DELIVERABLE 1.4

The energy assessment of buildings in BIM environment

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1 Introduction

1.1 Overview of the SmartWins Project

The SmartWins project is a forward-thinking initiative aimed at tackling the urgent issues of sustainability and efficiency in our built environments. With urbanization on the rise worldwide, the way we construct and manage buildings plays a huge role in energy consumption and carbon emissions, making up about 40% of global energy use and 36% of greenhouse gas emissions. To combat this, the SmartWins project brings together innovative technologies like Digital Twins (DTs), Life Cycle Assessment (LCA), and Building Information Modelling (BIM) to support smart, data-driven decisions throughout the entire lifecycle of a building.

Deliverable D1.4, known as "Energy Assessment of Smart Buildings in a BIM Environment," aims to create a robust methodology for evaluating both energy and non-energy performance of buildings in a BIM context. It draws from the EN52000 standards and other relevant guidelines, incorporating elements such as energy efficiency, water consumption, noise, and acoustic quality, all based on performance data gathered throughout the building's life cycle. Additionally, this deliverable will include the creation of APIs to facilitate this comprehensive assessment within the BIM framework, providing a solid technical base for more accurate and integrated evaluations of building performance.

1.2 Context and Rationale for Energy Assessment in BIM Environments

The built environment is experiencing a significant transformation, fuelled by the urgent need for decarbonization and the push for digitalization. Traditional energy assessment methods have mainly concentrated on operational energy efficiency—think HVAC and lighting—but they often overlook essential non-energy aspects like water usage, material sustainability, and the well-being of occupants. Additionally, these conventional approaches tend to lack interoperability across the design, construction, and operational stages, leading to fragmented data and less effective decision-making.

1.2.1. Limitations of Current Energy Assessment Practices

Energy evaluation protocols, particularly those based on the EN 52000 series, are currently facing three significant challenges:

1. **Narrow Scope**: They tend to focus too much on operational energy (Scope 1 emissions) and neglect important factors like embodied carbon (Scope 3) and the use of non-energy resources (for instance, water and raw materials).
2. **Static Analysis**: Reliance on static simulations that fail to incorporate real-time data from IoT sensors or adaptive building management systems.
3. **Fragmented Workflows**: Disconnects between BIM design platforms and energy simulation tools, necessitating manual data re-entry and increasing error margins.

1.2.2. The Transformative Role of BIM and Digital Twins

BIM and Digital Twins address these limitations through:

- **Dynamic, Whole-Life Cycle Analysis**: BIM's parametric models' factor in the lifecycle of data from sourcing materials to deconstruction, whilst DTs allow for feedback loops via IoT sensors in real time.
- **Multi-Criteria Decision-Making**: Allowing for energy performance (kWh/m²/yr), water efficiency (litres/occupant/day), and acoustic quality (dB thresholds) at the same time within the same digital environment.
- **Interoperability**: APIs creating bridges between BIM software and energy simulation tools, enriching data exchanges and avoiding unnecessary human input.

Table 1. Current Challenges vs. SmartWins Solutions

Challenge	SmartWins Innovation
Static energy models	Real-time DT updates via IoT sensor integration
Siloed non-energy metrics	BIM-based unified assessment framework
Manual data transfer	Automated APIs (IFC, gbXML)
Limited policy alignment	Compliance with EN 52000, EPBD, and Green Deal

1.2.3. Scientific and Technological Advancements

Recent developments in machine learning, IoT technology, and open-source BIM applications have opened new possibilities to:

- **Predict Energy-Environment Trade-Offs**: Algorithms will allow HVAC settings to be adjusted to maximize cooling, minimize fan energy use, and meet acoustic comfort.
- **Automate Compliance Reporting**: BIM plugins generate EN 52000-compliant reports, reducing administrative overhead.
- **Enhance Stakeholder Collaboration**: Cloud-based BIM platforms enable architects, engineers, and facility managers to co-optimize designs in real time.

1.3 Scope and Objectives of Deliverable D1.4

The purpose of this deliverable is to progress the evaluation of energy and non-energy performance in smart buildings through the combination of BIM with Digital Twin technologies. SmartWins researchers focused on four key research pillars:

1. **Development of an Asset-Based Energy Assessment Methodology**:

   Establishing a standardized framework for evaluating building energy performance within BIM environments, aligned with the EN 52000 series and ISO 16346. This includes dynamic simulations of operational energy (e.g., HVAC, lighting) and embodied energy calculations via LCA tools.

2. **Integration of Non-Energy Parameters into BIM Workflows**:

   Expanding traditional energy assessments to incorporate non-energy factors such as water consumption efficiency, acoustic performance, and material circularity. IoT sensor data, hydraulic simulations, and noise mapping tools are integrated into BIM to quantify these impacts.

3. **Interoperability and API Development for BIM Platforms**:

   Designing an open-source API for BIM software to allow seamless integration with energy simulation software (i.e., EnergyPlus, IESVE, etc.). Particular attention will be paid to the usability of Industry Foundation Classes (IFC) and gbxml as a means of enabling interoperability across software platforms.

4. **Whole-Life Cycle Energy and Resource Tracking**:

Utilizing BIM and Digital Twins enables us to evaluate building performance throughout its entire life cycle—covering design, construction, operation, and decommissioning. This strategy incorporates real-time data streaming from IoT sensors, which helps optimize predictive maintenance and identify necessary retrofits.

These key components collaborate to form a strong, scalable framework that improves energy efficiency, minimizes carbon footprints, and enhances resource management in smart buildings. These deliverable bridges BIM and energy standards with other non-energy metrics, supporting the SmartWins project's vision of creating sustainable, data-driven urban ecosystems. Figure 1 illustrates the layered structure of these components, highlighting their interconnected roles in smart building management.

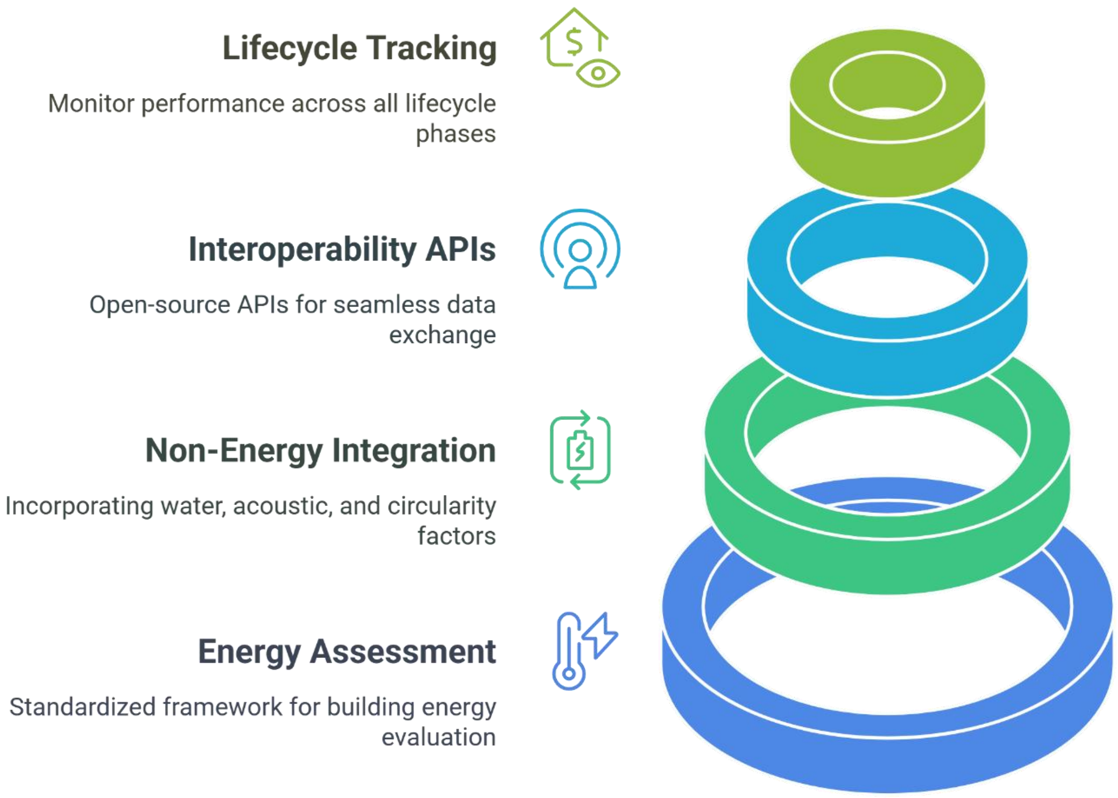


Figure 1. Smart Building Performance Framework (Source: Author)

1.4 Deliverable Structure and Research Significance

This deliverable is constructed to provide an understandable structure that not only describes the methodology of the SmartWins project and details the experimental results, but it also highlights the research importance of the project within the context of smart building technologies as they are evolving. Such an approach provides clarity on how unified BIM and Digital Twin technologies can positively disrupt practices associated with energy performance assessments and help enable a more sustainable built environment.

1.2.4. Structure of the Deliverable

The deliverable is divided into several key sections that progressively build upon one another:

- **Introduction and Project Overview:** Context, purpose, and justification for having energy and non-energy metrics integrated within a BIM context. Building this section provides context by discussing challenges to traditional energy assessments and describes the innovations proposed and approved in the SmartWins project.
- **Background and State-of-the-Art Review:** This part offers a comprehensive analysis of the current methodologies and standards, including EN 52000, while also shining a light on the latest technological advancements in BIM, IoT, and machine learning. It emphasizes the importance of taking a comprehensive approach to energy assessment that aligns with the changing regulatory landscape, like the European Green Deal.
- **Methodology and Achievements:** Details the experimental setup, the design of the asset-based energy assessment framework, and the addition of non-energy parameters to BIM workflows. This includes case studies and performance analysis examples to provide applications of the APIs developed, and present examples of interoperability with simulation tools.
- **Gained Knowledge by KTU:** This section presents the technical, methodological, and organizational knowledge acquired by KTU through hands-on collaboration with Contecht GmbH in developing digital twin frameworks and evaluating BIM-to-BEPS (Building Energy Performance Simulation) workflows. KTU gained practical experience with toolchain testing (e.g., Revit–SketchUp–EnergyPlus, Revit–TRNSYS), IFC data handling, semantic fidelity, and interoperability diagnostics. Additionally, the university deepened its expertise in dashboard-based real-time data visualization, IoT integration for occupancy monitoring, and user-cantered interface design through the Vercel use case. Scientific work conducted in parallel contributed to advanced understanding of simulation workflows, standards analysis, and interdisciplinary collaboration, reinforcing KTU’s capacity to support digitalization and sustainability in the building sector.

- **Conclusions and Future Directions:** Summarizes the key findings and suggests avenues for future research and technological enhancements. It emphasizes the importance of continuous innovation and iterative feedback loops, enabled by Digital Twins, to meet the dynamic challenges of urban sustainability.

1.2.5. Research Significance

The significance of this output extends beyond more technical value as follows:

- **Bridging Traditional and Emerging Paradigms:** Energy and non-energy metrics compliment the provision of gap filling prior to the start of the assessment process, transitioning from static siloed to dynamic holistic across the building's entire lifecycle.
- **Enhancing Interoperability:** The significance of open access APIs and standard data formats - such as IFC and gbXML - will assist more readily in transferring activities across different technical systems, reduce inherent communication barriers and administrative costs associated, and promote collaborative work across architects, engineers, and facility managers.
- **Supporting Regulatory and Sustainability Goals:** The output adheres to EU efforts such as the Renovation Wave Strategy and the European Green Deal, increasingly performing as a methodological framework to inform policy and help advance the industry towards carbon neutrality and resource efficiency.
- **Facilitating Real-Time Decision-Making:** The relevance of Digital Twin technology will provide real time feedback to incorporate back into the building management systems (BMS) to engage in implementing adaptive control strategies balancing operational performance, occupant comfort, and product longevity of the building.

In conclusion, the structured content of this deliverable is not simply a record of the SmartWins project technical innovations, but also a clear basis for smart building design and sustainable urban development initiatives in the future. This represents a major step to reconcile what is possible technically with what we will be allowed to build in the coming years, and the bent work directing future research and implementation in the built environment.

2 Background

The evolution of building energy performance assessment has moved in parallel with technological advancements in digital design tools, data analytics, and performance monitoring systems. This section explores the current academic and technical landscape across key dimensions relevant to the SmartWins project: energy assessment standards, integration of BIM, Digital Twin technologies, and the emergence of holistic, life-cycle-based evaluation frameworks.

