoperability "is the ability of two or more systems or components to exchange and use information" (Standard 90 Standards Coordinating Committee, 1990). Eastman et al. (2008), defined interoperability as the flawless exchange of data between applications and the ability to achieve a smooth workflow and automated transaction of models. This flawless workflow aims to avoid human errors and data repetition, consequently accelerating model reproduction. (Eastman et al., 2008).

Nevertheless, seamless BIM-BEM integration is still a research topic and an area that needs further development in the industry (Bastos Porsani et al., 2021). As O'Donnell et al. (2013) described, the lack of suitable interoperability leads to the modellers' frustration and squandered efforts. Seamless interoperability between BIM and BEM aims to save time and effort, reduce errors, and achieve a reproducible model (Hitchcock and Wong, 2011). However, this task usually requires a manual intervention to transform data.

In their research about interoperability between BEM and BIM, Bastos Porsani al. (2021) explained that BEMs can be divided into three categories of models: Physics-based models (white-box), pure data-driven or statistical models (black-box), and hybrid models (grey-box) (Porsani et al., 2021). The white box model contains all elements that impact the energy behaviour of a building (weather, construction, internal loads etc.) but are suitable for research purposes as their control strategies are proven not accurate and thus not satisfactory since the real building parameters are unknown and tend to vary from the real values used in the control system design (Reynders, Diriken and Saelens, 2014). In contrast, the black-box model is considered more reliable as it is a purely statistical or data-driven model, and it can have self-learning capabilities (Dodier and Henze, 2004). Grey-box relies mainly on physical knowledge where the model structure represents the physical behaviour of the system, and statistical methods are then used to estimate the unknown parameters. Therefore, this model solves the problem of the substantial amount of accurate data required for a model predictive control (Reynders, Diriken and Saelens, 2014).

BIM-BEM interoperability could significantly reduce costs and time of re-creation of the model during the design phase. However, it remains one of the digital gaps in the design process (Porsani et al., 2021).

According to the authors, interoperability problems, repetitive and manual operation during the creation of the energy model, and the non-standardized process are the main causes of information loss and model rework. Therefore, the solution proposed by other researchers (Kamel and Memari 2019, Sanhudo et al. 2018) is to provide clear standards for the BIM-BEM interoperability process, provide up-to-date energy models with real-time information, and automation in building energy modelling and simulation.

The BIM-BEM process is divided into three parts: the BIM tool, the model schema exchange format, and the Energy Simulation software. The interoperability issues may arise at any step (Akbarieh 2018). There are several exchange formats including HTML, XHTML, bcXML, IFCXML, IFC and gbXML. IFC and gbXML are considered the main open BIM standards (Dimitriou et al., 2016)

BIM software packages offer different ways for model data extraction. They can generate 'lists' or 'schedules', then create an output file in one of the industry-standard protocol formats such as:

• gbXML = Green Building XML. "An industry-supported schema for sharing building information between disparate building design software tools…Allows disparate 3D building information models (BIM) and architectural / engineering analysis software to share information with each other." (AREO blog, 2016) It is more flexible and produces a direct approach to the ES (Elagiry et al., 2020).

• IFC = Industry Foundation Classes. It is “the open and neutral data format for openBIM.” It generates a complex data schema and large data files. One of the limitations of the IFC format is that it cannot be edited. Consequently, any required changes must be carried out within the BIM authoring tool.

Both formats transfer data related to material properties, HVAC systems and thermal zones, yet only the gbXML format contains location data (Kamel and Memari, 2019).

On the other hand, Gao et al. (2019) proposed other observations about IFC and gbXML data transfer. The BIM-based-BEM classification system they formulated divides the information transfer process into six categories: geometry (step 1), material (step 2), space type (step 3), thermal zone (step 4), space load (step 5), and HVAC (step 6). They analysed the information transfer between software and concluded that the IFC format is step 1 and gbXML is step 3. Considering that there are many steps between BIM and BEM, the information transfer is not user-friendly (Gao, Koch and Wu, 2019).

2.2.6 Challenges, limitations, and future work

The limitations encountered in the previous studies could be grouped into two main types: the definition of the workflow issues and technical problems.

Jorge González et al. (2021) identified some limitations in their research, and the main one is the lack of information about material thermal properties, which leads to inaccurate results. They also stated that the climatic conditions retrieved from the Revit database of meteorological stations were defined without an accuracy check.

Other researchers like (Bastos Porsani et al., 2021) investigated interoperability between BIM and BEM and faced some challenges. They concluded that bigger and more complex buildings (in terms of shape and constructive systems) become more problematic, and the data transfer becomes less reliable and leads to bigger problems while transferring the models to BEM software. Some errors would result in fatal errors that make the energy simulation impossible to run.

Farzaneh (2019) identified some gaps and limitations, and most of them are related to the design process map:

- The existing BIM-BIM approaches and solutions are not comprehensive of all design stages, they consider the limited technical performance of one step of the whole BIM-BEM procedures for a specific design phase.
- Most BIM-based studies disregard BEM aspects (requirements and activities) in the design process.

- The lack of a generic, easy-to-use BIM-BEM process map that specifies all required details of proper tools, suitable model integration solutions, and work and data flow within a design process.
- Most current approaches require numerous processes such as simplifications, modifications, and re-entry of inputs at all BIM-BEM steps. This could occur in the absence of a reliable model to follow in terms of content of a BEM-based model. Clarity of IRS and detailed steps to follow from early design stage are needed.

In conclusion, despite the continuous progress made in the BIM-BEM integration, this area still offers opportunities for improvement with:

- Solve building energy calculation accuracy, thus increasing the efficiency of the final model.
- Improve BEM-related data standards, such as IFC, to create a smooth and seamless model transfer between applications and a comprehensive design process map to assist the designer during the energy model development.
- Develop a complete digital twin containing not only the architectural model but also the energy performance data. This would include building owners and facility managers and engage them in the energy-saving process by increasing energy efficiency and reducing maintenance and daily operations costs (Butler, 2019).
- To solve some of the often-recurring problems, it is suggested that various BEM applications should be investigated in addition to evaluating their integration capabilities with BIM. The results would help deepen the understanding of the available tools and how we can improve their interoperability, modelling capabilities and selection of inputs as well as their accuracy of results (Farid Mohajer, M., & Aksamija, A. 2019).

2.3 Case study

2.3.1 Project Location and IRs

2.3.1.1 Location and geometry

The project is an office building with a total area of 4861.8 m² spread on 4 levels. The building is simple L-shaped and was modelled in Revit. It is located in Ljubljana, Slovenia, in Vič District (46°02’ N, 14°28’ E).

Figure 16: Proposed project location

The weather and location data were set in Revit.

Figure 17: BIM model

2.3.1.2 Information Requirements IRs

Table 3, created by Farzaneh et al. (2019), describes the minimum IRs for a BEM Model at the preliminary concept stage. These minimum requirements must be defined while creating the building envelope based on the energy simulation needs. Modelling the building envelope is considered the most challenging step in the process, according to the authors. Therefore, they developed this table to list all the minimum requirements and property sets for this step. Additionally, they developed a minimum IR table for each design step with the proper elements required for energy calculation. As we investigate the preliminary design step, we will only consider table 3.

Table 3: Minimum IR1 (Farzaneh, 2019)

Elements	Property Members	Property set	Description
Building common	Net planned area	Pset_BuildingCommon.NetPlannedArea	Total planned net area for the building Used for programming the building.
	Number of storeys	Pset_BuildingCommon.NumberOfStoreys	The number of storeys within a building.
Wall common	Element	Pset_WallCommon	Properties common to the definition of all occurrences of wall.
	Thermal transmittance (U-value)	Pset_WallCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
Window common	Element	Pset_WindowCommon	Properties common to the definition of all occurrences of window.
	Thermal transmittance (U-value)	Pset_WindowCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
	Glazing area fraction	Pset_WindowCommon.GlazingAreaFraction	Fraction of the glazing area relative to the total area of the filling element.
Roof common	Element	Pset_RoofCommon	Properties common to the definition of all occurrences of Roof.
	Thermal transmittance (U-value)	Pset_RoofCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
Curtain wall common	Element	Pset_CurtainWallCommon	Properties common to the definition of all occurrences of curtain wall.
	Thermal transmittance (U-value)	Pset_CurtainWallCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
Door common	Element	Pset_DoorCommon	Properties common to the definition of all occurrences of door.
	Thermal transmittance (U-value)	Pset_DoorCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
	Glazing area fraction	Pset_DoorCommon.GlazingAreaFraction	Fraction of the glazing area relative to the total area of the filling element.

2.3.1.3 LOD

The LOD is defined for both graphical and non-graphical data. The LOD is also defined according to its capacity to support BIM-BEM. Therefore, we opted for level 200 as defined by AIA (2008): “At this level, approximate graphical and non-graphical information (such as approximate size, shape, location, and orientation) is provided as a generic system for building elements in the model.” (AIA, 2008). At this level, the thermal properties are missing and need to be specified in the BEM tool.

2.3.2 Proposed BIM-BEM Process Map

The proposed BIM-BEM process map is inspired by studies conducted by Wu and Issa (2016), Zanni et al. (2016), Farzaneh et al. (2019) and González et al. (2021), and adjusted to the design stage we are investigating.

The project information section is essential to define the IRs and LOD according to the design stage and to define the designer's and building owner’s sustainability objectives. To start building the model for energy simulation, the first step is to set the location and orientation on the authoring tool then build the project mass and define the floor levels. As Zanni et al. (2016) recommended, we did not consider the same author's level 0 of SBD (Figure 12) as we have one design stage and one role in this case study. The next step is adding details and data to the project to prepare the energy model. The building envelope is very important, so it is the first step – materials and openings need to be defined. At this stage, an energy simulation could be run to compare design alternatives and make a decision based on the information provided at this step. Afterwards, the internal partition could be added, and the spaces and zones should be set with thermal properties. A model check is always needed in the BIM tool to avoid errors and rework after exporting the model to the BEM tool. After defining the acceptable exchange format according to the BEM tool and exporting the model, another model check should be run to add missing information in case of need and ensure the simulation runs seamlessly. The final energy simulation followed by an optimization process is the key point in deciding the design option. At this early design stage, we omitted all information about HVAC systems as they are not needed and required experts to define them.

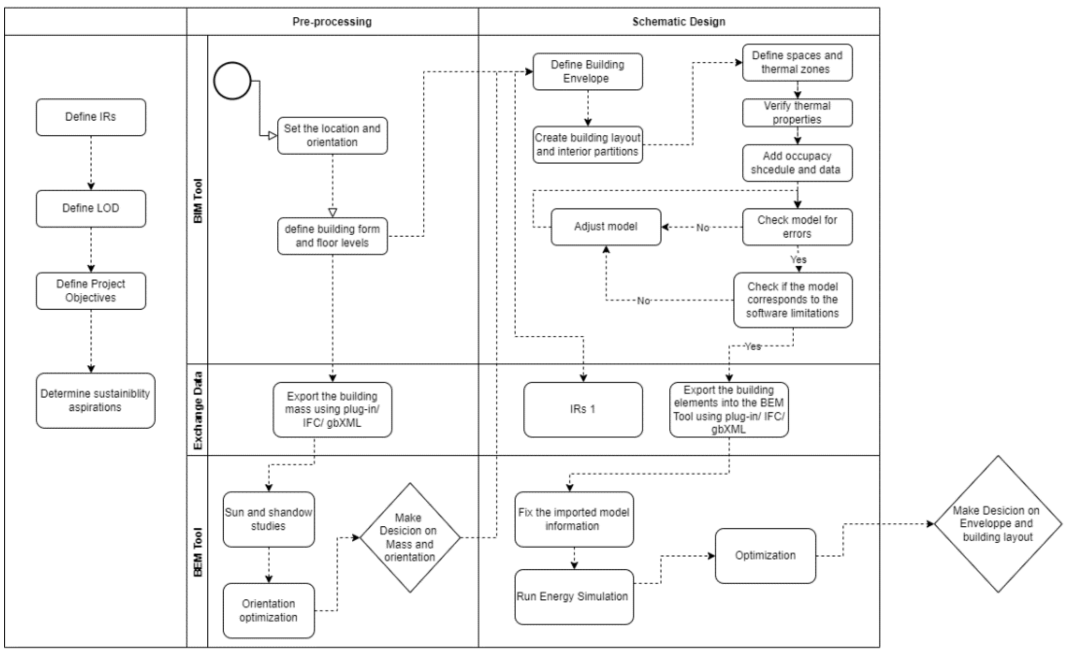


Figure 18: Proposed BIM-BEM workflow for the early design stage

Set the location and orientation of the project: the exact position of the building was set in the authoring tool Revit 2022, and the weather data was selected as the closest to the site.

Define building form and floor levels: the general shape and number of floors are defined according to the IRs and the project objectives and requirements.

Define Building Envelope: the exterior walls of the project are the most challenging, the envelope should be modelled seamlessly, and all the required information needs to be input properly according to the simulation needs and the energy target. The wall openings would play a major role in defining the thermal model. The roof and floors are modelled in parallel at this step.

Create building layout and interior partitions: the inside partitions, along with stairs and doors, are the last step of the modelling process.

2.3.3 Energy Simulation

2.3.3.1 Simulation Tool

The selection of the BEM tool was based on table 2 and the possibility of testing the software with a student trial version license. Among the six proposed software we opted for, the tool that uses more graphical data is intuitive and more suitable for early design stage studies, especially for architects and could invalidate standards like ASHRAE or LEED. All software was not free; however, most of them offered a free trial for students. This point could be decisive for professionals to use a specific tool as they are not very accessible and, in many cases, the free trial comes with limited functionality. The third selection criteria were the interoperability and exchange format to limit the errors that occurred during the export of the geometry to one format or another. Therefore, we opted for the tool that offers a Revit plugin that will help save time on exporting and checking for errors without the need to export into IFC of gbXML format as the data transferred is still error-prone and inconsistent.