2.1 Whole Building Performance Simulation (WBPS)

Whole Building Performance Simulation (WBPS) is an essential method for analysing the integrated performance of buildings under various physical, environmental, and operational conditions. Unlike component-based simulations, WBPS evaluates interactions among systems (e.g., HVAC, lighting, envelope) and environmental factors over the entire building lifecycle. It enables robust predictions of energy use, thermal comfort, indoor air quality, daylighting, and more.

Traditional WBPS workflows rely on tools such as EnergyPlus, TRNSYS, and IES-VE, which model thermodynamic behaviour over time. However, these tools often require manual data entry and geometry recreation, particularly when not directly integrated with BIM platforms. This fragmentation limits the uptake of performance simulation during early design phases where design flexibility and impact are highest.

2.2 Evolving Standards and Assessment Frameworks

Conventional building energy assessment protocols, such as those in the EN 52000 series (notably EN ISO 52000-1:2017), provide a standardized foundation for calculating the energy performance of buildings. However, they are primarily oriented towards operational energy consumption and do not fully encompass embodied energy, resource efficiency, or adaptive performance metrics enabled by IoT technologies.

Recent research (e.g., Johra et al., 2022; Salvalai et al., 2021) critiques these frameworks for lacking flexibility in integrating dynamic and real-time data from modern building systems. Moreover, with the European Green Deal and Renovation Wave Strategy emphasizing whole-life carbon and circular economy principles, these standards must now evolve to include Scope 3 emissions and non-energy-related environmental metrics.

2.3 Building Information Modelling (BIM) as a Digital Backbone

Recent studies emphasize the value of coupling BIM with WBPS tools to enable iterative and data-rich performance assessments. For instance, Asl et al. (2015) demonstrated a workflow linking BIM environments with EnergyPlus through an optimization engine, enabling real-time design feedback based on energy consumption. Similarly, Attia et al. (2018) reviewed state-of-the-art simulation practices and stressed the need for seamless interoperability, intuitive interfaces, and real-time responsiveness to support decision-making.

Significant progress has been made in enhancing WBPS through data-driven and semantic enrichment strategies. Fang et al. (2020) proposed a rule-based knowledge representation system embedded within BIM to automate energy compliance checking. Meanwhile, Santos et al. (2021) explored integrating BIM with cloud-based WBPS platforms for collaborative energy analysis across stakeholders, emphasizing the role of information standards like IFC and CityGML in supporting automation and interoperability.

It is not surprising that BIM has emerged as a critical enabler for integrating energy and environmental simulations within design workflows. Its object-oriented, parametric modeling environment supports data-rich representation of physical and functional building characteristics, facilitating deeper analysis across design stages. However, research identifies persistent interoperability issues with simulation tools such as EnergyPlus, DesignBuilder, and IES-VE, due to differences in data schemas and export formats (IFC, gbXML). A major part of the work on SmartWins focused on gaining experience in how to achieve seamless interoperability between BIM and whole building performance analysis tools.

Studies by Dong et al. (2018) and Volk et al. (2014) underline the promise of BIM in energy analysis but call for improved standardization and automation through APIs and middleware platforms. The emergence of openBIM approaches and semantic enrichment of IFC schemas is helping reduce data loss and model misinterpretation. These early reports have triggered several applied research efforts into interoperability between BIM and building performance simulation. Maybe the most prominent of these efforts was conducted on the Horizon 2020 project BIM-Speed. The project identified major bottlenecks between major software solutions (BIM-Speed D3.3). BIM-Speed also identified solutions for the seamless interchange between critical data, such as location and weather data, building geometry, building elements, thermal zones, HVAC systems and equipment, as well as about occupancy schedules.

2.4 Digital Twins and IoT-Enabled Building Performance

Leveraging the experience from BIM-based exchange, the Digital Twin concept, as articulated by Grieves (2014) and further developed in the built environment by Khajavi et al. (2021), introduces a powerful feedback mechanism for real-time monitoring and control of building operations.

The integration of WBPS into Digital Twin ecosystems further enhances the predictive capability of performance models. IoT-sourced operational data can recalibrate simulation assumptions, detect performance drift, and optimize control strategies based on real-world conditions. This dynamic coupling fosters adaptive energy management and predictive maintenance planning, as seen in SmartWins' asset-based and whole-life approach.

When coupled with IoT networks and edge computing, DTs enable continuous calibration of simulation models, predictive maintenance, and occupant-responsive controls.

Case studies from smart campuses and office environments (e.g., Qi et al., 2023; Foteinis et al., 2021) demonstrate the application of DTs in optimizing HVAC operations, reducing peak loads, and integrating renewable energy systems. However, implementation challenges remain in data governance, semantic interoperability, and scalability of twin models beyond single-use cases.

Moreover, recent work underscores the importance of machine learning models trained on WBPS datasets to predict energy and comfort outcomes across varying occupancy profiles and weather scenarios (Pang et al., 2023). These techniques are increasingly being used to augment simulation accuracy, reduce computation time, and support real-time feedback in Digital Twin applications.

2.5 Integration of Non-Energy Metrics in Smart Assessments

While energy has been the traditional focus of building performance, a growing body of literature recognizes the importance of non-energy metrics such as indoor environmental quality (IEQ), acoustic comfort, water usage, and material circularity.

Tools like SimaPro, OneClick LCA, and SoundPLAN are increasingly being coupled with BIM to evaluate environmental and acoustic performance, but integration is often manual or post hoc. Research by Klein et al. (2020) and Nguyen et al. (2022) highlight the need for multi-criteria decision-support systems (MCDSS) that can dynamically weigh trade-offs between thermal comfort, acoustic quality, and environmental impact—ideally embedded within a BIM or Digital Twin environment.

2.6 Toward Holistic, Life-Cycle Performance Analysis

Recent academic frameworks advocate for shifting from static, single-phase evaluations to whole-life performance analysis. This includes not only operational energy and emissions but also embodied impacts from material sourcing, construction, and end-of-life scenarios. Life Cycle Assessment (LCA) methodologies are central here, supported by standards like ISO 14040/44 and integrated through BIM-based plugins (e.g., Tally, eToolLCD).

Research by Zanni et al. (2019) and Mastrolembo Ventura et al. (2023) underscores the importance of combining LCA with BIM to perform early design optimization based on environmental impact, cost, and performance. The inclusion of Digital Twins adds a temporal dimension, enabling post-occupancy data to feed back into lifecycle models for improved predictive analytics and retrofit planning.

2.7 Summary of Research Gaps and Opportunities

While the integration of BIM, DTs, and energy assessment tools shows promise, several gaps remain that the SmartWins project directly addresses (Table 2):

Table 2. Comparison of Identified Gaps and Corresponding SmartWins Innovations

Gap	SmartWins Response
Limited non-energy metrics integration	Incorporation of acoustic, water, and circularity metrics

Fragmented tool ecosystems	Development of standardized APIs using IFC and gbXML
Lack of real-time adaptation	IoT-driven DTs enabling adaptive control and simulation recalibration
Static life-cycle assessments	Dynamic BIM-DT-LCA pipelines with temporal updating

By responding to these technological, regulatory, and methodological shortcomings, SmartWins aims to establish a more holistic, dynamic, and interoperable approach to evaluating smart building performance throughout the entire life cycle.

3 Methodology and Achievements

3.1 Introduction to the Methodology

3.1.1 Context and Rationale

In the evolving landscape of building performance simulation, traditional methods have long been challenged by fragmented data sources, manual workflows, and limited interoperability between BIM and Building Energy Simulation (BES) tools (Fig.2). Conventional assessment practices, based largely on static analysis and isolated datasets, fail to capture the dynamic nature of modern buildings—especially when addressing both energy and non-energy performance metrics such as water consumption, thermal comfort, and acoustic quality.

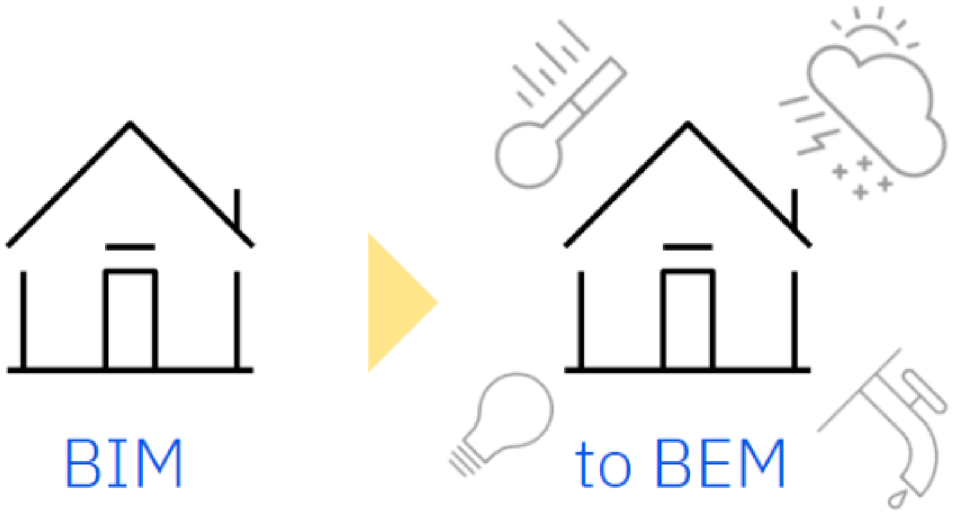


Figure 2. From BIM to BEM: Integrating energy and environmental data.[1]

[1] https://www.modelical.com/en/digitalisation-for-building-energy-simulation/

To bridge these gaps, our methodology which is based on a three-phased process, (Fig. 3), builds upon lessons learned from innovative projects like BIM-SPEED[2] and PRECEPT[3]. The methodology presented in this report is designed to:

- **Enhance Data Integration:** By streamlining the acquisition of architectural, structural, thermal, and environmental data into a unified BIM framework.
- **Automate Model Conversion:** Through the development of standardized procedures and support tools for transforming BIM data into calibrated Building Energy Models (BEM).
- **Foster Real-Time Adaptation:** By incorporating dynamic inputs from IoT sensors and environmental data streams, enabling adaptive simulation and predictive maintenance.
- **Improve Interoperability:** Leveraging open standards such as IFC and gbXML to ensure seamless data exchange between design, simulation, and performance assessment platforms.

[2] https://www.bim-speed.eu/en

[3] https://www.precept-project.eu/

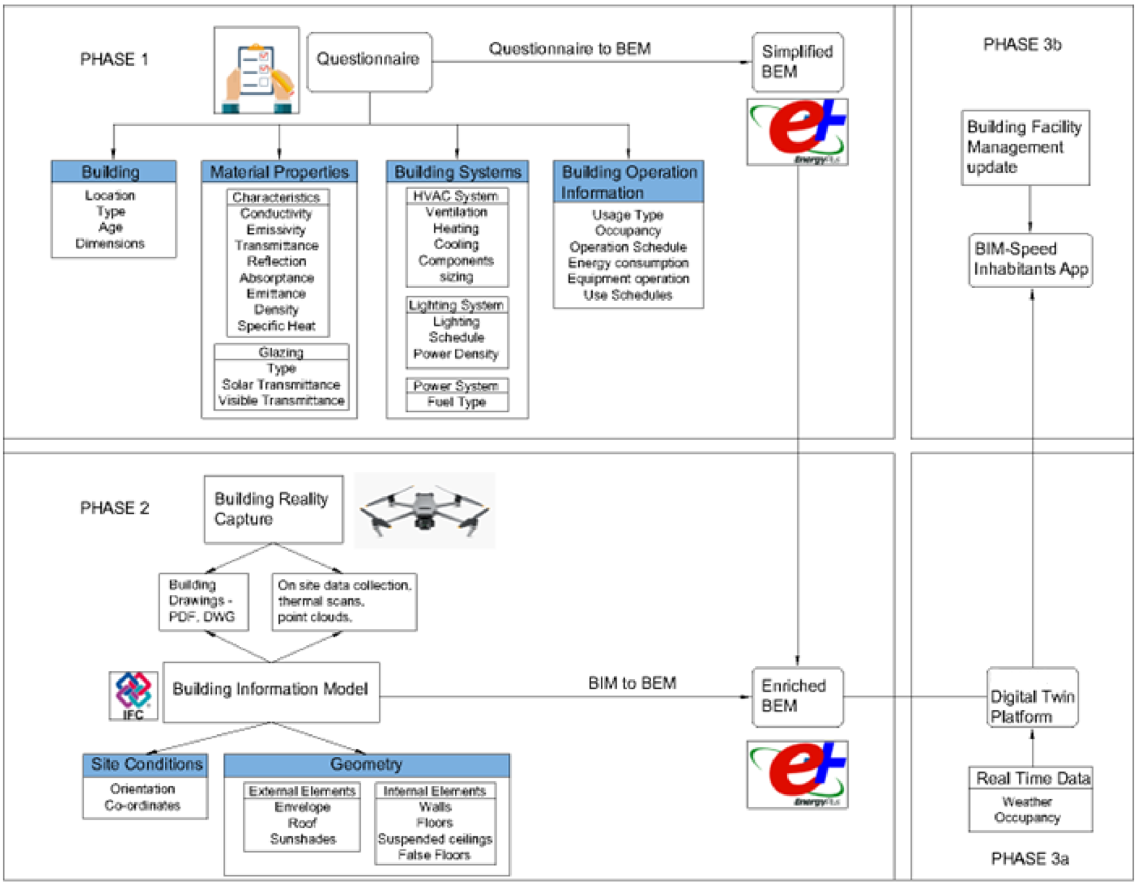


Figure 3. The three-phased process to capture building data and set-up building performance models[4]

3.1.2 Objectives of the Methodology

The methodology is structured around several key objectives:

- **Standardization of Data Acquisition:** Develop and document methods for collecting high-quality BIM data that encompass architectural, structural, and thermal characteristics, along with supplementary environmental parameters.