Amongst the simulation tools we investigated, we chose cove.tool, an online platform. After building the BIM model using Revit, we used a plug-in that synchronizes the geometry on the cove.tool platform. The key features that helped us to decide to use this tool are as follow:

- The tool is suitable for the early design stages and for architects who are not specialists in energy analysis and uses the graphic presentation of analysis results.
- The tool uses a plug-in compatible with the BIM authoring software we used and helps with a smooth transition between the two tools, it also avoids interoperability problems.
- The analysis results (shadow, daylight, glare, COVID occupancy assessment, EUI (energy use intensity), LEED core etc.…) are presented graphically and in 3D.
- It creates a report that summarizes all the results.

- It offers energy optimization options.
- It offers a feature that allows for the comparison of up to four projects based on EUI, Window-to-Wall Ratio (WWR), Utility Cost (UC), LEED Points and Indoor Water Use Intensity (WUI).
- It supports energy codes and guidelines (such as ASHRAE and (National Energy Code for Buildings NECB) and LEED Assessment.
- It offers a Façade Guidance Feature where you have a room mock-up, and you can manipulate the WWR and window features and have real-time feedback on the energy consumption. This is a quick way to define roughly the façade system to be used according to the project goals and it reduces the time spent reworking different options in Revit.

2.3.3.2 Targets and performance indicators

This simulation has two targets: the first one is to determine the optimal orientation angle of the building. and the second one is optimizing the façade solution to reduce energy consumption and provide a comfortable and sustainable environment.

The below-stated parameters were used to assess the buildings' performance.

sDA: Spatial Daylight Autonomy describes the percentage of space that receives sufficient daylight or the percentage that does not need artificial lighting. The higher this percentage the more lit the space is and the less energy the space needs for lighting (Cove.tool).

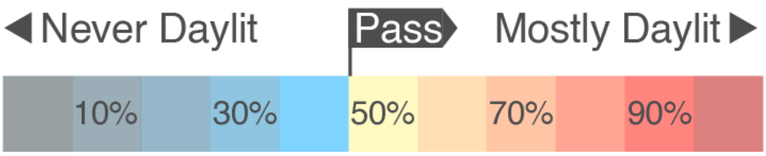


Figure 19: Legend for sDA metric used in the cove.tool app (Chopson et al., 2021)

ASE: Annual Sunlight Exposure defines the percentage of the space that receives direct sunlight at the work plane height. Too much direct sunlight can cause glare which disturbs performance, especially for office spaces, and it could increase cooling loads (Cove.tool).

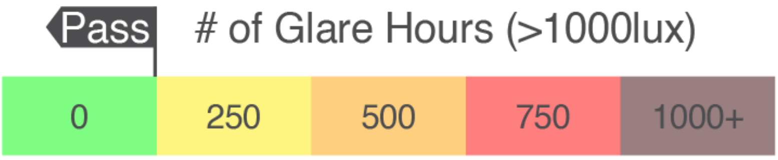


Figure 20: Legend for ASE metric used in the cove.tool app (Chopson et al., 2021)

LEED Score the software calculation method follows the Building Design and Construction BD+C LEED v4.0 – daylight credit of sDA% and ASE% guidelines. The analysis rates LEED compliance and reports it.

EUI: Energy Use Intensity, refers to the required energy for operating and sustaining the buildings once occupied. It measures the total energy per unit of area that a building consumes on an annual basis.

2.3.3.3 Software Specific process map and inputs

The detailed process map (Figure 18) was adapted to the early design stages and then readapted following the BEM tool requirements and simulation strategies. The major difference is that it simplifies the work on the BIM model to just the massing. All material properties, such as wall insulation, glass type, etc., are defined and automated according to the requirements of the local energy code. The components that are exported to the tool are the orientation, the surface area, and the placement of the floors, walls windows, roof and skylights which are necessary to create the energy model. Although, using cove.tool avoid all interoperability problems, special care needs to be taken while exporting the building elements. The views created in the BIM tool should be checked to assure that every element is in the view it belongs to, and this is essential to ensure that the geometry is exported properly. The tool ignores the material properties that originated from BIM to avoid mistakes resulting from bad modelling practices. Thus, it saves much time inputting material data that will not be used and correcting data that is out-of-date, incorrect, or not code-compliant. The tool ignores thermal zones as they are not needed in the early stage of schematic design. This limitation avoids junk information and facilitates a fast energy analysis for conceptual design stages as the tool accepts geometry that is not 100% closed for example. (Cove.tool)

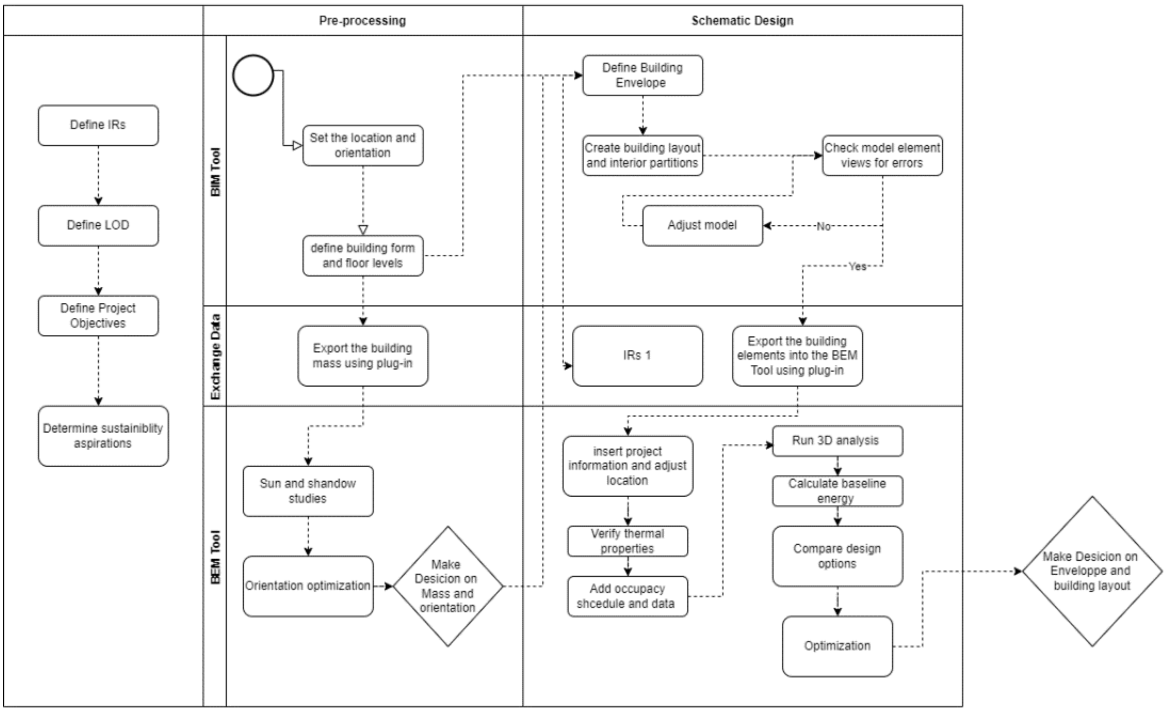


Figure 21: Cove.tool specific process map

Baseline model inputs

The baseline model uses the envelope components' characteristics to calculate energy use. These calculations are based on how effective the materials are as insulators. They are referred from international codes based on the location of the project:

- Window Wall and Roof U-Value: it measures the effectivity of the material as an insulator. The default values are referred to (according to the user's selection) from ASHRAE table 5.5, or California title 24 table 140.3-B or NECB Division B-Part 3 when selected and the tool will populate the values according to the project's location. cove.tool makes the assumption of the material assembly based on Pacific Northwest National Laboratory PNNL building prototypes.
- Glazing SHGC: Solar Heat Gain Coefficient. The higher the SHGC value is, the more heat the space will receive. This value varies from 0 to 1. In the hot/warm climate (ASHRAE climate zones 1,2,3 and 4), the Solar Heat Gain Coefficient (SHGC) has precedence over U-value as the heat coming in is considerably higher than the heat transferred out of the space. On the other hand, the cold climates (ASHRAE climate zones 5,6,7 and 8) benefit from having a lower U-Value for windows as it is really important to retain the heat inside the maintained space from flowing outside.

The baseline energy assessment is divided into two parts:

- Outputs that are the results of the energy simulation. They detail the whole building EUI assessment and breakdown, the LEED score, CO2 reduction and the energy cost divided into electricity and gas (figure 22).

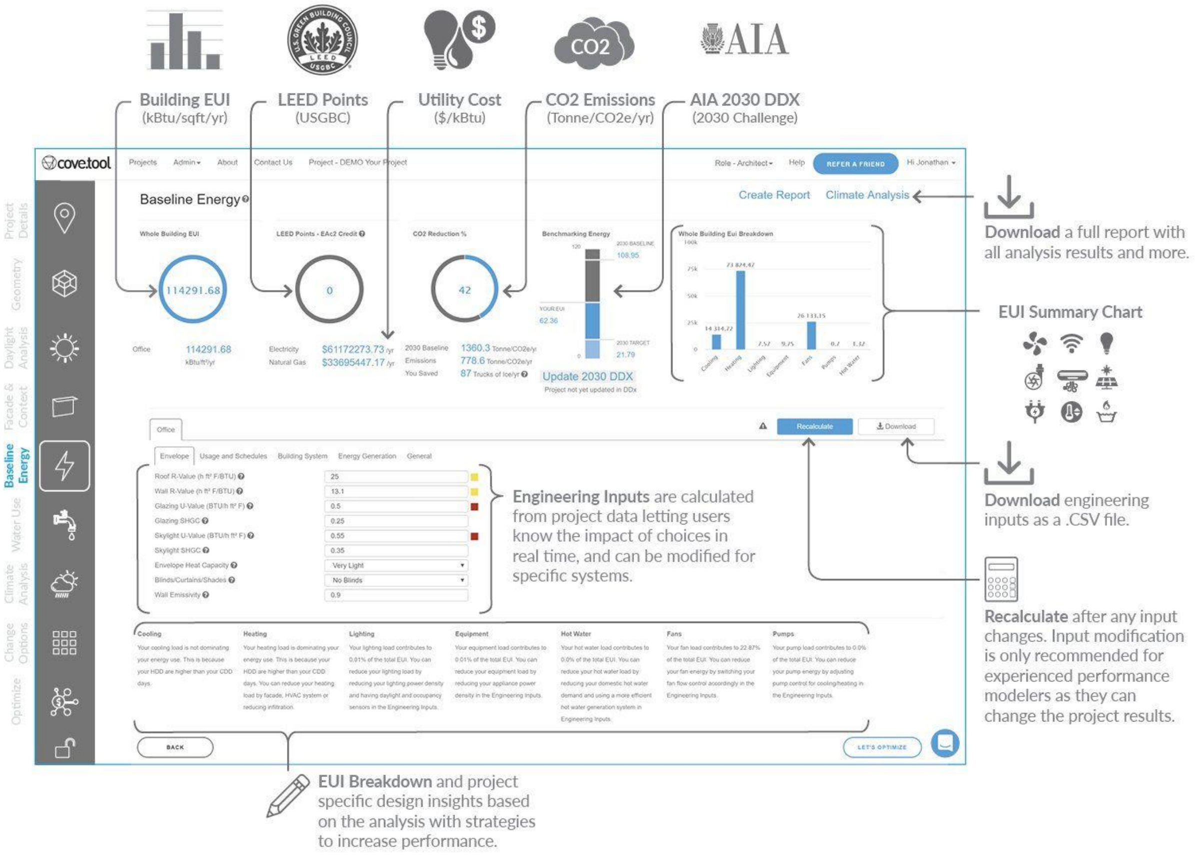


Figure 22: Baseline energy inputs and outputs (Cove.tool)

- Inputs: where parameters concerning the envelope, the usage and schedules, the building systems, energy generation and other general parameters can be inserted to run the energy simulation. As for the simulation, non-geometric data is set to the standards and is automatically assigned based on the local energy code or an equivalent ASHRAE-IECC (International Energy Conservation Code) energy code (users can contact the sales department to request the addition of the national code). Cove.tool assumes the material assembly based on Pacific Northwest National Laboratory PNNL building prototypes. They can nevertheless be modified, and the energy assessment can be recalculated (Figures 23 and 24).

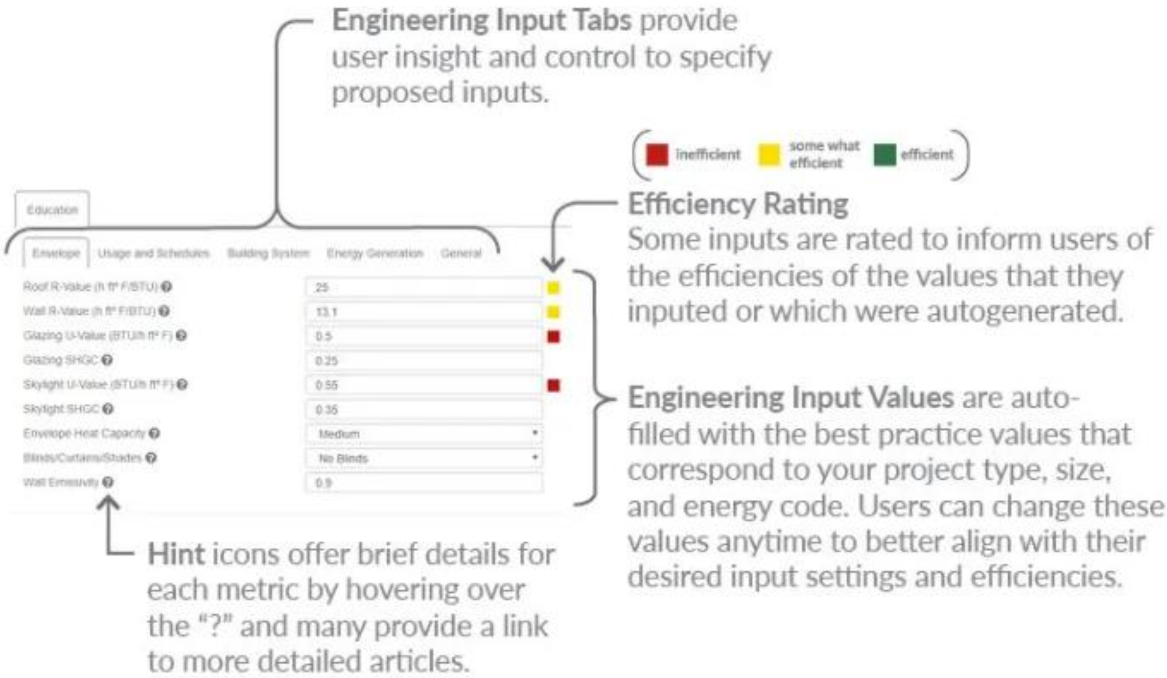


Figure 23: Cove.tool energy analysis results and envelope inputs (Cove.tool)

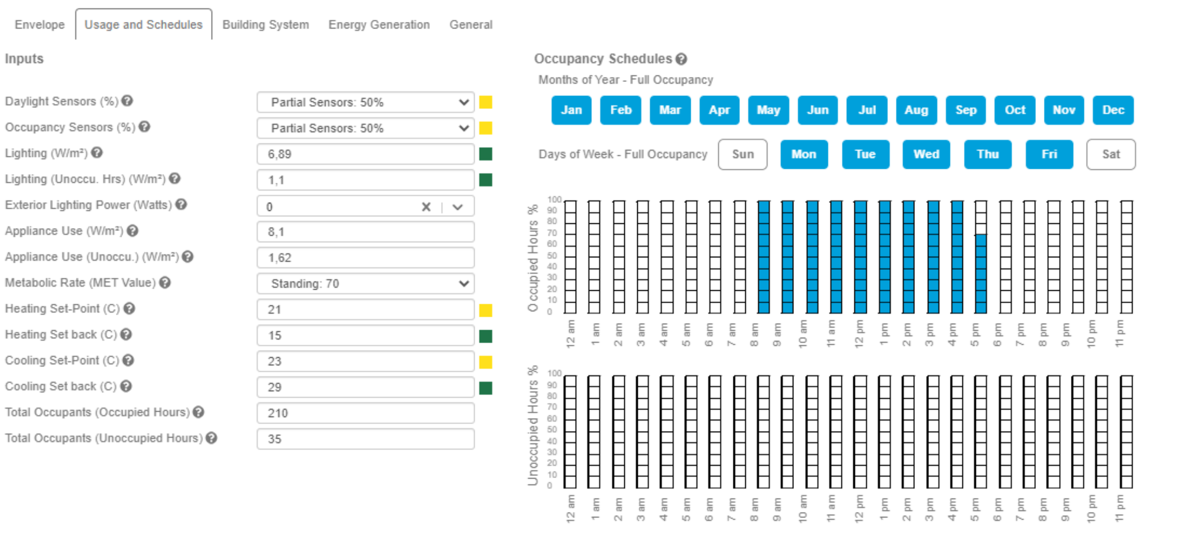


Figure 24: Cove.tool inputs and occupancy schedule (Cove.tool)

Optimization

By the end of the simulation, a cost vs energy optimization process is possible to define the optimum solution according to the designer's aspirations and targets by using the cost as a decision-making factor. It helps to parametrically explore the different alternatives and select the most beneficial multi-objective alternative. At this step, LEED points are also considered. The optimization parameters include Glazing, Wall, Roof and Skylight U-values, Occupancy sensors, System type, Ventilation calculation type, Daylight sensor, cooling and heating set-points, LEED points, emissions of greenhouse gasses in CO2e, cost, payback, energy savings and EUI.

The design teams opt to explore different scenarios and the impact of improving some parameters such as wall and roof insulation and its effect on the cost, for example, or improving the HVAC system. The reference points are the baseline model inputs. The optimization aims to identify top bundles that perform better than the baseline model offered by the tool in terms of energy performance and cost. The tool runs hundreds of simultaneous simulations for this end and calculates payback periods, LEED points earned, embodied carbon, and energy savings for each bundle. Users can also add alternatives they want to explore and rerun the energy calculation. Afterwards, the bundles are ranked from best to least improved. Combining different strategies and targets simultaneously and defining the goals and parameters required to achieve them is undoubtedly advantageous for both designers and the assigning party. As a matter of fact, this is the goal of the Energy Simulation, especially in the design phase, which is to control input parameters and their target outputs from the numerous possibilities.

3 RESULTS

The simulation process and the generated results would reflect the BIM-BEM integration process we implemented using the case study for an early design phase executed by a designer. The three simulations stated in the process map would help the designer decide the best design solution they should implement following their goals and eventually optimize that solution for better outcomes. The results, alongside the integration process of the integration, will guide us to validate our specific process map and identify the best practices and limitations designers would face during their energy simulation.

In this section, the results of three simulations are presented:

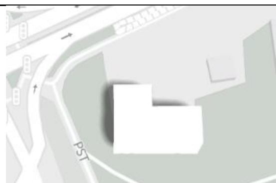
- 1st Simulation – building orientation optimization.
- 2nd Simulation – façade design strategy selection and WWR optimization (i.e., three design options – conventional design, uniform window distribution design and curtain wall with external shading).
- 3rd Simulation – façade thermal envelope optimization.

3.1 Energy Simulation and Comparative study

3.1.1 First simulation

The first simulation concerns orientation optimization. We set three angles 0°, 90° and 315° (from the North) and then compared each option's sDA, ASE, Sun hours and EUI. We aim to achieve the lowest EUI and ASE with the highest sDA values. We used the 3D analysis tool of the cove.tool to compare the three projects and the results are detailed below.

Table 4: Energy simulation results of different rotation angles

Parameter	Rotation Angle		
	0 °	315°	90°
Plan			
sDA [%]	50	50	51
ASE [%]	27	29	31
EUI [kWh/m²/yr]	81.81	81.73	81.72

As shown in table 4, the rotation of the building did affect the total building EUI but not dramatically. A 90° rotation where the building is oriented East-West results in the lowest. However, at 315° rotation, the building receives less direct sunlight with ASE of 29 %, which corresponds with a slight increase in energy use, a better and more comfortable environment to work and could decrease cooling loads. To validate our results, we used the comparison tool to compare the energy use of the different design options.

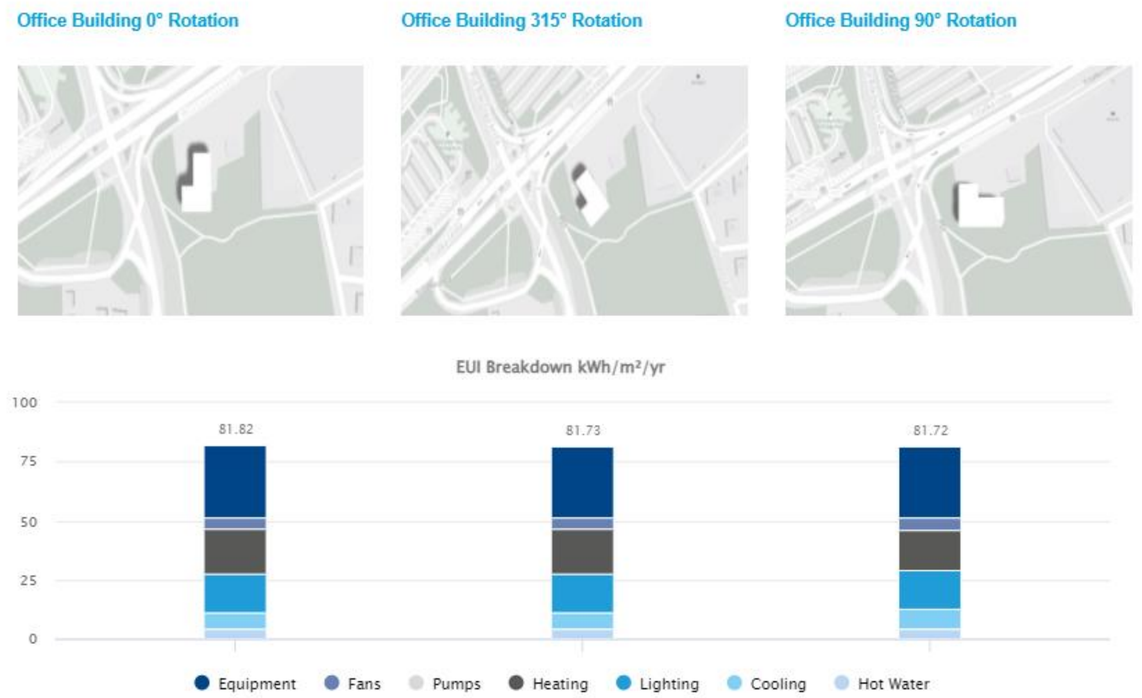


Figure 25: Building EUI comparison for different rotation angles

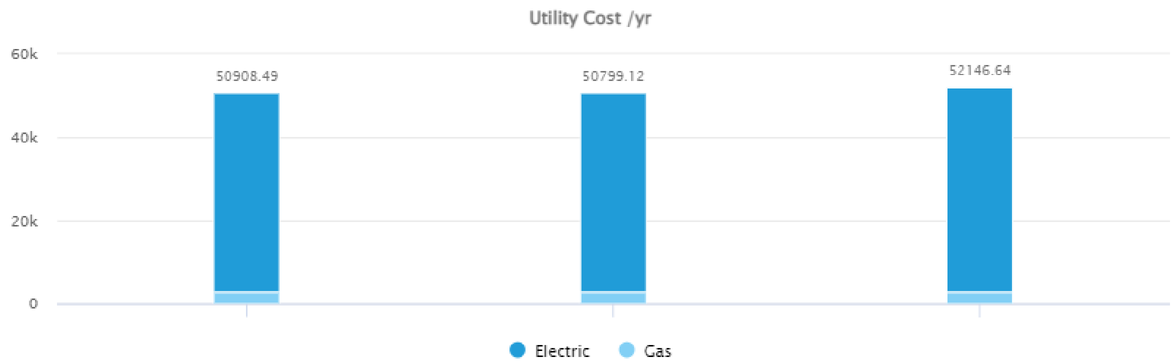


Figure 26: Utility cost per year comparison (€)

The software generates a preliminary assessment of the cost of utilities (gas and electricity) per year. The results show that with a 315° rotation angle, we can save around 1,400 € per year on utility costs (Figure 25). The cost forms a crucial decision-making point while designing the project. The decision is left to the project owner and managers to decide whether utility cost is the major factor in choosing a design solution or whether they have other criteria for selection.

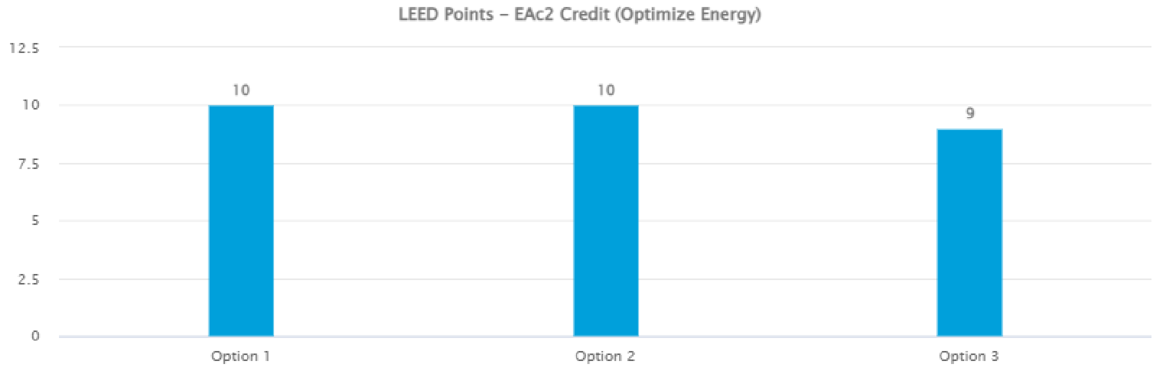


Figure 27: Comparison results of the different rotation angles

LEED points are another factor contributing to decision-making (Figure 26). Whether the project is designed to be LEED certified or not, these criteria reflect the sustainability aspects of the project.

The results showed that the whole building's EUI values are close. Therefore, we considered other factors such as sDA, Annual Energy Cost and LEED points. Although the 90° degrees rotation provides the lowest EUI, we opted to rotate the building at 315°, save energy and costs, and score more LEED points.

3.1.2 Second simulation

The second simulation concerns the facade's design strategies and WWR optimization. After selecting the proper rotation angle, we created two additional façade design options for the conventional scenario: small windows and a curtain wall on the NW façade.

In the second option, we replaced the curtain wall of the northwest façade with wide (i.e. strip) windows. We decreased the glazing on the NW façade by 35% and increased it by 25% on the SE façade, creating a more uniform glazing distribution consequently, as shown in figure 27.

Figure 28: Window pattern 2

The tool offers a real-time calculation of sDA for different façade options and WWR values for every direction on a simple shoebox model. This could help the designer to quickly decide on the WWR they want to use and the shading strategies they could implement to reach their desired performance without having to rework or work with different façade options on the BIM authoring tool. This strategy minimizes significantly the time spent on rework and design of different options and avoids possible interoperability problems.

The shoebox dimensions are known as the Base Case 600 model, and it comes from ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 140 ("Standard Method of Test for Building Energy Simulation Computer Programs”). It is a mock-up generated concerning the designed building and the geometry inputs such as WWR.

After using the façade tool, we decided to also test the efficiency of using a curtain wall on all building facades. The façade mockup showed that using a curtain wall of 100% WWR maximizes the sun intake but we would have to use shading elements so we tested vertical and horizontal options to decide on which strategy we would use on the NE SW and NW facades. For all variations we used 4 horizontal overhangs with 400 mm depth with a spacing of 1 m and 6 vertical fins with also 400 mm depth and 1.5 m spacing. The results of the comparison are listed in table 5.