[4] Desai, D., & Hartmann, T. (2024). *Capturing building data for establishing digital twins of buildings for quick energy performance assessment* [Technical report]. Contecht GmbH.

- **Seamless BIM-to-BEM Transformation:** Design automated workflows and toolchains that minimize manual intervention while preserving data integrity, thereby enabling accurate energy simulations.
- **Dynamic Model Calibration:** Utilize real-world demonstration cases to continuously refine simulation models, ensuring that energy performance metrics reflect actual building behaviour over time.
- **Interoperability and Validation:** Establish robust protocols for semantic consistency, model checking, and data validation to ensure that all simulation inputs are accurate and reliable.
- **Stakeholder Collaboration:** Create guidelines and technological frameworks that enhance communication between architects, engineers, energy modelers, and facility managers, fostering collaborative efforts in optimizing building performance.

3.1.3 Structure of the Section

This section is organized into several subsections that collectively outline the entire process:

- **Data Acquisition and Integration:** Detailing the methods and technologies used to capture and integrate diverse data sources into a coherent BIM environment.
- **BIM-to-BEM Conversion and Calibration:** Describing the development of automated toolchains and support tools designed to facilitate the transformation of BIM models into calibrated energy models.
- **Interoperability and Validation:** Explaining the strategies employed for ensuring semantic fidelity and data integrity across the entire workflow.
- **Achievements and Case Studies:** Presenting concrete examples and performance metrics derived from real demonstration cases, which validate the effectiveness of the proposed methodology.
- **Future Directions and Recommendations:** Discussing potential improvements and avenues for further research to sustain continuous innovation in the field.

3.2 Data Acquisition and Integration with BIM

BEM is the practice of using computer-based simulation software to perform a detailed analysis of a building’s energy use and energy-using systems. The simulation software works by enacting a mathematical model that provides an approximate representation of the building. Setting up such simulation models requires gathering different types of information about a building. Capturing this information is often hard within the limited resources available for building managers and without disrupting the occupants of the building.

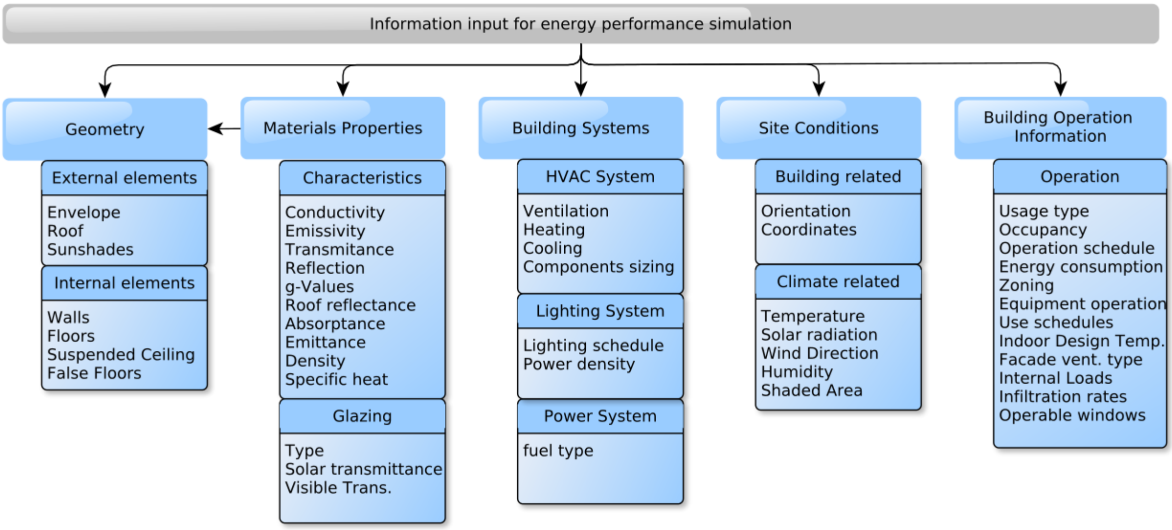


Figure 4. Types of information required of a building for energy capturing[5]

Collecting all the information depicted in Figure 4 that is required is a cumbersome task. While geometrical information can usually be obtained with the help of state-of-the art surveying methods, such as laser scans (Chen et al., 2023), obtaining accurate material data would require more complex measurements (Ham & Golparvar-Fard, 2013). Additionally, information about the building's mechanical, electrical, and plumbing systems is required (Utkucu et al., 2024). Collecting all this information is expensive and often disrupts the operations of the building. The question arises whether it is required to undertake such an extensive data collection effort to establish the basis for a meaningful digital twin or whether simpler models that rely on much less accurate and fewer data, and much more on general assumptions, could be an equally suitable starting point. To shed light on this question, SmartWins partner(Contecht)tested a minimalistic data collection approach that relies on a short questionnaire developed in an European innovation project, inquiring about some main characteristics of a specific building (Desai & Hartmann, under review). Contecht then tested the method by comparing simulation models based on the questionnaire with

[5] Gutsche, C., & Hartmann, T. (2017). 4m process roadmap and implementation guidelines. Retrieved April 26, 2024

detailed simulation models generated from a careful assessment of seven buildings in Europe. The next section described the overall structure of the minimalistic questionnaire method.

3.2.1 Building Energy Model derived from the Questionnaire

For the construction of the BEM, the EnergyPlus software was employed. EnergyPlus is a comprehensive whole-building energy simulation engine widely utilized by engineers, architects, and researchers to analyse energy and water consumption across various building systems—including heating, cooling, ventilation, lighting, and other process loads. The development of EnergyPlus is currently supported by the U.S. Department of Energy's Building Technologies Office. Rather than providing a dedicated user interface, EnergyPlus is designed to function as the simulation engine that can be integrated within a third-party graphical interface.

EnergyPlus operates using an input data file, known as an IDF (Input Data File), which is an ASCII-formatted document containing detailed information about the building's structure and its HVAC systems. Within an IDF, building data are encapsulated as objects, each assigned specific names (for example, "FenestrationSurface:Detailed" for a detailed window description). To ensure a successful, error-free simulation, the IDF must include a precise and logically organized set of objects; omissions or misconfigurations can lead to simulation failures or erroneous results.

The legacy format of the IDF is text-based and arranges input objects sequentially. Each object begins with a declaration of its type, followed by a list of field values in a designated order separated by commas, with the entire object concluded by a semicolon. Comments, indicated by an exclamation mark ("!"), are ignored by the simulation engine. Typically, these objects are distributed across multiple lines, with one field per line. Although field names are often provided as special comments following each value (preceded by "! -"), they are not essential to the simulation.

Figure 5 below illustrates the hierarchical structure of an IDF file. In the figure, the "Simulation Control" class is categorized under the "Simulation Parameters" group. The section labelled "Do Zone Sizing Calculation" represents the fields, and the corresponding parameter entries (e.g., "Yes") are identified as objects.

```
!-   ===========  ALL OBJECTS IN CLASS: SIMULATIONCONTROL ===========

SimulationControl,
    Yes,                     !- Do Zone Sizing Calculation
    Yes,                     !- Do System Sizing Calculation
    Yes,                     !- Do Plant Sizing Calculation
    No,                      !- Run Simulation for Sizing Periods
    Yes,                     !- Run Simulation for Weather File Run Periods
    No,                      !- Do HVAC Sizing Simulation for Sizing Periods
    ;                        !- Maximum Number of HVAC Sizing Simulation Passes
```

Figure 5. Structure of an IDF File

The components of an IDF file are organized into several groups, each contributing to the overall fidelity of the model. For instance, the site location is defined within the “Group – Location – Climate – Weather File Access”, which provides essential data for determining weather conditions at the building’s geographic site. The various groups and components include:

- **Site: Location:** This object, belonging to an upper-level group, defines the building’s geographical parameters, which are critical for the acquisition of appropriate weather data.
- **Building:** Falling under the "Simulation Parameters" group, the building object encapsulates key information used during the building simulation process.
- **Zone List, Zone, Zone Control, and Building Surface:** Grouped under “Thermal Zone Description/Geometry,” these objects are indispensable for accurately simulating the building. They define the thermal characteristics and geometric details of the building’s zones and surfaces, including shading surfaces. The Zone List is used to aggregate multiple zones, while Zone Control objects facilitate the management of zone-specific setpoints.
- **Schedule:** This group enables the modulation of various operational aspects, such as occupancy density, lighting levels, thermostat settings, and occupant activities. Additionally, schedules can control the density of shading elements on the building.
- **Internal Gains:** Comprising objects such as People, Lights, ElectricEquipment and GasEquipment, and HotWaterEquipment, this group accounts for internal gains that affect energy consumption beyond the impacts of envelope performance or external environmental conditions.
- **Construction and Materials:** Associated with the “Surface Construction Elements” group, these objects detail the physical characteristics and

configurations of the building envelope and interior structures, including walls, roofs, floors, windows, and doors.

- **Zone Equipment:** This group describes various components of zone-specific equipment including objects such as ZoneHVAC:AirDistributionUnit, EquipmentConnections, and ZoneHVAC:EquipmentList.

In addition to the groups, the IDF file accommodates numerous other elements such as HVAC sizing, simulation run periods, and shadow calculation. Each component further enhances the flexibility and accuracy with which the building's energy system is represented and simulated.

3.2.2 Data Processing and Automated IDF Generation

The overall objective of the data collection and processing workflow is to generate an initial building energy simulation model from minimal input data acquired via a questionnaire. In this approach, user-provided information is complemented with default assumptions to develop a coarse energy simulation model that can be enriched further through advanced data capturing techniques and digital model integration. This document details the methods employed in transforming questionnaire responses into a functional EnergyPlus IDF file and outlines subsequent phases designed to enhance the BEM with additional geometric and operational details.