Table 5: sDA comparison results for curtain wall shading system

Parameter		Façade orientation		
		NE	SW	NW
sDA [%]	No fins	49	40	45
	4 overhangs	49	41	47
	6 fins	31	22	25

The results of the real-time façade simulation demonstrated that using vertical fins would provide shade and more daylight intake compared to using overhangs or not using any sunshade system. Therefore, we readjusted the BIM model with curtain wall and vertical fins (Figure 28)

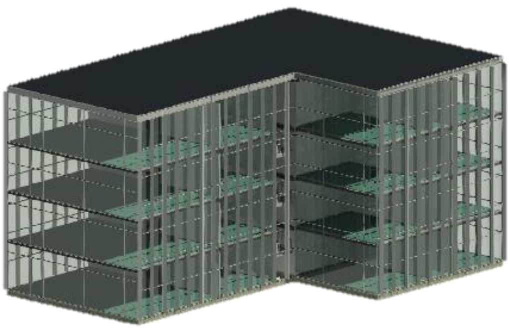


Figure 29: Window pattern 3 with curtain wall

The next simulation concerns the energy consumption comparison of the three façade options: the original design, the curtain wall option, and the window variation option to evaluate the best performing design solution. Similarly, to the orientation optimization step, we started with the 3D analysis tool to evaluate the building behaviour regarding daylighting and its energy use. We then used the comparison tool in the online platform. The results are shown in figures 29 to 31 and table 6.

Table 6: Comparative table of the three facade design solutions

Parameter	Options		
	(1) Reference design	(2) Window variation	(3) Curtain wall
sDA [%]	50	54	68
ASE [%]	29	37	55
EUI [kWh/m2/yr]	81.73	100.68	112.55

The figures below represent the side-by-side performance comparison of the three options. The WWR distribution is graphically presented and reveals a more uniform distribution of the glazing area that corresponds with more use of glazing. This increase in the transparency on the surface correlates with higher sDA but also higher ASE percentage and more energy use (higher EUI). According to figure 29, the additional energy is used for heating, and the increase becomes significant with a higher WWR ratio. Yet, less energy is used for cooling compared to the other options. On the other hand, option 1, the reference model, provides the lowest overall energy use with less glare ASE% and the lowest sDA. Although it seems the most comfortable in terms of sDA%, the curtain wall solution consumes the most energy in heating, cooling and use of fans. Therefore, it is the least sustainable solution.

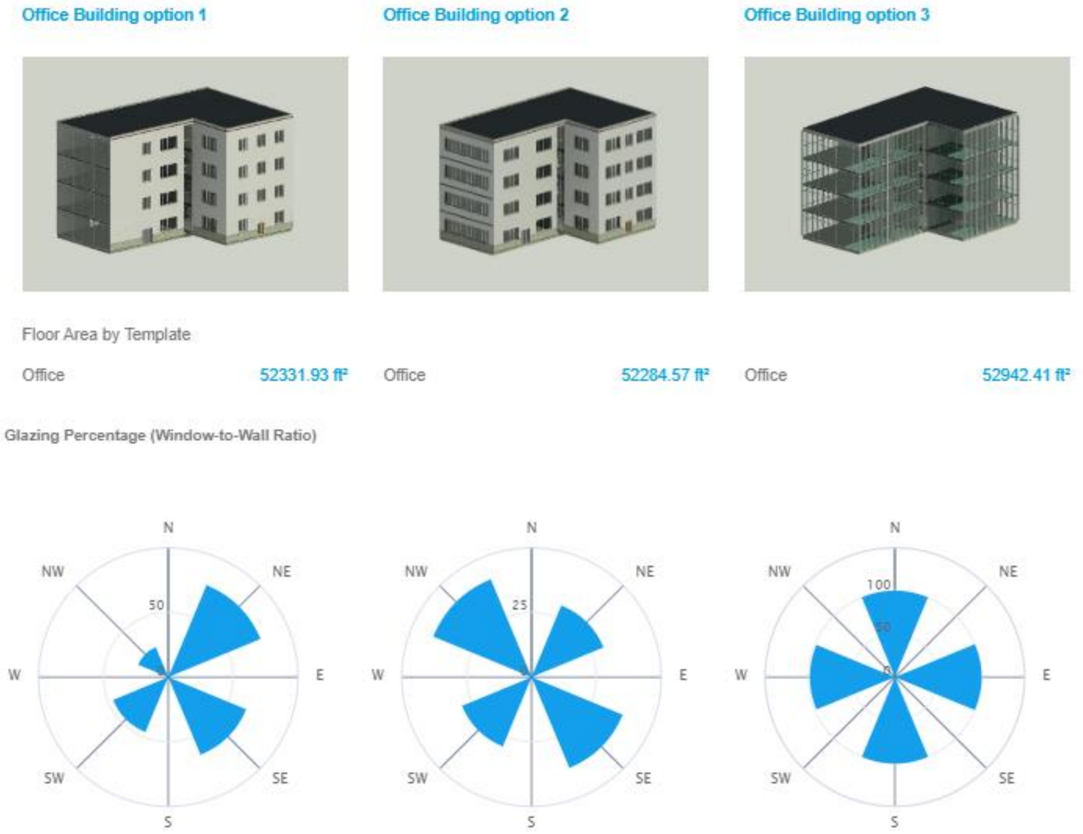


Figure 30: WWR distribution comparison

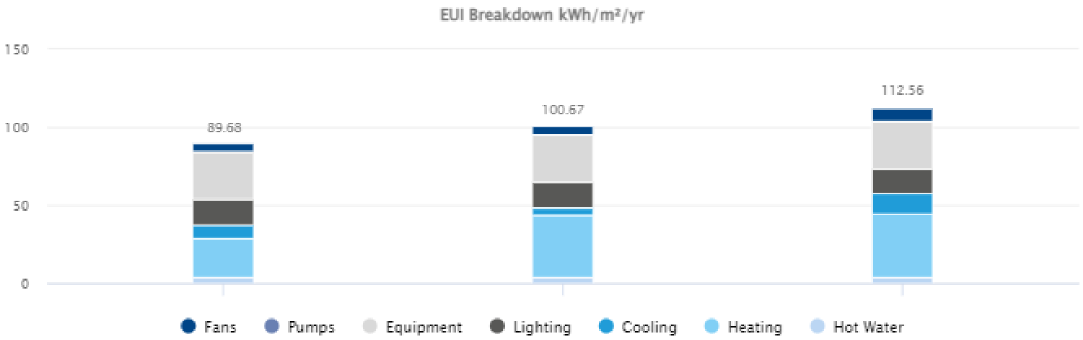


Figure 31: EUI breakdown comparison

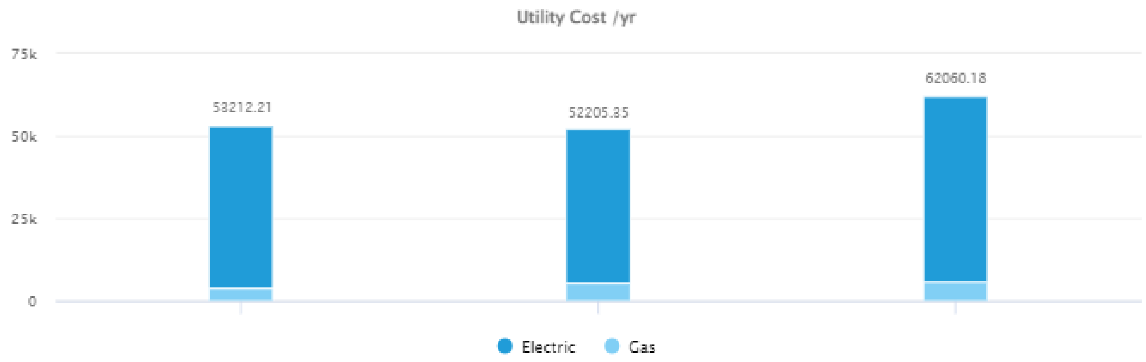


Figure 32: Annual utility cost comparison

The graph in figure 32 details the annual cost of utilities (electricity and gas). Between options 1, 2, and 3, the cost increases significantly due to elevated gas usage. This fact is due to more energy used for heating. Option 2 uses the least electric energy (81% comparing to 93% for option1 and 91% for option 3). We examined the EUI breakdown for each option to understand the reason behind it and compared them in figure 33 below.

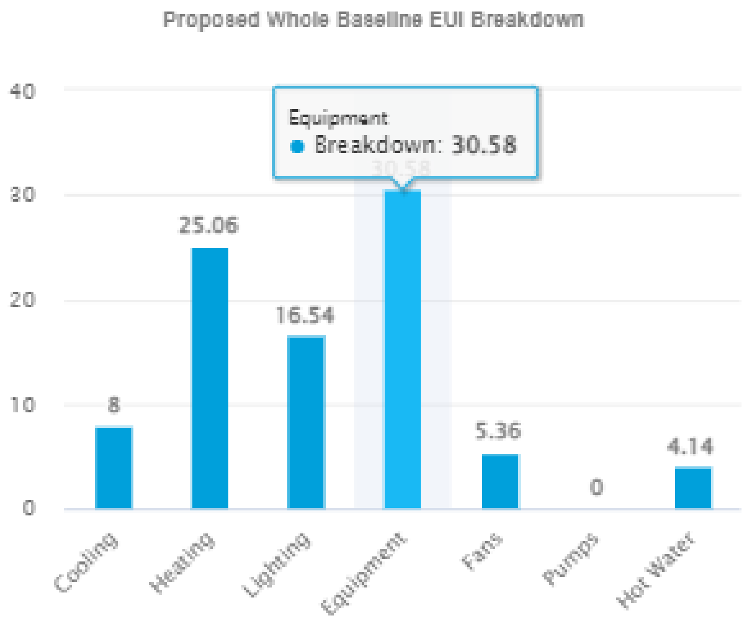


Figure 33: Whole building EUI breakdown of option 1

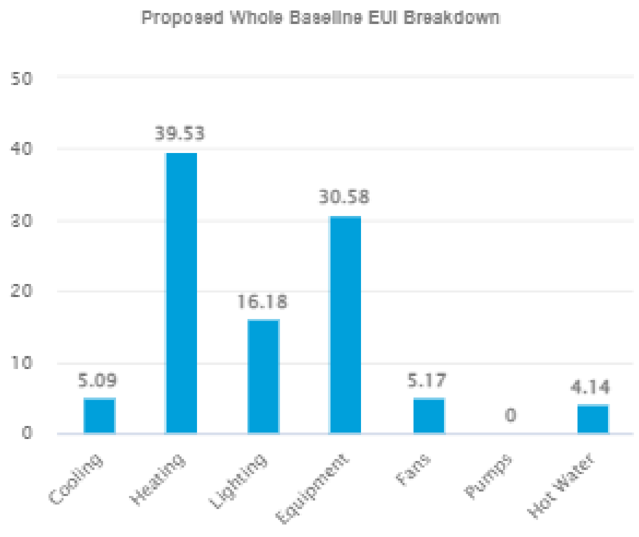


Figure 34: Whole building EUI breakdown of option 2

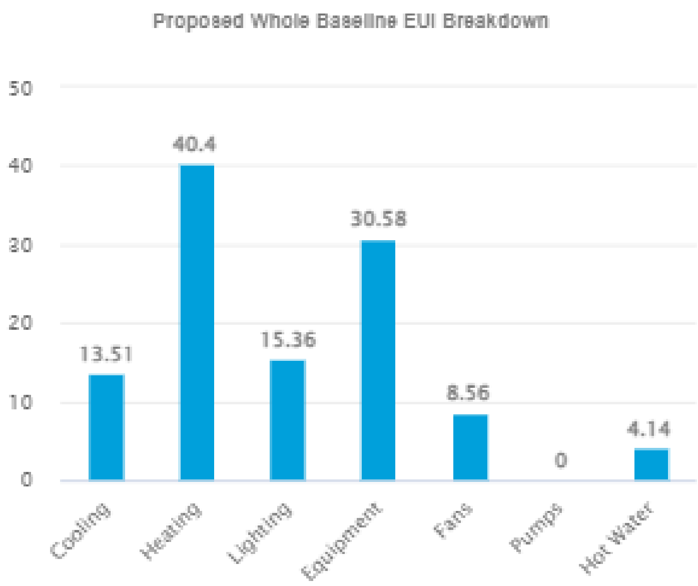


Figure 35: Whole building EUI breakdown of option 3

The graphs show that option 3 of the curtain wall uses more electricity for heating and cooling but less energy for lighting, which is attributed to higher sDA. This difference in the lighting load is not significant for energy saving. Option number two, on the other hand, uses the most energy for heating but has the lowest cooling energy use of the three. It also uses less energy for artificial lighting compared to option 1. Even though option 2 consumes more energy for heating than option 1, its annual energy cost is the lowest due to a lower cooling load.

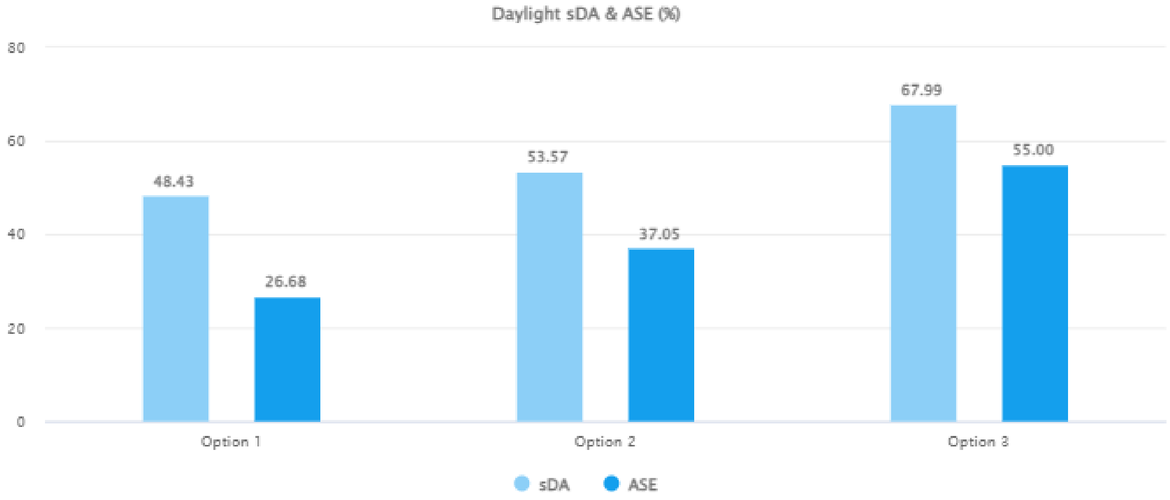


Figure 36: sDA and ASE comparison

The side-by-side graphical presentation of the sDA and ASE is very helpful to detect the optimum solution and retrieve the conclusion quickly. The maximization of the WWR significantly increases the ASE percentage. However, option 1 offers a significant difference, while it has a 5% lower sDA compared to option 2, the ASE is significantly reduced by around 11%. on the other hand, the sDA percentage of 48% does not satisfy the LEED criteria and it is below the recommended level.