3.2.2.1 Conversion from Questionnaire to IDF

The initial stage involves the translation of questionnaire data into an EnergyPlus IDF. A dedicated software component automates this conversion, mapping user responses to specific EnergyPlus objects (Fig. 6). Due to the limited scope of the questionnaire, several IDF classes are configured with default values. These defaults include critical simulation parameters such as:

- Version
- Simulation Control
- Building (only name would be used as an input)
- Shadow Calculation
- Heat Balance Algorithm
- Timestep
- Run Period
- Daylight Saving Time
- Global Geometry Rules

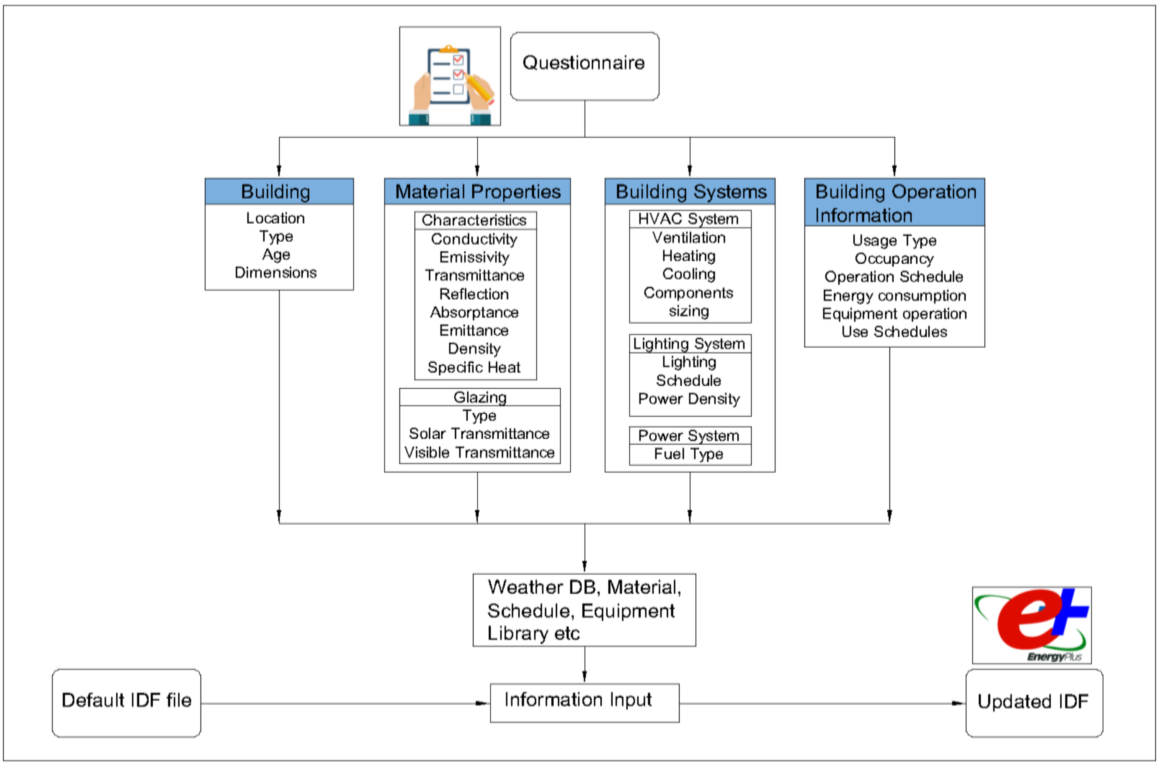


Figure 6. Overview of Contecht proposed questionnaire approach[6]

3.2.2.2 Geographic and Climatic Data Integration

The automated script utilizes building location information from the questionnaire to retrieve the appropriate climate data. Specifically, the system downloads the relevant EnergyPlus weather file (EPW) and design day file (DDY) corresponding to the building's geographic site. Latitude and longitude values, as provided by the user, are incorporated into the **Site:Location** object, ensuring that the simulation accurately reflects the local climatic conditions. An example of this translation is illustrated in Figure 7.

[6] Desai, D., & Hartmann, T. (2024). *Capturing building data for establishing digital twins of buildings for quick energy performance assessment* [Technical report]. Contecht GmbH.

```
!-   ===========  ALL OBJECTS IN CLASS: SITE:LOCATION ===========

Site:Location,
    DELFT_NLD Design_Conditions,  !- Name
    52.3,                        !- Latitude {deg}
    4.77,                        !- Longitude {deg}
    1.00,                        !- Time Zone {hr}
    0;                           !- Elevation {m}
```

Figure 7. Site:Location class generated from the questionnaire

3.2.2.3 Scheduling and Other IDF Classes

Schedules in the simulation are populated using a precompiled library that includes templates for different building types (residential, commercial, etc.) and various load profiles. For instance, occupant behaviour in a residential setting is mapped to an appropriate schedule (see Figure 8).

```
Schedule:Day:Interval,
    Residential BLDG_EQUIP_SCH_Sat,  !- Name
    Fractional,                 !- Schedule Type Limits Name
    No,                         !- Interpolate to Timestep
    06:00,                      !- Time 1 {hh:mm}
    0.238136,                   !- Value Until Time 1
    08:00,                      !- Time 2 {hh:mm}
    0.384143,                   !- Value Until Time 2
    12:00,                      !- Time 3 {hh:mm}
    0.480179,                   !- Value Until Time 3
    17:00,                      !- Time 4 {hh:mm}
    0.336125,                   !- Value Until Time 4
    19:00,                      !- Time 5 {hh:mm}
    0.288107,                   !- Value Until Time 5
    24:00,                      !- Time 6 {hh:mm}
    0.238136;                   !- Value Until Time 6
```

Figure 8. IDF Schedule class generated from the questionnaire

Beyond location and scheduling, further EnergyPlus classes—such as those pertaining to materials, occupancy, lighting, equipment, and HVAC systems—are generated from multiple questionnaire responses. Table 3 summarizes how individual components of the questionnaire relate to various IDF classes, ensuring a systematic integration of the data.

Table 3. Questionnaire-to-IDF Class Mapping for Simulation Parameterization

Questionnaire component	IDF classes
Intro(location)	Group – Location – Climate – Weather File Access : Site:Location, SizingPeriod:DesignDay, Site:Precipitation ..etc
Building	Group – Simulation Parameters : Building Group – Airflow : ZoneInfiltration:EffectiveLeakageArea ..etc
General	Group – Thermal Zone Description/Geometry: Zonelist Group – Internal Gains :People
Well-being	ZoneContaminantSourceAndSink:CarbonDioxide, Carbon Dioxide Outputs, ZoneVentilation:DesignFlowRate ..etc
User experience	Group – Energy Management System (EMS) EnergyManagementSystem:Sensor EnergyManagementSystem:Actuator ..etc
Energy performance	System Component Energy Use Outputs System Energy Use Outputs ZoneInfiltration:EffectiveLeakageArea ..etc
Structural	Group – Surface Construction Elements

3.2.2.4 Conditional Data Correlation

A notable advanced feature of the automated process is the correlation of answers across different sections of the questionnaire to fine-tune simulation inputs. For example, the building's infiltration rate is determined by correlating the occupant's perception of indoor air quality with the reported building age. Literature and governmental guidelines suggest that older buildings generally exhibit higher infiltration rates; therefore, conditional logic is applied to set approximate values based on the two respective inputs (Table 4). Figure 9 graphically represents the logic used to determine these infiltration rates.

Table 4. Assumptions of infiltration rates based on questionnaire answers

		Old building	New building
Are you satisfied with the air quality inside your apartment?	yes	0.0006 m^3/s per m^2 facade	0.0003 m^3/s per m^2 facade
	maybe	0.0003 m^3/s per m^2 facade	0.0003 m^3/s per m^2 facade
	no	0.0003 m^3/s per m^2 facade	0.0001 m^3/s per m^2 facade

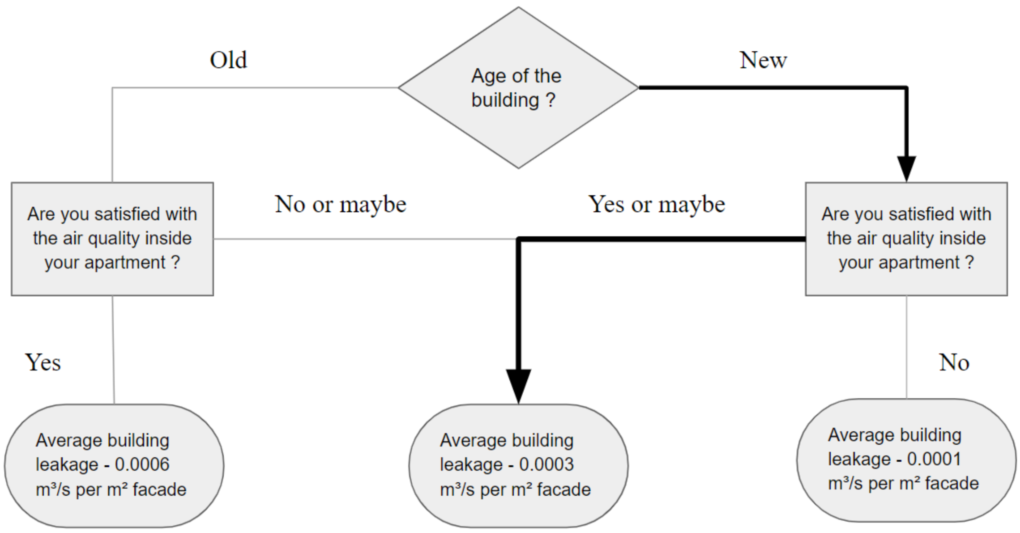


Figure 9. Logic of determining the assumed infiltration rate[7]

3.2.2.5 Construction Elements and Fenestration

Material selections for the external envelope and glazing options are mapped using a material library containing standard values from the ASHRAE_2005_HOF_Materials dataset. Construction sets are automatically loaded into the IDF based on these selections, as exemplified in Figure 10.

```
!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========

Construction,
    Medium Exterior Wall,     !- Name
    M01 100mm brick,          !- Outside Layer
    I02 50mm insulation board,  !- Layer 2
    F04 Wall air space resistance,  !- Layer 3
    G01a 19mm gypsum board;   !- Layer 4

Construction,
    Medium Roof/Ceiling,      !- Name
    M14a 100mm heavyweight concrete,  !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    F16 Acoustic tile;        !- Layer 3

Construction,
    Medium Floor,             !- Name
    F16 Acoustic tile,        !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    M14a 100mm heavyweight concrete;  !- Layer 3
```

[7] Brennan T et al, ASHRAE 1478: Measuring Airtightness of Mid- and High-Rise Non-Residential Buildings

Figure 10. IDF classes for construction elements based on the questionnaire[8]

Additionally, the questionnaire allows users to specify building shapes (e.g., Rectangular, L-Shaped, U-Shaped) and fenestration details, such as wall-to-window ratios. Detailed geometric inputs, including fixed parameters for lintel and windowsill heights, enable the calculation and placement of fenestration surfaces (Fig.11 and 12).

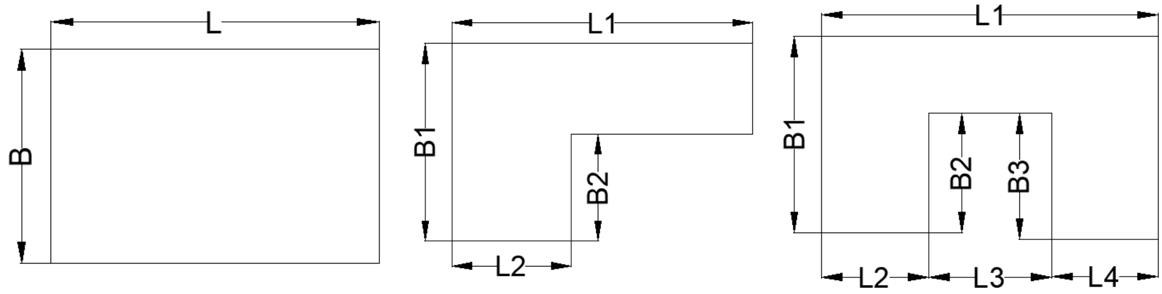


Figure 11. Different building shape options provided in the questionnaire

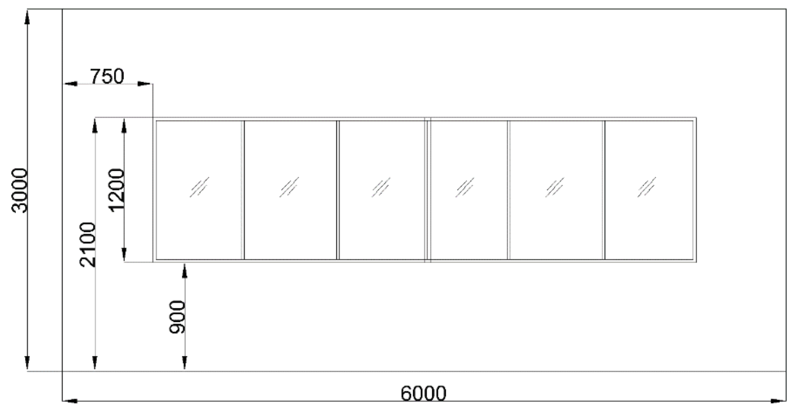


Figure 12. Calculation logic to generate Fenestration surfaces from the wall to windows ratio asked for in the questionnaire

3.2.2.6 HVAC System Representation

In our initial building energy model, the HVAC system is represented using a structured approach that leverages predefined EnergyPlus templates while incorporating detailed

[8] The dataset file from the EnergyPlus installation file. Source folder\EnergyPlusV22-1-0\DataSet\ASHRAE_2005_HOF_Materials.IDF ASHRAE_2005_HOF_Materials.IDF

user responses from the questionnaire. This process is designed to rapidly generate a simulation-ready model while capturing critical system behaviour for meaningful energy performance analysis. The HVAC representation is elaborated as follows:

1. **Selection and Customization of HVAC Templates:**

   The questionnaire collects data regarding the types of HVAC systems present—such as air-to-air heat pumps, boilers, or chillers—and specific operational features. Based on these responses, the model selects an appropriate HVAC template from a comprehensive library. For example, if a packaged terminal air-to-air heat pump (PTHP) is indicated by the user, the corresponding template is loaded. This template, depicted in Figure 13, incorporates a DX cooling coil, a DX heat pump heating coil, and provisions for a supplemental heating coil (with electric as the default, unless alternative options are specified).

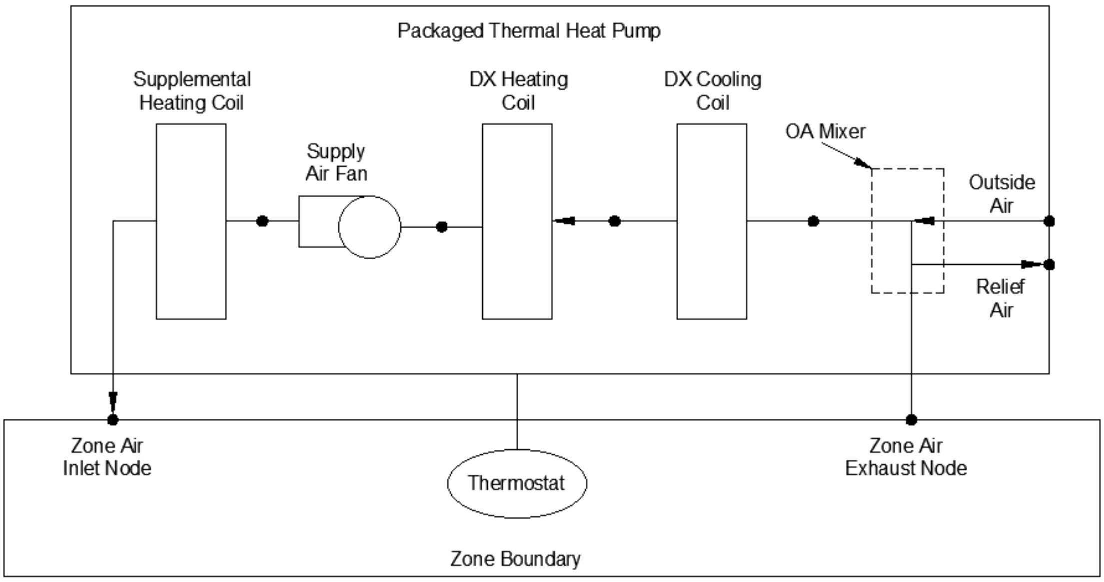


Figure 13. Schematic of a packaged thermal heat pump (draw through fan placement)

2. **Thermostat Control and Scheduling**

   An integral element is the thermostat control logic. Instead of fixed setpoints throughout the simulation, the model employs a dual setpoint control mechanism with a deadband to manage transitions between heating and cooling phases. The thermostat configuration utilizes predefined schedules sourced from a schedule library (Fig. 14). These schedules dynamically adjust setpoints in response to occupancy and internal load variations, thus reflecting realistic building operation.

```
!-   ===========  ALL OBJECTS IN CLASS: HVACTEMPLATE:THERMOSTAT ===========

HVACTemplate:Thermostat,
    Building_Thermostat,     !- Name
    Building HTGSETP,        !- Heating Setpoint Schedule Name
    ,                        !- Constant Heating Setpoint {C}
    Building CLGSETP,        !- Cooling Setpoint Schedule Name
    ;                        !- Constant Cooling Setpoint {C}
```

Figure 14. IDF classes for HVAC templates based on the questionnaire

3. **Air Flow and System Sizing**

Critical airflow parameters are determined using EnergyPlus auto sizing algorithms. The supply air flow rate, along with zone-specific design outdoor air flow rates, is calculated by integrating data from internal load measurements (including occupancy and equipment use) and design conditions from retrieved climate files. Additionally, the model refines the infiltration rate by correlating building age and reported indoor air quality, ensuring that ventilation and leakage characteristics are realistically represented. These computations are integral to sizing the HVAC components that interact with the building's thermal zones (Fig.15).

```
!-   ===========  ALL OBJECTS IN CLASS: HVACTEMPLATE:ZONE:PTHP ===========

HVACTemplate:Zone:PTHP,
    Zone1,                   !- Zone Name
    Building_Thermostat,     !- Template Thermostat Name
    autosize,                !- Cooling Supply Air Flow Rate {m3/s}
    autosize,                !- Heating Supply Air Flow Rate {m3/s}
    ,                        !- No Load Supply Air Flow Rate {m3/s}
    ,                        !- Zone Heating Sizing Factor
    ,                        !- Zone Cooling Sizing Factor
    Flow/Person,             !- Outdoor Air Method
    0.00944,                 !- Outdoor Air Flow Rate per Person {m3/s}
    ,                        !- Outdoor Air Flow Rate per Zone Floor Area {m3/s-m2}
    ,                        !- Outdoor Air Flow Rate per Zone {m3/s}
    ,                        !- System Availability Schedule Name
    ,                        !- Supply Fan Operating Mode Schedule Name
    DrawThrough,             !- Supply Fan Placement
    0.7,                     !- Supply Fan Total Efficiency
    75,                      !- Supply Fan Delta Pressure {Pa}
    0.9,                     !- Supply Fan Motor Efficiency
    SingleSpeedDX,           !- Cooling Coil Type
    ,                        !- Cooling Coil Availability Schedule Name
    autosize,                !- Cooling Coil Gross Rated Total Capacity {W}
    autosize,                !- Cooling Coil Gross Rated Sensible Heat Ratio
    3,                       !- Cooling Coil Gross Rated COP {W/W}
    SingleSpeedDXHeatPump,   !- Heat Pump Heating Coil Type
    ,                        !- Heat Pump Heating Coil Availability Schedule Name
    autosize,                !- Heat Pump Heating Coil Gross Rated Capacity {W}
    2.75,                    !- Heat Pump Heating Coil Gross Rated COP {W/W}
    -8,                      !- Heat Pump Heating Minimum Outdoor Dry-Bulb Temperature {C}
    5,                       !- Heat Pump Defrost Maximum Outdoor Dry-Bulb Temperature {C}
    ReverseCycle,            !- Heat Pump Defrost Strategy
    Timed,                   !- Heat Pump Defrost Control
    0.058333,                !- Heat Pump Defrost Time Period Fraction
    Electric,                !- Supplemental Heating Coil Type
    ,                        !- Supplemental Heating Coil Availability Schedule Name
    autosize,                !- Supplemental Heating Coil Capacity {W}
    21,                      !- Supplemental Heating Coil Maximum Outdoor Dry-Bulb Temperature {C}
    0.8,                     !- Supplemental Gas Heating Coil Efficiency
    ,                        !- Supplemental Gas Heating Coil Parasitic Electric Load {W}
    ,                        !- Dedicated Outdoor Air System Name
    SupplyAirTemperature,    !- Zone Cooling Design Supply Air Temperature Input Method
    14,                      !- Zone Cooling Design Supply Air Temperature {C}
    11.11,                   !- Zone Cooling Design Supply Air Temperature Difference {deltaC}
    SupplyAirTemperature,    !- Zone Heating Design Supply Air Temperature Input Method
    50,                      !- Zone Heating Design Supply Air Temperature {C}
    30,                      !- Zone Heating Design Supply Air Temperature Difference {deltaC}
    ,                        !- Design Specification Outdoor Air Object Name
    ,                        !- Design Specification Zone Air Distribution Object Name
    None,                    !- Baseboard Heating Type
    ,                        !- Baseboard Heating Availability Schedule Name
    autosize,                !- Baseboard Heating Capacity {W}
    None;                    !- Capacity Control Method
```

Figure 15. IDF classes for a zone based HVACTemplate based on the questionnaire

4. **Supplemental and Backup Systems Integration**

Given that many HVAC systems operate on a hybrid basis, the model includes conditional logic for the integration of supplemental heating components. Based on user input, the HVAC template can be modified to incorporate additional heating systems—such as gas or hot water boiler—which serve as a backup during peak demand conditions. The conditional insertion logic guarantees that the overall system configuration reliably meets the building's thermal load, as illustrated by the adjustments in the supplemental boiler parameters shown in Figure 16.

5. **Integration with Building Geometry and Internal Gains:**

The HVAC system does not function in isolation. It interfaces closely with the building's geometry, thermal zones, and internal gains (derived from lighting, equipment, and occupant activities). Predefined HVAC templates are designed to integrate seamlessly with these elements, allowing the simulation to account for load distribution across various zones. For example, airflow adjustments are made based on thermal zone dimensions and occupancy data, a process that is visually summarized in Figure 15. This ensures a balanced integration between the HVAC system and the broader building performance model.

6. **Performance Metrics and Diagnostic Outputs:**

   To support rigorous analysis, the HVAC templates are configured to produce detailed performance metrics. Outputs include component energy usage, supply and return air flow rates, and system operation diagnostics under varying conditions (Fig. 16). These metrics, recorded in the EnergyPlus simulation log, facilitate subsequent validation of the model and provide insights into system performance—data that is critical for comparing simulated and measured results.

```
!-   ===========  ALL OBJECTS IN CLASS: HVACTEMPLATE:PLANT:BOILER ===========

HVACTemplate:Plant:Boiler,
    Boiler,                  !- Name
    HotWaterBoiler,          !- Boiler Type
    autosize,                !- Capacity {W}
    0.8,                     !- Efficiency
    Electricity,             !- Fuel Type
    1,                       !- Priority
    1,                       !- Sizing Factor
    1,                       !- Minimum Part Load Ratio
    1.1,                     !- Maximum Part Load Ratio
    9,                       !- Optimum Part Load Ratio
    99.1,                    !- Water Outlet Upper Temperature Limit {C}
    HotWater;                !- Template Plant Loop Type
```

Figure 16. IDF classes for a boiler HVAC template based on the questionnaire

3.2.3 Advanced Data Capturing and BIM-Based Enrichment

3.2.3.1 Detailed BIM Modeling

In the second phase of the workflow, advanced surveying techniques—such as 3D laser scanning, LiDAR, and photogrammetry—are employed to create a detailed (BIM). These methods capture both external and internal geometric details. The captured data (including as-built plans, geospatial coordinates, and drone imagery) form the initial input for subsequent model enrichment.

A variety of reality-capturing tools are considered based on project requirements. Technologies such as stationary 3D laser scanners, handheld devices, mobile LiDAR, and aerial photogrammetry each offer different advantages in terms of accuracy, accessibility, and coverage (Fig. 17) provide comparisons of these tools). When combined with expert site visits, the gathered data ensures that the BIM accurately reflects the current state of the building.

	Handheld	Stationary	Vehicle Mounted	Airborne Lidar	Airborne Photogrammetry
Range	0.4 -1 m	0.4 – 500 m	1 – 400 m	1000-4000 m	100-200 m
3D Points Accuracy	0.1 mm	1.2 mm – 5 mm	2 - 5 cm	10-15 cm	10-15 cm
Area Coverage	Small	Small to Medium	Medium to Large	Large	Large
Application	Manufacturing Small part scanning	AEC Vertical Structure and Industrial Facilities	AEC linear structures Rail Pipeline	Environmental Mapping. City Mapping.	Plot of land Wide area coverage

Figure 17. Comparison between different reality capturing tools[9]

3.2.3.2 BEM Enrichment via BIM Data

The detailed BIM serves as a foundation to enrich the initial BEM. A Python microservice, developed using libraries such as Ifcopenshell and PythonOCC, extracts precise information from IFC 2x3 files (Fig. 18). The enrichment process includes:

- Extracting building and site metadata (e.g., project name, geographic coordinates, elevation)
- Analysing geometric details by iterating through various building elements (walls, slabs, columns) and capturing openings (fenestration)
- Determining construction materials and updating the materials library
- Integrating user and equipment schedule data where available

Figure 18 illustrates the extraction of an IFC model from BIM for energy modeling. It shows the visualization and selection of building elements necessary for the energy

[9] Raj, T., Hashim, F. H., Huddin, A. B., Ibrahim, M. F., & Hussain, A. (n.d.). *A survey on LiDAR scanning mechanisms*. The National University of Malaysia.

simulation process. The automated enrichment is also depicted in Figure 19 and results in an updated IDF that reflects a more detailed thermal zoning model and enhanced HVAC configurations.