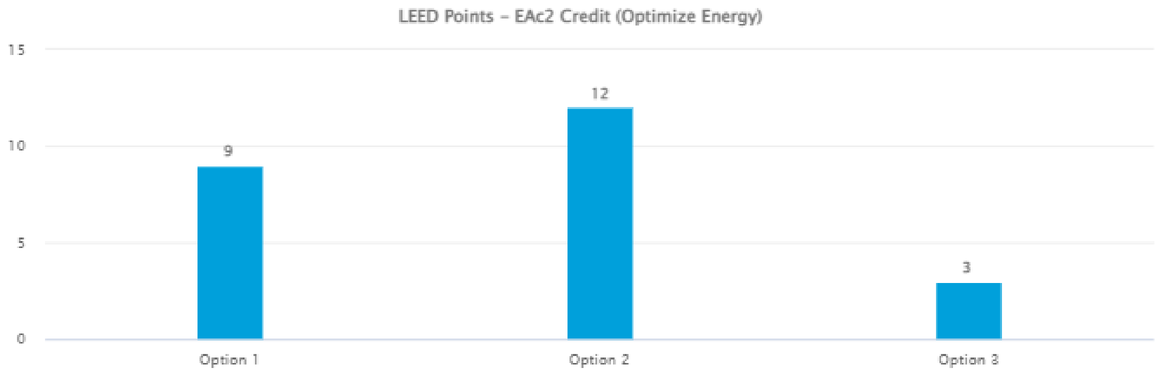


Figure 37: LEED point attributed for each design option

Another decision factor offered by the cove.tool, is the LEED score assessment. Among the three strategies, option 2 scored the highest 12 points in contrast with option three, which gets only three LEED points

Considering the Energy Consumption, the utility cost, and the LEED score, we decided to opt for the second façade design strategy and optimize it for the next energy simulation.

3.1.3 Third simulation

At this step, we decided to change the external walls' material composition and test how it affects the building's energy consumption. The material properties are automated on the cove.tool platform based on the local energy code requirement and can be modified. We tested three wall types whose composition and thermal properties are listed in table 7. For each option, we modified the U value deducted from the table on the cove.tool and recalculated the baseline energy for each wall type

Table 7: R values of the different wall types' materials and the total U value

Masonry wall		Wood wall		Concrete wall	
Material	R-value [m^{2}K/W]	Material	R-value [m^{2}K/W]	Material	R-value [m^{2}K/W]
Outdoor air film	0.17	Outdoor air film	0.17	Outdoor air film	0.24
Brickwork 110mm	0.14	Wood siding	0.40	Stucco 12mm	0.10
Air cavity 50 mm	0.28	Rigid insulation	2.70	Foam board insulation 50mm	1.7
Reflective paper	0.00	Wall batt 90mm	2.52	Poured concrete 100 mm	0.52
Wall batt 120 mm	3.36	Plywood 12mm	0.1	Indoor air film	0.68
Plasterboard	0.10	Wood panelling 6mm	0.31		
Indoor air film	0.68	Indoor air film	0.68		
Total R-value	4.37	Total R-value	7.4	Total R-value	3.87
U-value [W/m^{2}K]	**0.211**	**U-value** [W/m^{2}K]	**0.135**	**U-value** [W/m^{2}K]	**0.258**

The comparison of the three wall types and the automated wall type showed a reduction of the energy use EUI that consequently reflected in the electric and gas energy cost, which is the highest for the reference wall (U-value 0.313 W/m^{2}K). The most important difference is related to gas consumption and heating load. We selected the wood wall of the three types of walls as it assures the lowest EUI and energy cost while the concrete wall has the highest. However, the wood wall provides the least CO2 reduction compared to the other wall types (table8). The CO2 reduction is calculated based on the difference between the 2030 Baseline and the project's emissions results. It provides a tangible idea of the environmental impact of the project. The 2030 baseline emissions are calculated through Architecture 2030's ZeroTool.

Table 8: Energy consumption and cost comparison of the different wall types

	Reference wall	Masonry wall	Wood wall	Concrete wall
U-value [W/m²K]	0.313	0.211	0.135	0.258
EUI [kWh/m2/yr.]	100.84	98.92	97.49	99.80
Heating %	39.74	37.82	36.39	38.71
Cooling %	5.03	5.12	5.18	5.08
CO2 reduction [%]	63	63	64	63
Electricity [€/y]	46,525.72	46,521.68	46,523.34	46,522.83
Gas [€/y]	5,658.91	5,411.31	5,226.6	5,525.44
Total energy cost [€/y]	52,184.63	51,932.99	51,749.94	52,048.27

3.2 The optimization

From the previous comparison series, we opted for option 2 of WWR, which is rotated 315° from the north with exterior wood walls. We used the optimization feature of the cove.tool in order the optimize the energy performance based on the cost. Figure 36 shows the proposed best bundle offered by the tool that helps reduce the EUI to 77 kWh/m²/yr compared to 96 kWh/m²/yr for the baseline model, providing thus 20% energy saving and getting us closer to our 2030 target. This reduction comes with a cost premium (Additional cost to reduce the EUI) of 117,437 €. The cost premium is an estimation of the improvements that could be implemented in the materials and equipment to increase the building’s efficiency. It is due to improving the U value of the glazing, wall, and roof, using 100% occupancy sensors, and adjusting the heating set-point. The optimization increased the LEED points to 13 instead of 11. The optimization proposes also the lowest cost bundle which figures the minimum premium cost estimation for improving the building's performance.

Figure 38: Optimization bundles

Since the tool runs hundreds of simulations, it also offers the opportunity to filter the solution according to the team's objectives. We used this feature to filter the bundles that could allow us to have a cost premium between 25,000.00 € and 70,000.00 € by highlighting the portion of the vertical axes that represent the cost feature. This filtering helped us shortlist the bundles and re-rank the list to the most beneficial strategies. We chose to control the additional cost of energy saving (cost premium) vs other parameters. The tool proposed three solutions that will make us reach our goal, from the most beneficial to the least efficient. Figure 37 shows that with bundle number 1, we get the closest to our objectives in terms of cost and other considerations such as LEED point, CO2 emission and payback. Bundle 1 proposes the highest cost premium of 65,383.00€ that saves 16% of energy reducing consequently the EUI to 81%. On the other hand, bundle 2 reduces the cost premium to 31,160.00 € but saves only 3% of energy. Bundle 3 is the least efficient despite being the least costly, it saves 2% of energy with EUI 94 kWh/m²/yr.

Figure 39: Application of a filter on the result graph and the proposed bundles

4 DISCUSSION

The literature review and the case study elaborated in this research were used to explore the BIM-BEM integration process and to divulge its potential and limitations from a designer's standpoint.

The comprehensive literature review guided us to elaborate on the process map we implemented during our case study. The review revealed that this area lacks a holistic integration approach between BIM and BEM. State of the art showed that more recently, the research was focused on the technical aspects of BIM-BEM, such as interoperability and data transfer, and far less on the implementation workflows. This fact is attributed to technological advancements and the urgency to solve technical and software-related issues. Nevertheless, having a comprehensive integration design process is crucial to limit reworks at each design phase and make the process more efficient than traditional ways. The literature review helped us to elaborate our early design process map, which, later on, we adapted to the operating mode and features of the BEM tool we chose (Cove.tool). The pre-processing was revealed to be an essential step of the BIM-BEM integration process. Throughout the implementation of the process map, we discovered how essential it is to specify the objectives, the IRs, and the sustainability aspirations before launching the project. These details help the designer to develop the model with the needed components and without unnecessary information. They will also help her/him decide on the design options later during the energy simulation. At the same time, this critical step pushes the designer to create a clear plan and a list of objectives they want to achieve with the client. In most cases, when starting the project, the design team would set different objectives but maybe not as elaborate as they would do in the pre-processing step. The list of objectives would usually be design related, and the sustainability goals would be set in a concise way.

The practical case was used not only to verify the implementation of a workflow inspired by previous studies and readapted to an early design stage but also to shed light on some of the issues and limitations that a designer might encounter during BIM-BIM integration. This part depended substantially on the specifics of the selected BEM software we used, the Cove.tool online platform. Although we developed a primary process map specific to the early design stage, we had to readjust the workflow according to the functionalities of the BEM tool and the tool's proper workflow. The general workflow was limited to the concept design stage, and all aspects related to the detailed design steps were discarded. Since the tool used a plug-in to export the model from Revit directly to its platform, the exchange formats (e.g. IFC, gbXML) were not considered. Within the BEM integration part, the continuous simulations were linked to each design step, and the shoebox model was integrated in the process without linking it to the BIM tool. In addition, HVAC and thermal zones were not considered as the software does not require them for the simulations. Furthermore, there was less need for model checking as the model had only basic components. As a matter of fact, it was the tool's target to avoid model errors by importing only the basic geometry from the authoring tool and then adding information on its online platform. The resulting process map was more concise and straightforward than the flowcharts on which we based our research.

The energy analysis was based on parametric energy simulations and comparisons between different design options. Our goal was to keep optimising design solutions using energy studies, improve the energy performance step by step through the design process, and then use the cove.tool's optimisation function to optimise the cost vs energy. In the BEM tool-specific process map, we avoided a lot of exchange and interoperability steps since the tool imports directly from Revit using a plug-in. There was also more back and forth between the BIM tool and the BEM tool, reflecting the comparison and decision-making points we evoked. In addition, this workflow directly reflected the goals and aspirations of both the design team and the client. At each step, the energy report had to be analysed, and the choice of the design solution was based on the targets and sustainability aspirations set in the pre-processing step. Each piece of information added to the building model required a decision-making step, and it is the role of the ES to provide the designer with the needed data to choose one design option over another.

The integration process we implemented with the ES tool cove.tool allowed the designer to be fully involved in energy analysis even without specific knowledge about energy modelling and sustainability. In addition, the energy simulation was implemented from the first step of the concept design, which is the massing and orientation, till the choice of building materials. It also allowed us to go as far in energy analysis without specialised knowledge of HVAC systems or building materials. However, this does not affect the quality of the project in terms of sustainability and energy saving as building massing orientation, and thermal envelope features can still be optimised. The automated analysis and code compliance check were set to assist the designer without needing to resolve with the help of energy specialists. This contributes to the efficiency of the design process and saves time on transferring the model and waiting for recommendations from the sustainability team, making it easier for the designer to take the decision and alter the model and design options. Furthermore, it limits the rework time using functionalities such as a shoebox model to simulate the daylighting in real-time and to simulate the building and the façade behaviour with its surroundings and the environmental parameters. The repetitive energy simulations we executed reflect each decision point and design step that the designer faces during the elaboration of the concept design.

During the practical case study, the process map was an essential starting point to approach energy analysis. The energy simulation played a significant role in the elaboration of the project and assisted us greatly in choosing the right design solution that satisfied our goals and sustainability aspirations. Furthermore, using BEM made the traditional energy analysis more efficient, integrated into the early design and limited a lot of rework and data loss. On the other hand, our biggest challenge during this work was choosing the proper BEM tool. Much commercial software offers different features. Choosing the proper one depends on the user's objectives, maturity level with manipulating the software and the exact features she/he is interested in. As a matter of fact, while selecting the software, we faced issues with other tools related to interoperability, and the export was full of errors. This issue is still not solved so far and could affect the efficiency of the BIM-BEM work while using other tools. Using an online platform such as the cove.tool could be a solution. However, it also comes with its challenges, such as depending on the online network and the limited features offered if the designer wants to proceed to the detailed design stage. This means that the project would have to be further studied using a different tool for the more detailed stages, eventually complicating the workflow. Furthermore, before choosing the proper tool for our research, it was recommended by the studied literature to use a small-scale project in order to avoid any technical issues connected to the model complexity. This is a significant limitation that would eventually be faced while working on large-scale and complex projects. Solving big-scale and mixed-use projects is yet another area to be tested and studied in the future.

5 CONCLUSIONS

This thesis work aims to study the BIM-BEM integration process in the early design stage from an architect's standpoint. We studied literature to identify not only the opportunities that BIM-BEM offer but also the gaps and limitations in the industry. We used a practical case to implement the integration map and solve the challenges that might arise. In sum, we wanted to assess if the BIM-BEM integration at the early design stage brings more benefits and opportunities than the opposite. Moreover, we wanted to investigate how it contributes to the workflow's efficiency and how it affects the design itself.

There is an urge in the AEC sector to implement more sustainable ways of building from design to construction. Architects provide the first layer toward more efficient and sustainable buildings. With the advancement in technologies and design tools, BIM is bringing more advantages and assistance to designers. Energy simulations are a widely used tool to assess and control energy use in a building, and BEM, although lacking research in some areas, presents a great tool. Technical problems such as interoperability issues play a major limitation in the BIM-BEM integration. Along with technical problems, the main issue that previous research wanted to solve was a process map to follow during the BIM-BEM integration and standardised methods. Few of elaborated maps are either software specific or sustainability certification specific. The limitations identified in the literature mainly focus on the standards, interoperability and absence of a comprehensive standardised BIM-BEM execution plan that identifies IRs, LOD, sustainability goals, and limits rework.

A comprehensive execution map allows designers to readapt it to their specific design phase or ES software, which was the case with our practical case study. A clear and elaborated process map adapted to the proper design phase influenced the design and made the process more efficient. The pre-processing step is essential at the beginning of every project. It helps with the decision-making point that the designer faces later in the design elaboration, which can affect the design considerably. When the ES is applied from the beginning of the project and for every design step, it makes the process more efficient, limiting the waste of information and the rework time. Every layer of the project elaboration is supported by an ES that justifies that choice. Allowing the designer to elaborate more design options throughout the project and run energy analysis himself instead of populating the model with data that is not relevant to the BEM and waiting for the specialist decision and then redoing all the work and wasting time and resources. BIM-BEM integration at the early design stage allows designers to explore more design options and unleash their creativity while controlling the energy efficiency of their projects. Some tools such as cove.tool offers features that can help them explore more options and make quick decisions like automated real-time simulations or cost vs energy optimisation.