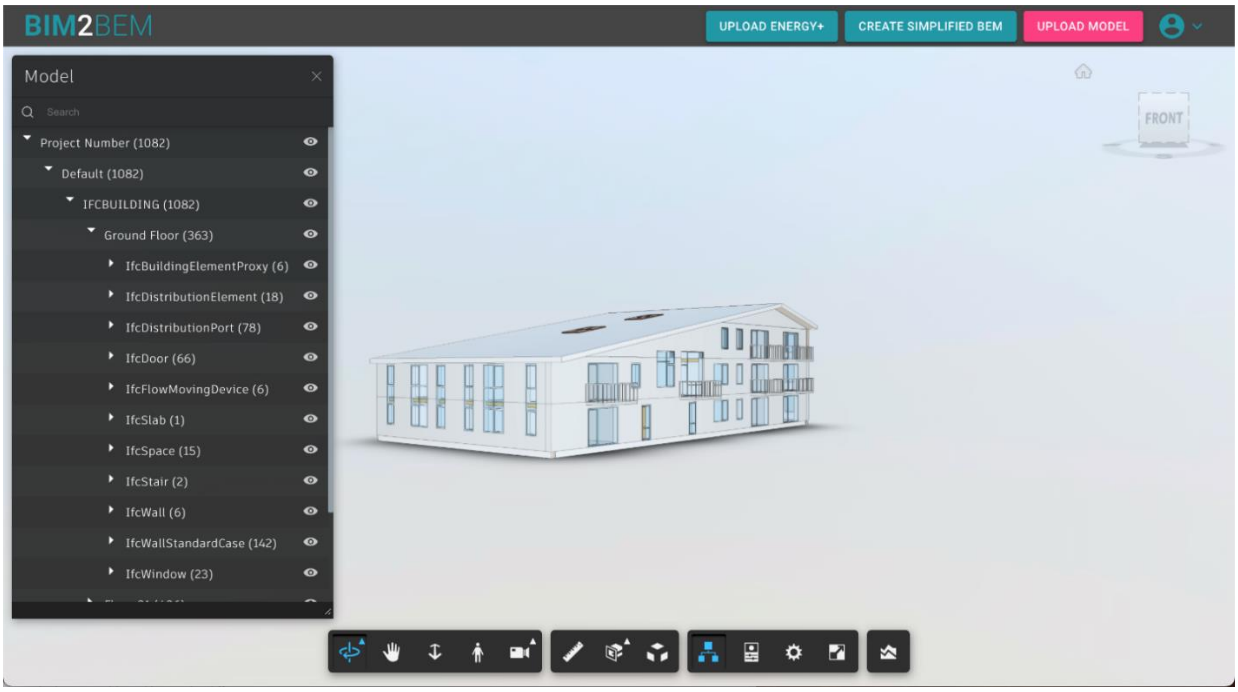


Figure 18. IFC Model Extraction in BIM2BEM: Visualizing and selecting building elements for energy modeling

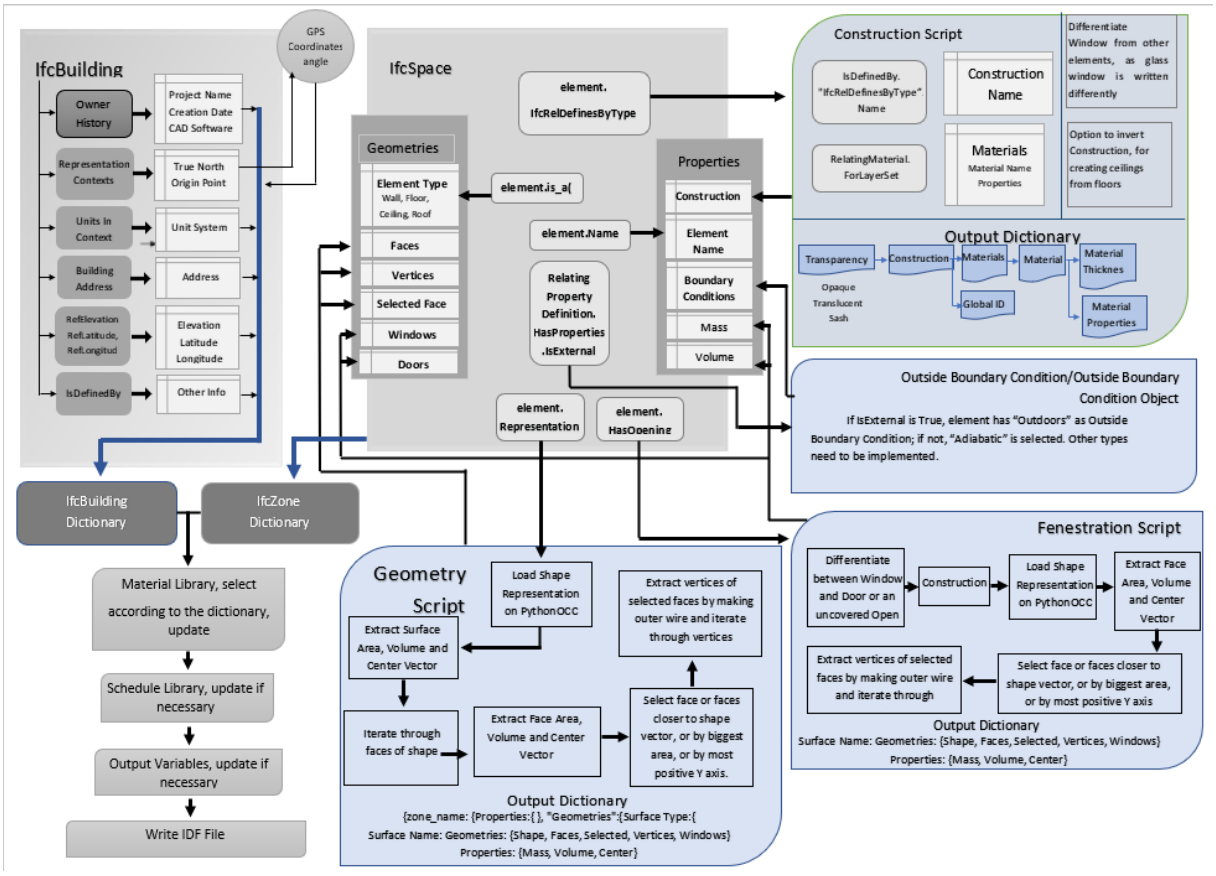


Figure 19. BEM Enrichment automation process[10]

The following table provides a comprehensive overview of the process used to extract and integrate detailed BIM data into the Building Energy Model. It outlines each major step, from gathering building and site information to processing geometric elements, updating construction and material properties, integrating scheduling data, and writing the final IDF file. This structured approach ensures that all critical aspects are accurately captured and translated into an enhanced thermal and HVAC simulation model.

[10] Desai, D., & Hartmann, T. (2024). *Capturing building data for establishing digital twins of buildings for quick energy performance assessment* [Technical report]. Contecht GmbH.

Table 5. Building Information and Geometry Data Processing for EnergyPlus IDF Generation

Section	Attribute/step	Details
Building and Site Information	Building	For the IDF field Building, the object name is extracted from the 'OwnerHistory' attribute of the IfcProject entity.
	Site: Location	Data is extracted using the IfcSite entity. The latitude, longitude, and elevation values are obtained from the attributes RefLatitude, RefLongitude, and RefElevation respectively.
Geometry	Zone Identification	Zones are identified using the IfcSpace entity.
	Element Iteration	Elements are iterated by type (e.g., Walls, Slabs, Columns). The name of each element is retrieved using its Name property.
	Construction Extraction	Each element is processed with the Construction script to determine the construction (also known as the Materials Layer). The Construction Name is extracted via the RelatingType property, and associated materials are retrieved via the RelatingMaterial.ForLayerSet property. These details are saved in the materials_dictionary.
	Openings Detection	For surfaces, the process starts by checking if an element has openings (windows, doors) using the HasOpenings property. If openings exist, the Fenestration script is run. The presence of a door or window is determined by the RelatedOpeningElement.HasFillings attribute, and its name is extracted via the RelatedOpeningElement.Name property.
	Outside Boundary Determination	To determine if an element is external or adjacent to a zone, the properties IsDefinedBy.RelatingPropertyDefinition.HasProperties.IsExternal and ProvidesBoundary are examined.
	Shape Extraction	For all surfaces, shape data is extracted using IfcOpenShell and processed with PythonOCC to create a 3D representation (faces and vertices). This allows for the calculation of surface area, volume, and center, with the results appended to the respective dictionary based on surface type.
	Shading Elements	Shading element details are extracted via BuildingElementProxy, with vertices processed using PythonOCC.
	Data Consolidation	All gathered information from the geometric analysis is consolidated into the Zones_dictionary.
Construction and Materials	Material Comparison and Update	Each construction and material in the dictionary is compared with the material library. Missing properties are updated as needed, and a warning message is issued if any key property is absent.
Schedules	Schedule Integration	If BIM data includes user and equipment schedule information, the Schedule Library is read and updated accordingly.
Write IDF File	Initial Configuration	The IDFWriter script writes key sections of the EnergyPlus input file, including the IDF Version, TimeStep, and SimulationControl, followed by building information (North Axis, Terrain, Loads Convergence Tolerance, Temperature Convergence, Solar Distribution, and Number of Warmup Days).
	Site:Information	Inserts Site: Location details, including Latitude, Longitude, Time Zone, and Elevation.
	SizingPeriod and Schedules	SizingPeriod and schedules, as specified in the dictionary, are inserted into the file.
	Constructions and Materials	Construction details, along with their corresponding material properties from the updated dictionary, are written next.
	Geometric Elements	The Zones_dictionary is iterated to write each Zone and its properties. Each element within a zone is recorded as either a BuildingSurface or FenestrationSurface with attributes such as Name, Surface Type,

		Construction Name, Building Surface Name, Outside Boundary, Outside Boundary Object, View Factor to Ground, Space Name, and Vertices.
	Output Variables	Finally, the output variables required for the simulation are written into the IDF file.

3.2.4 Real-Time Integration and Ongoing Updates

3.2.4.1 Digital Twin Integration

The final phase of our methodology establishes a seamless data integration layer between the facility's operational environment and its digital twin representation. This integration supports continuous synchronization and real-time updates, enabling proactive monitoring and management of building performance.

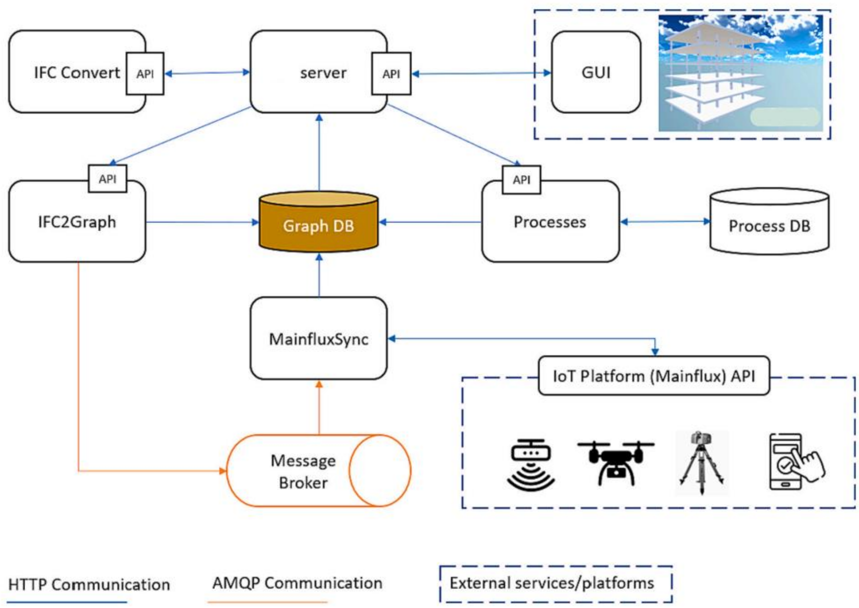


Figure 20: Digital twin integration of the system[11]

As illustrated in Figure 20, our digital twin platform integrates multiple core services via APIs and communication protocols (HTTP and AMQP):

- **Sensor Integration via Mainflux:**

[11] https://www.ashvin.eu/

A central component in our architecture is the IoT Platform (Mainflux) as shown in Figure 21, which facilitates the ingestion and processing of real-time data from various devices and sensors (e.g., environmental sensors, drones, and mobile applications). These devices feed into the platform through the MainfluxSync module, which ensures secure and structured transmission of data into the system.