In conclusion, despite some of the industry's gaps and technical limitations, BIM-BEM integration offers designers more support than perceived. It can significantly affect the design and the design process by making it more efficient and effective. Nevertheless, this area still lacks adequate technical solutions.

Therefore, future work should be done on solving technical problems that would limit the designers to using one tool than another and restrain their work to a specific scale in order to avoid data loss and interoperability problems and to guarantee the energy assessment of the project through different design phases without discontinuity.

The advancement in the BIM-BEM integration offers a great opportunity for designers to get more involved in energy simulations, it offers the chance for better coordination and productivity. We believe that using BIM-BEM would facilitate using energy simulations and controlling the design following national and international standards. We also believe it bridges the gap between concrete projects and sustainability certificates and will encourage design teams to use more sustainable design approaches. Finally, we believe that the existing gaps and limitations offer a chance for researchers to improve both the technical aspects and the processes.

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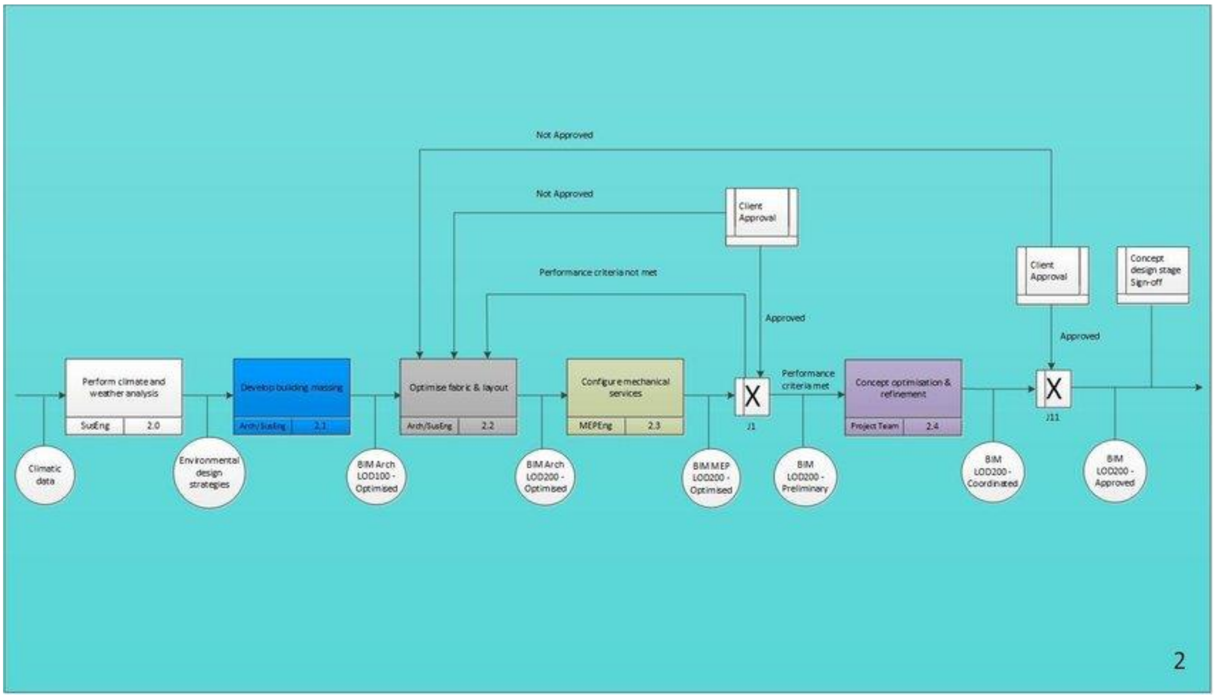
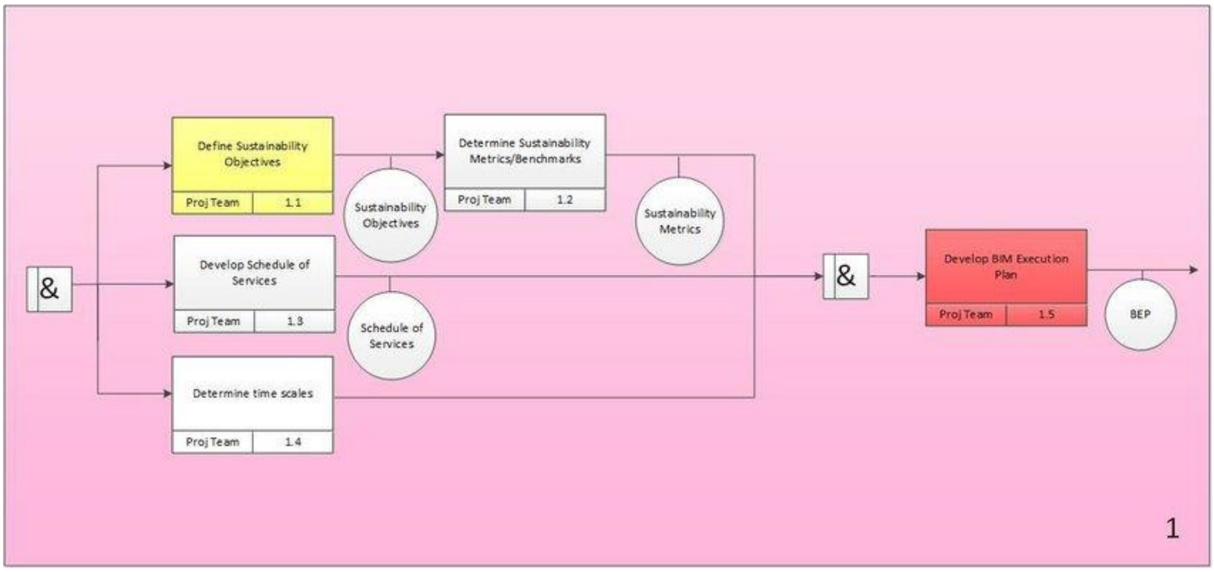
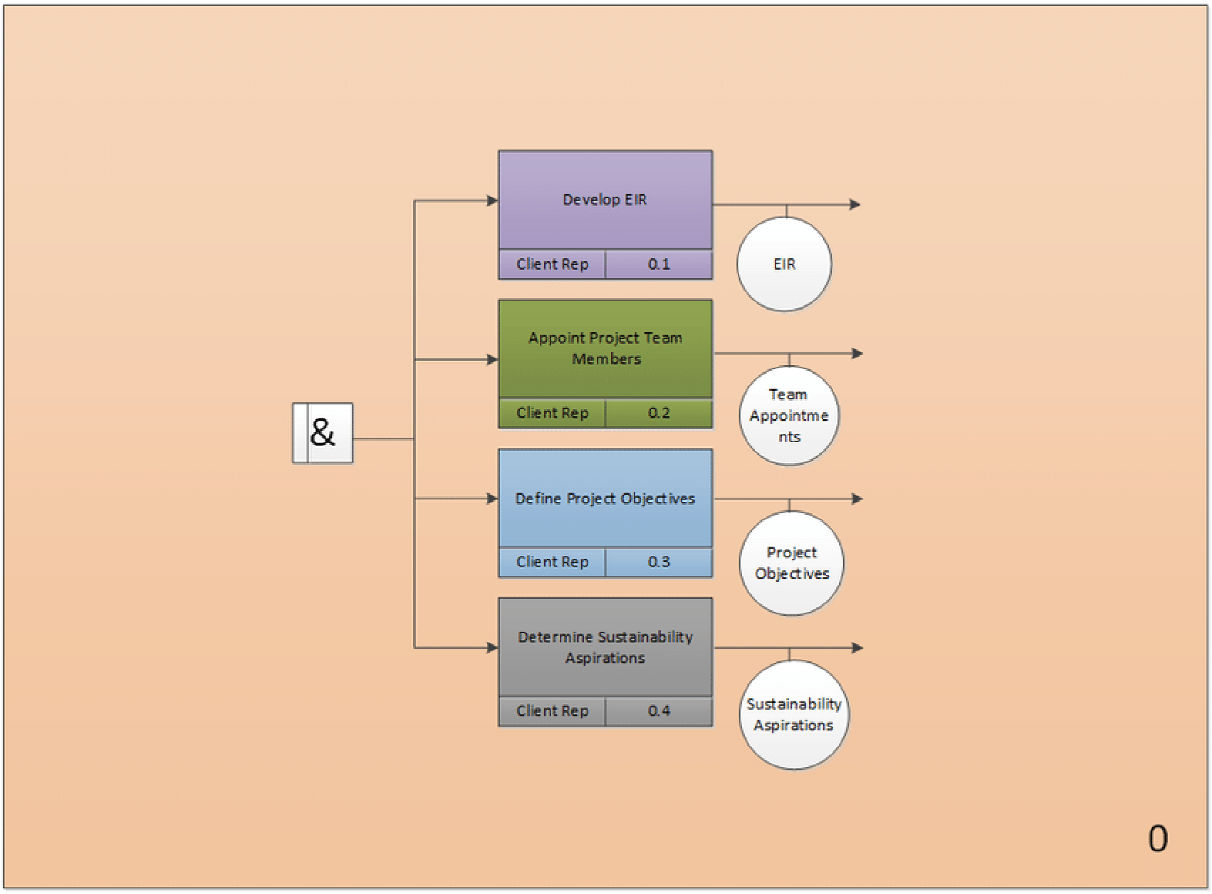
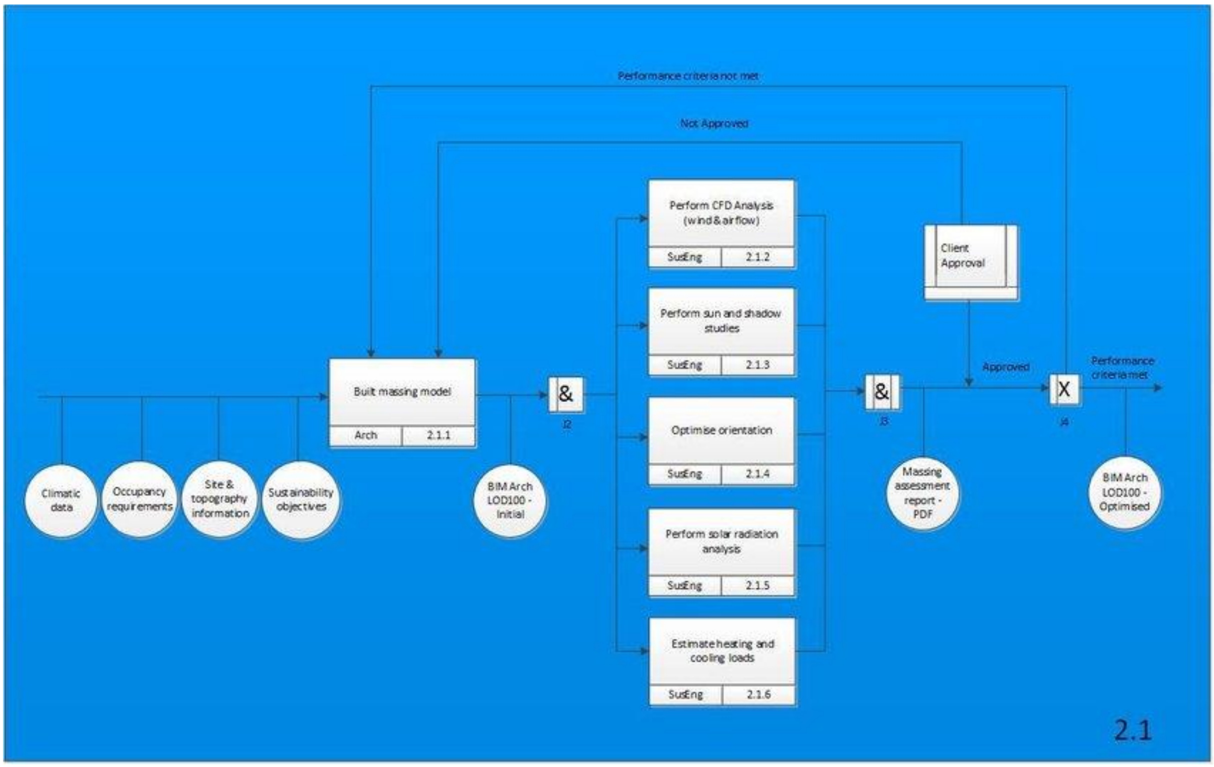
7 ANNEX

7.1 Annex 1: Developed level of Zanni, Soetanto and Ruikar IDEF process master-map






Develop EIR
Client Rep
0.1
EIR
Appoint Project Team Members
Client Rep
0.2
Team Appointments
&
Define Project Objectives
Client Rep
0.3
Project Objectives
Determine Sustainability Aspirations
Client Rep
0.4
Sustainability Aspirations
0


Performance criteria not met
Not Approved
Perform CFD Analysis (wind & air flow)
SusEng
2.1.2
Client Approval
Perform sun and shadow studies
SusEng
2.1.3
Approved
Performance criteria met
Built massing model
Arch
2.1.1
&
J2
&
J3
X
J4
Optimise orientation
SusEng
2.1.4
Climatic data
Occupancy requirements
Site & topography information
Sustainability objectives
BIM Arch LOD100 - Initial
Massing assessment report - PDF
BIM Arch LOD100 - Optimised
Perform solar radiation analysis
SusEng
2.1.5
Estimate heating and cooling loads
SusEng
2.1.6
2.1

7.2 **Annex 2:** Baseline energy analysis of each wall type

7.3 **Annex 3:** Optimization report and bundles

Office Building option 2

Parametric Study - Cost vs Energy Optimization

Sep. 03 2022

.

ANALYSIS SUMMARY

Location

Vič District, Ljubljana, Slovenia

Climate Zone

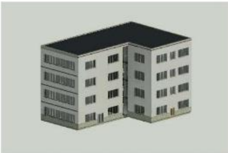
ASHRAE Climate Zone 5

17

Walk Score®

Car-Dependent

Building Type



Office

96

Overall Energy

The current model is done using ASHRAE 2019 - IECC 2021 Equivalent energy code assumptions. The current design is better than the national average and can be significantly improved by higher performance of envelope, HVAC and more. The building load is driven by Heating and Equipment.