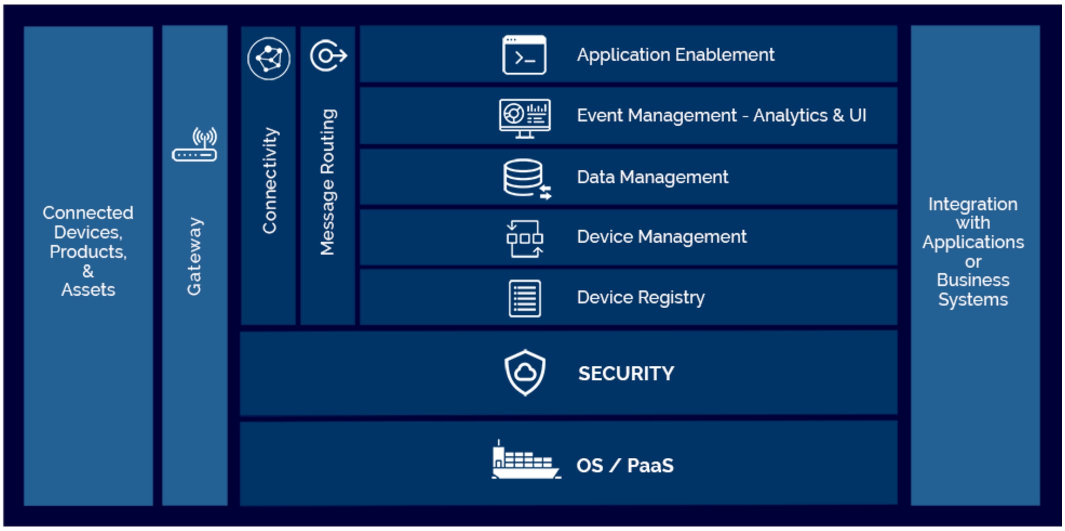


Figure 21. Mainflux IoT platform [12]

- **Message Broker for Data Routing:**

The Message Broker plays a key role in managing asynchronous communication, enabling reliable message delivery across services. It works closely with MainfluxSync to handle time-sensitive and event-driven data updates.

- **Graph DB for Semantic Representation:**

The Graph DB acts as the central data model where relationships and hierarchies of building components are stored. Incoming data from both static BIM sources and live sensors are integrated here to enrich the model and keep it current.

- **Platform Services and BIM Viewer:**

On the front-end, users interact with a GUI that includes our custom BIM Viewer using APS Autodesk (Forge) and Questionnaire-based modules for manual data acquisition (Fig.22 and 23). These components are deployed through the same unified company

[12] https://mainflux.com/cloud.html

platform, enhancing the user experience by combining visual model navigation and structured feedback collection.

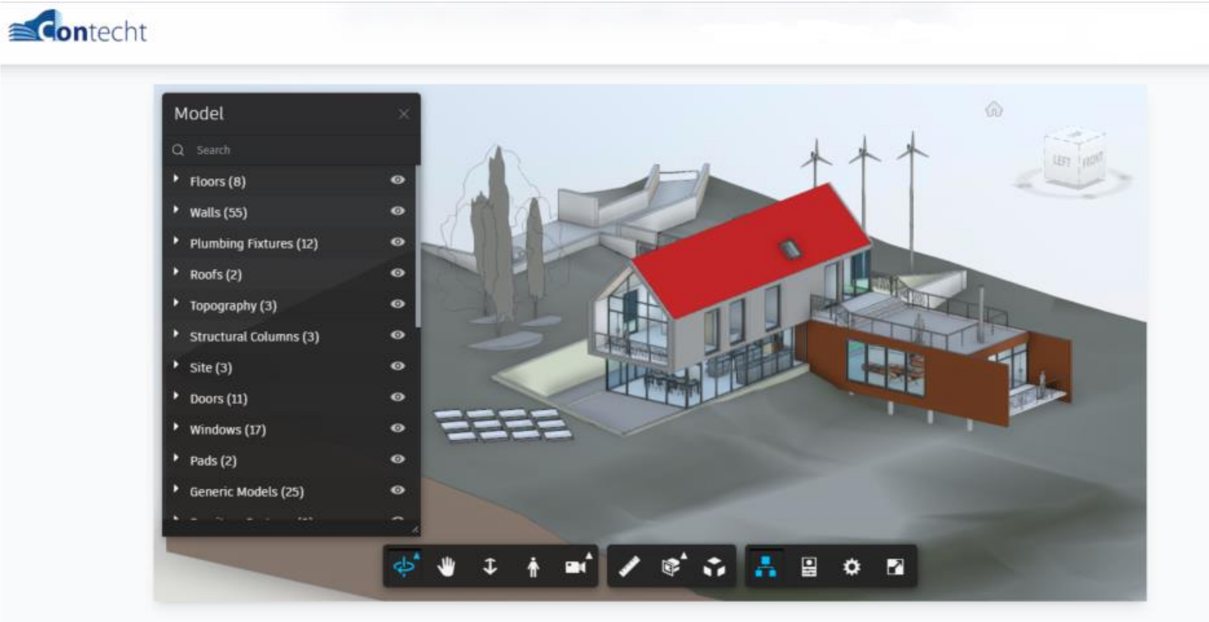


Figure 22. BIM viewer of Contecht platform using APS Autodesk

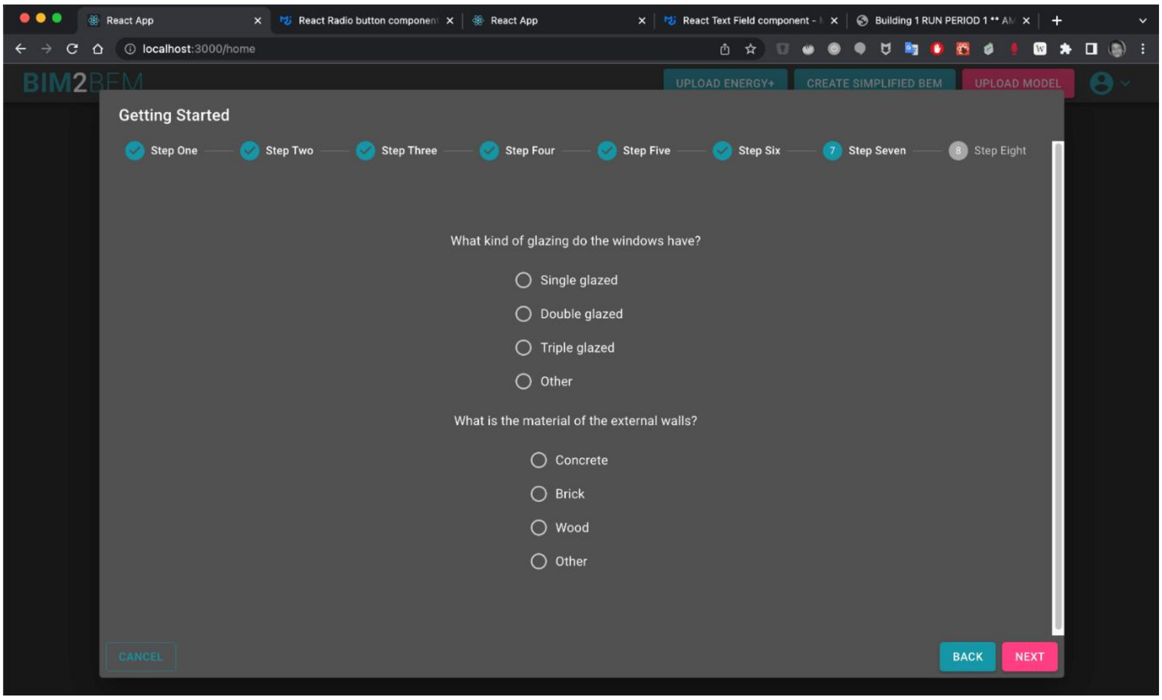


Figure 23. Contecht platform - implementation of the questionnaire (window and materials)

- **Data Conversion and Processing:**

Modules such as IFC Convert and Processes handle data transformation and workflow execution. These ensure that the digital twin remains aligned with both the original IFC models and evolving real-world conditions. As shown in Figure 24, the enriched BIM view incorporates BEM-ready data and structure, which enables accurate simulations. Figure 25 demonstrates the resulting energy analysis, providing insights into energy consumption distribution across the building systems.

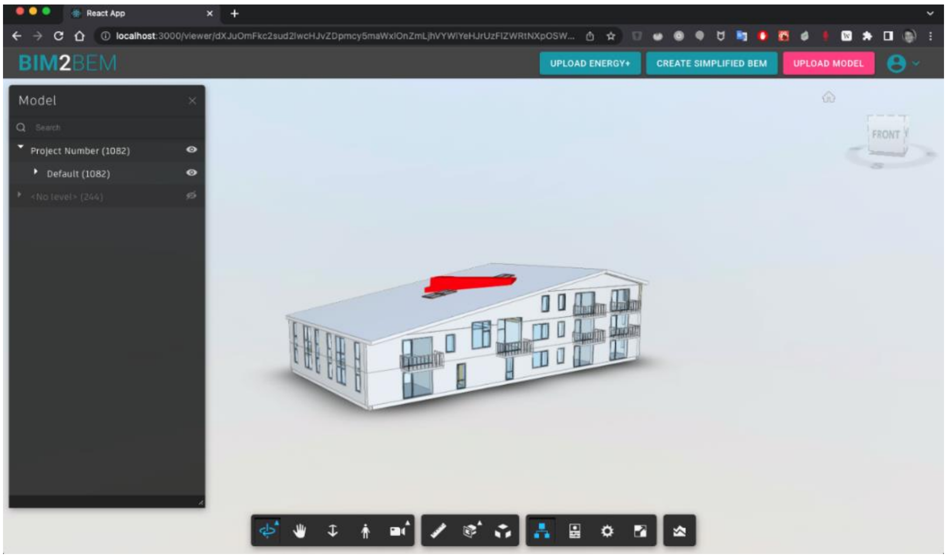


Figure 24. Enriched BIM View: Model enhanced with BEM-ready data and structure

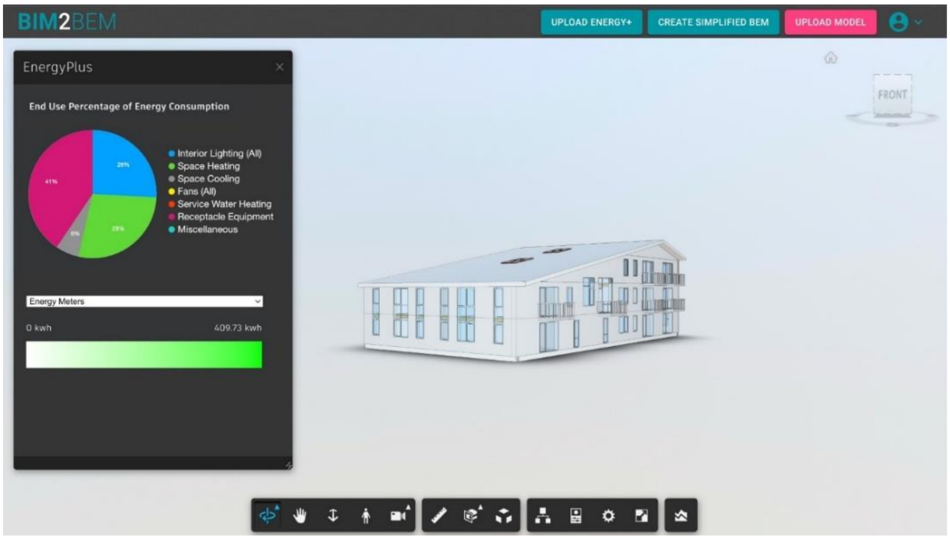


Figure 25. Energy Simulation Results

3.2.4.2 Crowd Sourced Data via the BIM-SPEED Inhabitant App

In parallel, the BIM-SPEED Inhabitants App (adapted from the DEMO's RE Suite) offers a crowd-sourcing approach to gather occupant feedback on building performance and comfort levels. This feedback is then linked to specific elements of the building performance model, further refining the prediction accuracy and ensuring that the model remains responsive to user experience.

3.3 Interoperability

The adoption of BIM varies largely between different countries and different companies. When the client commissions the planners and construction firms, the usage of BIM requires the interoperability of the individual software solutions every player uses. Thereby, a distinction between "open" and "closed" BIM is made, which refers to the formats used for the exchange of data. Closed BIM uses commercial formats like RVT (Autodesk Revit 2019) or PLN (Nemetschek Graphisoft) that are proprietary, while open-BIM approaches rely on vendor-neutral, open-source formats like the (IFC) or Green Building XML (gbXML).