BENCHMARKS

WHERE DO WE NEED TO BE?

Energy

273 National Average

55 2030 Target

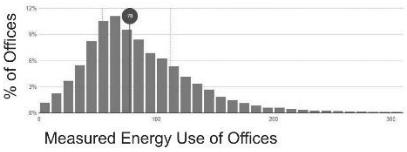
55 % Daylight

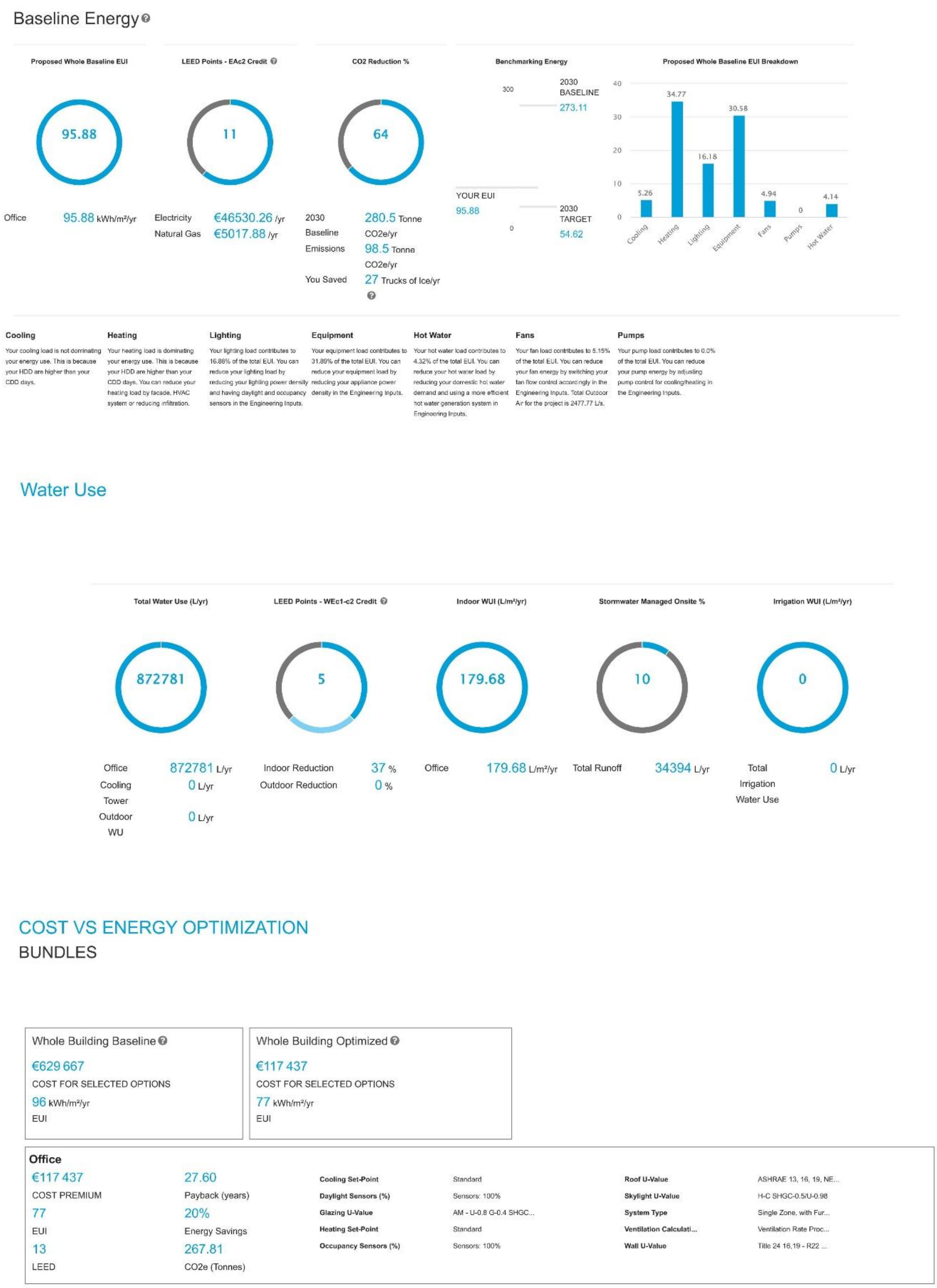
10 % Glare

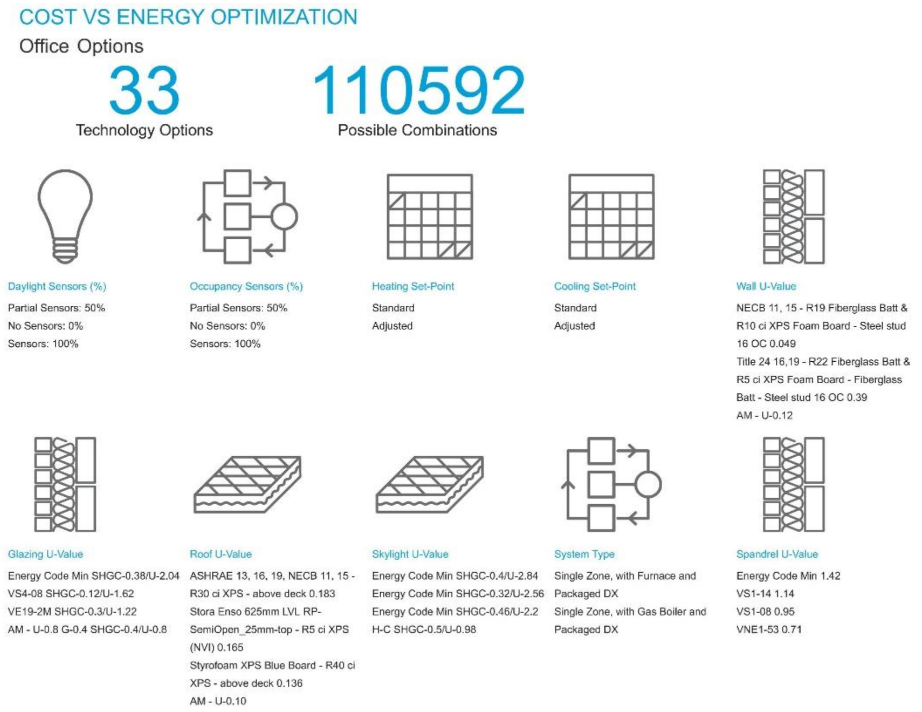
EUI is expressed as energy per square meter per year. It is calculated by dividing the total energy consumed by the building in one year (measured in kWh) by the total floor area of the building. The most common unit for EUI is kWh/m²/year.

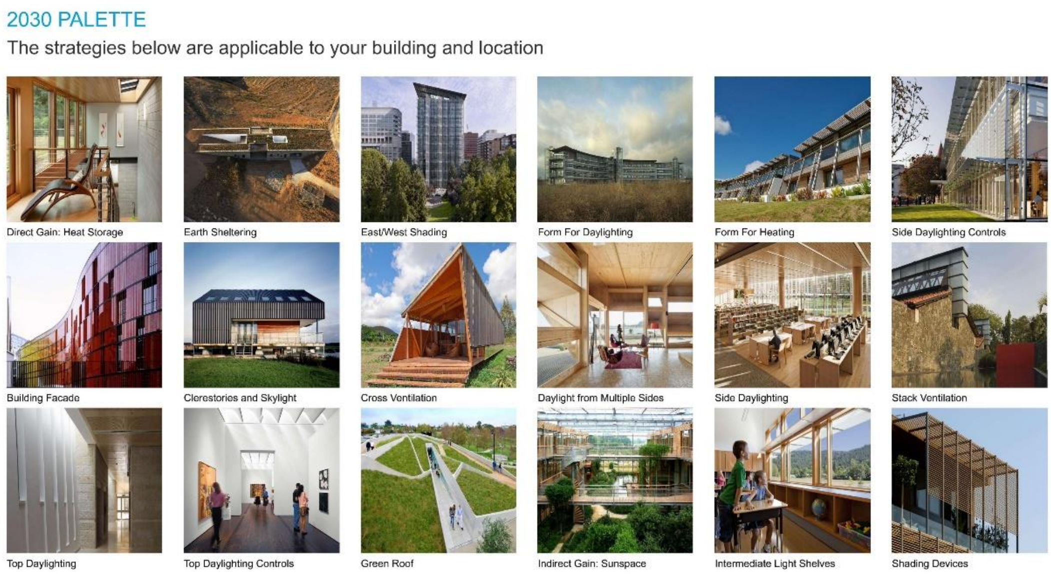
Spatial Daylight Autonomy (sDA) describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours.

Annual Solar Exposure (ASE) refers to the percentage of space that receives too much direct sunlight (1000 Lux or more for at least 250 occupied hours per year), which can cause glare or increased cooling loads.



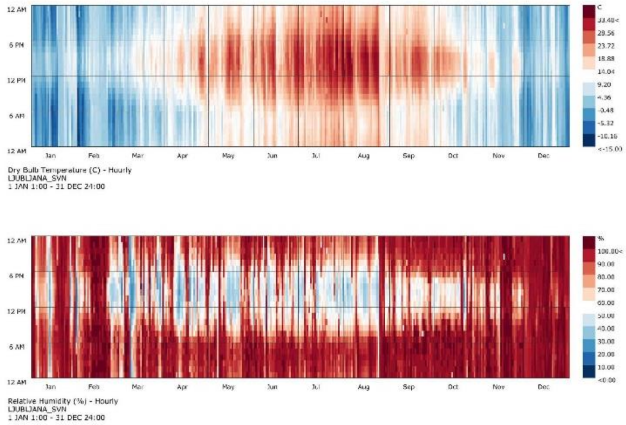

Baseline Energy
Proposed Whole Baseline EUI
95.88
Office 95.88 kWh/m²/yr
LEED Points - EAc2 Credit
11
Electricity €46530.26 /yr
Natural Gas €5017.88 /yr
CO2 Reduction %
64
2030 Baseline Emissions 280.5 Tonne CO2e/yr
98.5 Tonne CO2e/yr
You Saved 27 Trucks of Ice/yr
Benchmarking Energy
300
2030 BASELINE 273.11
YOUR EUI 95.88
0
2030 TARGET 54.62
Proposed Whole Baseline EUI Breakdown
40
30
20
10
0
5.26
34.77
16.18
30.58
4.94
0
4.14
Cooling
Heating
Lighting
Equipment
Fans
Pumps
Hot Water
Cooling
Your cooling load is not dominating your energy use. This is because your HDD are higher than your CDD days.
Heating
Your heating load is dominating your energy use. This is because your HDD are higher than your CDD days. You can reduce your heating load by facade, HVAC system or reducing infiltration.
Lighting
Your lighting load contributes to 16.88% of the total EUI. You can reduce your lighting load by reducing your lighting power density and having daylight and occupancy sensors in the Engineering Inputs.
Equipment
Your equipment load contributes to 31.89% of the total EUI. You can reduce your equipment load by reducing your appliance power density in the Engineering Inputs.
Hot Water
Your hot water load contributes to 4.32% of the total EUI. You can reduce your hot water load by reducing your domestic hot water demand and using a more efficient hot water generation system in Engineering Inputs.
Fans
Your fan load contributes to 5.15% of the total EUI. You can reduce your fan energy by switching your fan flow control accordingly in the Engineering Inputs. Total Outdoor Air for the project is 2477.77 L/s.
Pumps
Your pump load contributes to 0.0% of the total EUI. You can reduce your pump energy by adjusting pump control for cooling/heating in the Engineering Inputs.
Water Use
Total Water Use (L/yr)
872781
Office 872781 L/yr
Cooling Tower 0 L/yr
Outdoor WU 0 L/yr
LEED Points - WEc1-c2 Credit
5
Indoor Reduction 37 %
Outdoor Reduction 0 %
Indoor WUI (L/m²/yr)
179.68
Office 179.68 L/m²/yr
Stormwater Managed Onsite %
10
Total Runoff 34394 L/yr
Irrigation WUI (L/m²/yr)
0
Total Irrigation Water Use 0 L/yr
COST VS ENERGY OPTIMIZATION
BUNDLES
Whole Building Baseline
€629 667
COST FOR SELECTED OPTIONS
96 kWh/m²/yr
EUI
Whole Building Optimized
€117 437
COST FOR SELECTED OPTIONS
77 kWh/m²/yr
EUI
Office
€117 437
COST PREMIUM
77
EUI
13
LEED
27.60
Payback (years)
20%
Energy Savings
267.81
CO2e (Tonnes)
Cooling Set-Point Standard
Daylight Sensors (%) Sensors: 100%
Glazing U-Value AM - U-0.8 G-0.4 SHGC...
Heating Set-Point Standard
Occupancy Sensors (%) Sensors: 100%
Roof U-Value ASHRAE 13, 16, 19, NE...
Skylight U-Value H-C SHGC-0.5/U-0.98
System Type Single Zone, with Fur...
Ventilation Calculati... Ventilation Rate Proc...
Wall U-Value Title 24 16,19 - R22 ...


COST VS ENERGY OPTIMIZATION
Office Options
33
Technology Options
110592
Possible Combinations
Daylight Sensors (%)
Partial Sensors: 50%
No Sensors: 0%
Sensors: 100%
Occupancy Sensors (%)
Partial Sensors: 50%
No Sensors: 0%
Sensors: 100%
Heating Set-Point
Standard
Adjusted
Cooling Set-Point
Standard
Adjusted
Wall U-Value
NECB 11, 15 - R19 Fiberglass Batt & R10 ci XPS Foam Board - Steel stud 16 OC 0.049
Title 24 16,19 - R22 Fiberglass Batt & R5 ci XPS Foam Board - Fiberglass Batt - Steel stud 16 OC 0.39
AM - U-0.12
Glazing U-Value
Energy Code Min SHGC-0.38/U-2.04
VS4-08 SHGC-0.12/U-1.62
VE19-2M SHGC-0.3/U-1.22
AM - U-0.8 G-0.4 SHGC-0.4/U-0.8
Roof U-Value
ASHRAE 13, 16, 19, NECB 11, 15 - R30 ci XPS - above deck 0.183
Stora Enso 625mm LVL RP-SemiOpen_25mm-top - R5 ci XPS (NVI) 0.165
Styrofoam XPS Blue Board - R40 ci XPS - above deck 0.136
AM - U-0.10
Skylight U-Value
Energy Code Min SHGC-0.4/U-2.84
Energy Code Min SHGC-0.32/U-2.56
Energy Code Min SHGC-0.46/U-2.2
H-C SHGC-0.5/U-0.98
System Type
Single Zone, with Furnace and Packaged DX
Single Zone, with Gas Boiler and Packaged DX
Spandrel U-Value
Energy Code Min 1.42
VS1-14 1.14
VS1-08 0.95
VNE1-53 0.71

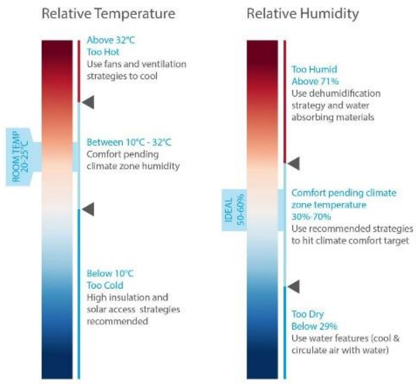

2030 PALETTE
The strategies below are applicable to your building and location
Direct Gain: Heat Storage
Earth Sheltering
East/West Shading
Form For Daylighting
Form For Heating
Side Daylighting Controls
Building Facade
Clerestories and Skylight
Cross Ventilation
Daylight from Multiple Sides
Side Daylighting
Stack Ventilation
Top Daylighting
Top Daylighting Controls
Green Roof
Indirect Gain: Sunspace
Intermediate Light Shelves
Shading Devices

CLIMATE ANALYSIS

RELATIVE TEMPERATURE & HUMIDITY

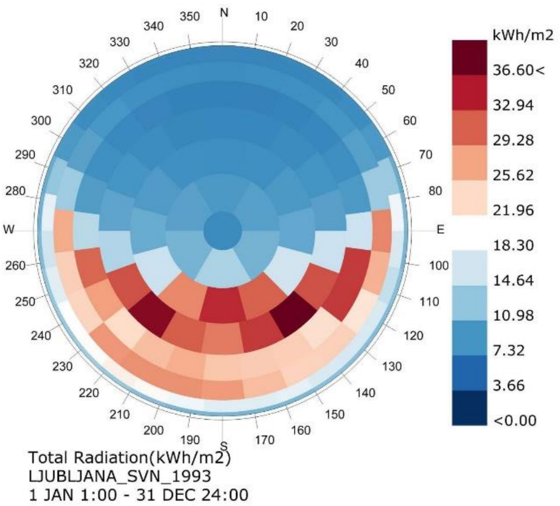


This graph shows the outdoor comfort in Ljubljana using the yearly range of temperatures and humidities.

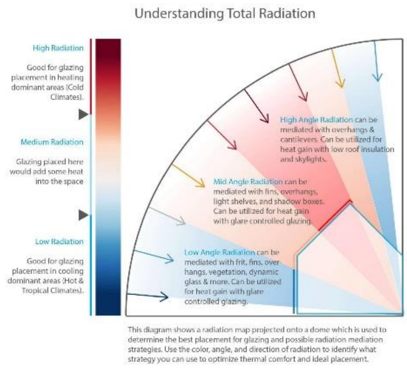


CLIMATE ANALYSIS

RADIATION BY SKY SEGMENT

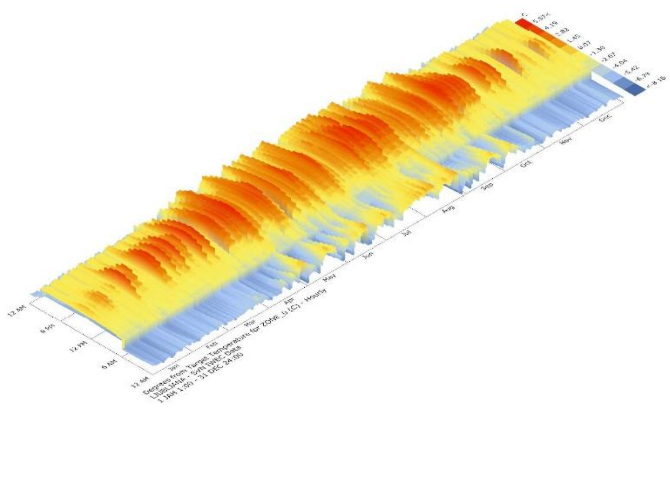


This graph maps the radiation onto a sky dome to show the intensity of the direction and intensity of solar radiation on a yearly basis around the cardinal points for Ljubljana.

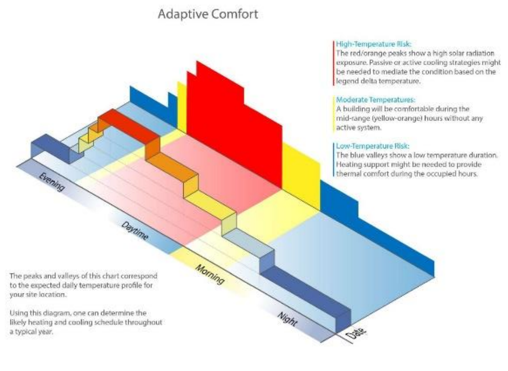


CLIMATE ANALYSIS

ADAPTIVE COMFORT

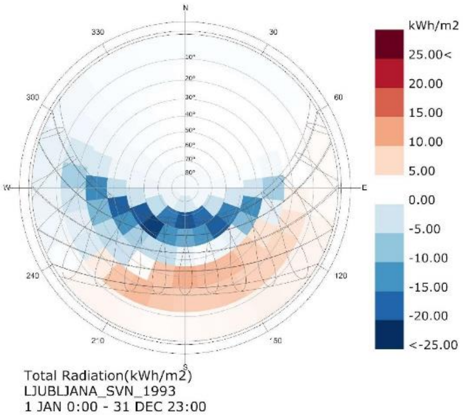


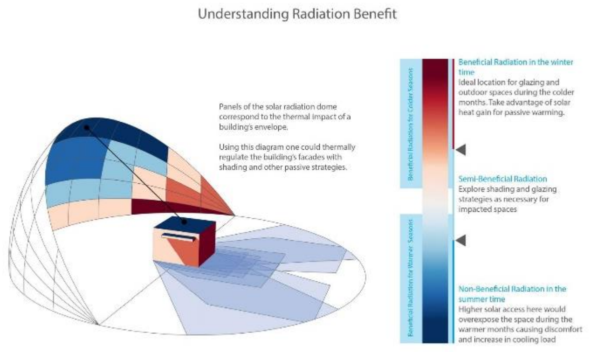
Adaptive Comfort chart showing the time of day and time of year with the greatest human comfort for your location.



CLIMATE ANALYSIS

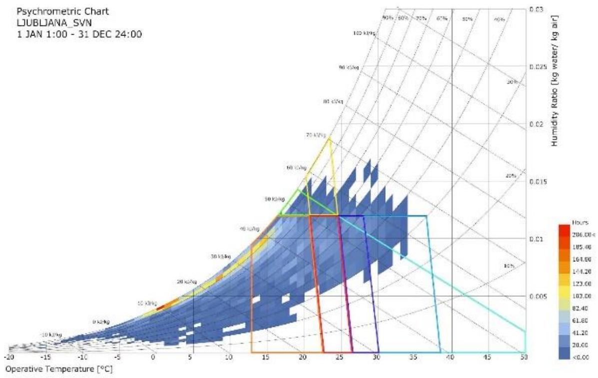
RADIATION BENEFIT





CLIMATE ANALYSIS

PSYCHROMETRIC CHART



5.75 % COMFORT - NO PASSIVE STRATEGIES

Impact of Design Strategies

% of additional comfort - higher is better

2.79 % EVAPORATIVE COOLING

3.03 % THERMAL MASS + NIGHT VENTILATION

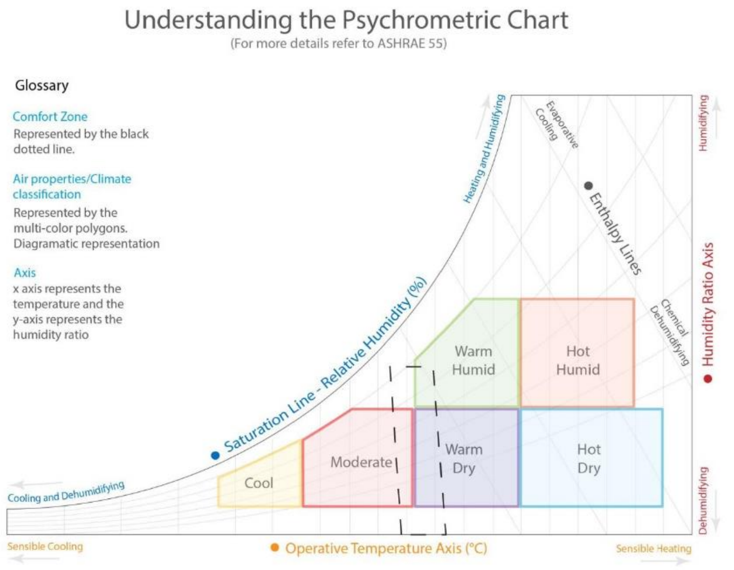
2.85 % OCCUPANT USE OF FANS

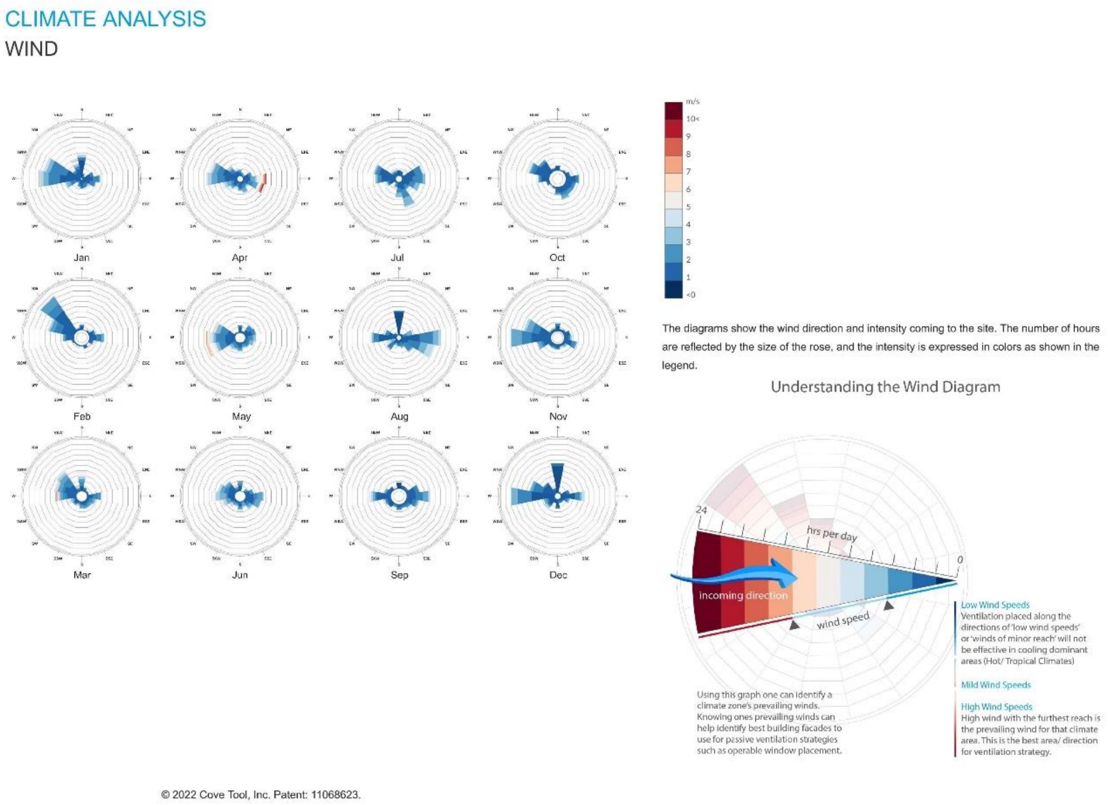
25.68 % INTERNAL HEAT GAIN

0.80 % DESICCANT DEHUMIDIFICATION

0.48 % DEHUMIDIFICATION

This chart shows the relationship between dry bulb, humidity ratio, and enthalpy. The polygons overlaid on the chart represent different strategies to increase comfort. Based on ASHRAE 55-2013 under standard conditions.


Understanding the Psychrometric Chart
(For more details refer to ASHRAE 55)
Glossary
Comfort Zone
Represented by the black dotted line.
Air properties/Climate classification
Represented by the multi-color polygons. Diagramatic representation
Axis
x axis represents the temperature and the y-axis represents the humidity ratio
Heating and Humidifying
Evaporative Cooling
Enthalpy Lines
Humidifying
Humidity Ratio Axis
Chemical Dehumidifying
Saturation Line - Relative Humidity (%)
Warm Humid
Hot Humid
Cool
Moderate
Warm Dry
Hot Dry
Cooling and Dehumidifying
Dehumidifying
Sensible Cooling
Operative Temperature Axis (°C)
Sensible Heating


CLIMATE ANALYSIS
WIND
Jan
Apr
Jul
Oct
Feb
May
Aug
Nov
Mar
Jun
Sep
Dec
m/s
10<
9
8
7
6
5
4
3
2
1
<0
The diagrams show the wind direction and intensity coming to the site. The number of hours are reflected by the size of the rose, and the intensity is expressed in colors as shown in the legend.
Understanding the Wind Diagram
24
hrs per day
0
incoming direction
wind speed
Low Wind Speeds
Ventilation placed along the directions of 'low wind speeds' or 'winds of minor reach' will not be effective in cooling dominant areas (Hot/ Tropical Climates)
Mild Wind Speeds
High Wind Speeds
High wind with the furthest reach is the prevailing wind for that climate area. This is the best area/ direction for ventilation strategy.
Using this graph one can identify a climate zone's prevailing winds. Knowing ones prevailing winds can help identify best building facades to use for passive ventilation strategies such as operable window placement.
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