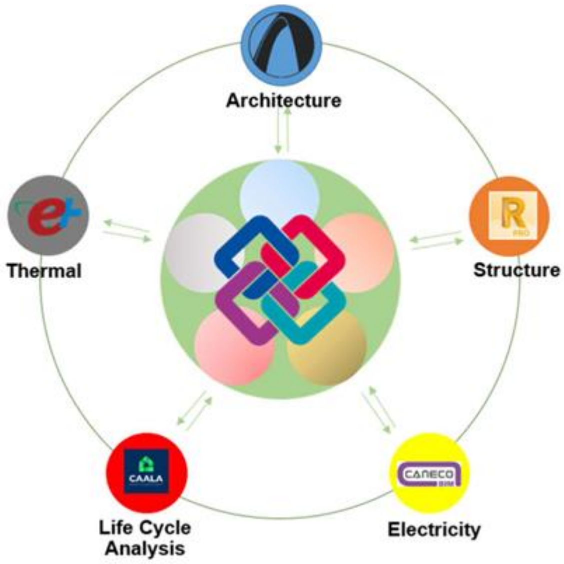


Figure 26. Simplified interaction schema between stakeholders in the BIM process[13]

[13] Nait-taour, A. (2024). *Enhancing building energy performance simulation by automating the thermal zoning process in a BIM-based BEM approach* (Master's thesis, Technical University of Munich)

Those exchange formats are developed by non-profit organizations to be independent of specific vendors and bear the potential to lower the number of interfaces to be developed and hence the quality and cost of development for BIM-based applications. But the usage of open exchange formats also introduces an additional interface to trespass, bearing a potential loss of information and a complication of the workflow compared to a solution embedded in the authoring format. These are challenges to be accounted for when designing a data exchange between two BIM-compatible applications. The integration of (BIM) and (BEPS) is a complex process that requires careful attention to data exchange and quality verification. As illustrated in Figure 26, a simplified interaction schema between stakeholders highlights the multidirectional flow of information among various disciplines such as architecture, structure, thermal analysis, electricity, and life cycle analysis, all of which are integral to the BIM process.

3.3.1 Minimum IFC Requirements for BEPS Analysis

The (IFC), developed and maintained by buildingSMART International, are a widely recognized and globally adopted standard for data exchange in the AECO industry. The IFC schema represents a monolithic data model designed to encompass all aspects of the domain. This provides significant benefits, such as semantic consistency and internal data compatibility, but also results in large model sizes and high complexity of the schema. The IFC aims to cover the entire spectrum of the built environment, including buildings, roads, railways, bridges, tunnels, geotechnical assets, ports, and waterways (as of IFC 4.4). It also considers a wide range of relevant domains, such as architecture, HVAC, electrical systems, and building controls, which naturally contribute to its size and complexity (Schlenger, J. et al., 2022).

The IFC schema uses object-oriented modeling while incorporating proxy elements, dynamically definable properties, and objectified relationships. Initially, the IFC was encoded using the EXPRESS modeling language according to the ISO 10303-11:2004 "Industrial automation systems and integration — Product data representation and exchange", with XML used for property set templates. Due to its underlying EXPRESS architecture, the IFC is not limited to file-based information exchange, it can also be used in databases. However, IFC file-based exchange remains the primary method of information transmission. Additionally, the IFC schema mainly addresses information related to the building design phase and lacks a straightforward approach to integrate as-built data and dynamic information from the Use stage, which is essential for Digital Twin applications (Borrmann, A et al., 2024).

These requirements are crucial to ensure accurate and reliable results. They primarily pertain to the building shell, which includes: · External walls · Floors · Roofs · Windows · Exterior doors. These elements must meet certain criteria related to their geometry and material information.

3.3.2 Automated Validation Approach

One way to verify these requirements is through an automated routine that Contecht have developed using DynamoBIM. This routine checks the categories of the elements for the existence of parameters such as: · Heat Transfer Coefficient (U) · Thermal Resistance (R) · Thermal Mass (limited to walls, floors, and roofs) · Visual Light Transmittance (limited to windows and external doors) · Solar Heat Gain Coefficient (limited to windows and external doors)

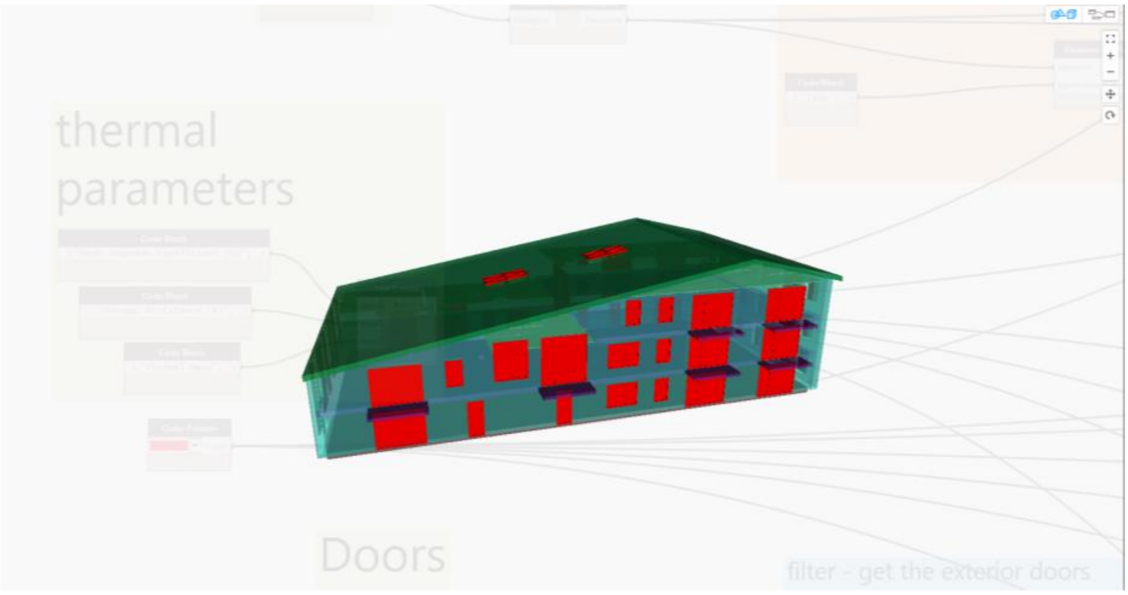


Figure 27. Automated DynamoBIM check flags missing thermal data (Source: Author)

If this information is missing, the elements are highlighted in red, and these values are filled with default values. A request-for-information is then issued to the use case owner. This process is visualized in Figure 27 (Information validation algorithm visualization). The building used for this visualization belongs to one of the pilot buildings from the project Precept.

3.3.3 Data Requirements for Energy Simulation

In addition to the information related to the building shell, other data necessary for building energy simulation includes:

- Geometrical properties
- Material properties
- Building Systems
- Site conditions
- Building Operation Information

Each piece of information is required to reproduce an energy model that is analogous to a real energy-building system.

3.3.4 Technical Limitations

Achieving interoperability between BIM and Energy Modelling Software presents challenges. The generation of a (BEM) often requires detailed manual input and the use of two or more software due to its complexity and different levels of detail.

3.3.5 Conversion Workflows

The popular methods of generating a BEM using EnergyPlus involve converting building geometry from CAD software such as Revit, ArchiCAD, blender3D, and rhino3D using multiple multilayer intermediate applications such as Designbuilder, ladybug tools, Visuite, and Open studio. This is due to the lack of a geometric visualization interface for the EnergyPlus application and the complex input file format.

The utilization of BIM data holds immense potential for expediting the generation of BEPS inputs. However, significant obstacles exist in the path of automating the transformation of complex geometric shapes from BIM to the IDF format used in EnergyPlus. These obstacles can lead to geometric errors during the conversion process.

Furthermore, hurdles with the description of HVAC and internal load details pose additional challenges. For buildings with extensive operational histories, access to BIM models may be restricted, necessitating the use of external data acquisition technologies for further modeling.

3.4 Validation: Case Study on Multiple Buildings in Europe

Contecht (SmartWins partner) validated the simplified energy simulations using four buildings in different European states: the Netherlands, Germany, Greece, and Spain. The Dutch demonstration (Fig. 28 and 29) are two buildings in a recently constructed residential building complex that includes 18 NOM (Zero Energy) 60 m2 apartments (three rooms) for social renting. Each unit is energy-efficient, with high-quality insulation, ventilation equipment, and a -floor heating system linked to a geothermal heat pump. The German demonstration site is a three-story residential/multifamily building in Velten. The building was constructed in 1907 and comprises six -ats totalling 335 m2. The building is situated in an Oceanic Climatic, which is the major climate type throughout much of Western Europe. In this facility, a dedicated sensor network is employed to continuously gather real-time data for our digital twin platform.

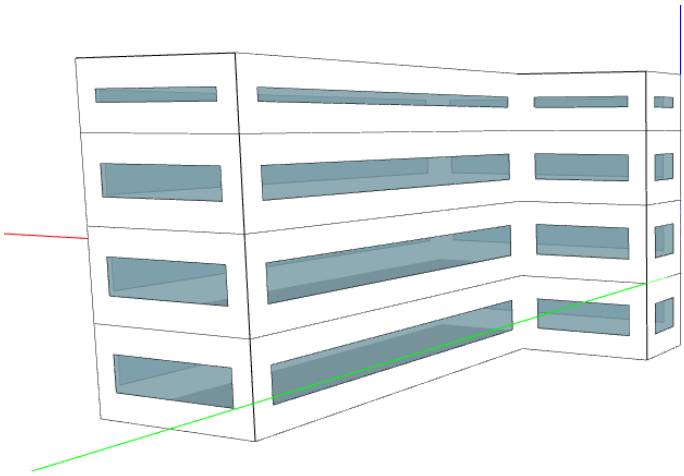
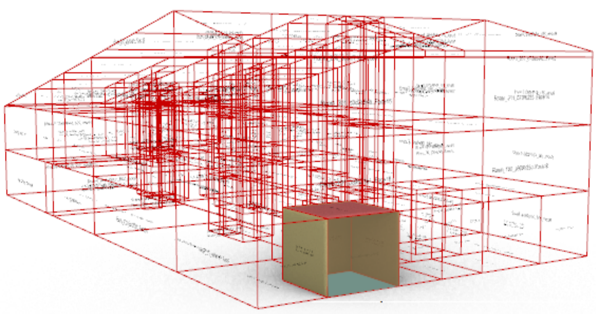


Figure 28. Simplified Geometry from the Questionnaire results- Building A, Netherlands



```
BuildingSurface:Detailed,
  Livingroom...Face0,     !- Name
  Wall,                   !- Surface Type
  Generic Interior Wall,  !- Construction Name
  Livingroom...           !- Zone Name

BuildingSurface:Detailed,
  Livingroom...Face10,    !- Name
  Floor,                  !- Surface Type
  Generic Interior Floor, !- Construction Name
  Livingroom...           !- Zone Name

BuildingSurface:Detailed,
  Livingroom...Face7,       !- Name
  Ceiling,                  !- Surface Type
  Generic Interior Ceiling, !- Construction Name
  Livingroom...             !- Zone Name
```

Figure 29. Building Geometry extraction- Building A, Netherlands

Table 6. Results of the validation comparing energy simulation results of models generated from the questionnaire and calibrated model with detailed energy models developed based on careful building inspection and survey activities (Yearly energy consumption per square meter of building surface).

Pilot	Buildings	Simplified Model [kWh/m²]	Calibrated model using sensors value [kWh/m²]	Detailed Model [kWh/m²]	Difference with simplified model [%]
Netherlands	Building A	108.51	-	77.19	40.57
	Building B	106.33	-	94.63	12.36
Germany	Building 1	141.95	130.84	125.93	12.72
Greece	Building 1	134.59	-	107.86	24.78
	Building 2	119.64	-	115.83	3.28
Spain	Building 1	96.90	-	70.57	37.28
	Building 2	95.88	-	81.25	18

The Greece demonstration sites consist of six apartments in two different building complexes. These apartments vary in their construction years between 1950 and 2000 with an area totalling 120 m2 to 200 m2. These buildings are situated in a Hot summer Mediterranean climate typical to that part of Greece and were selected for their diverse consumption and occupancy profiles (Fig. 30 and 31).

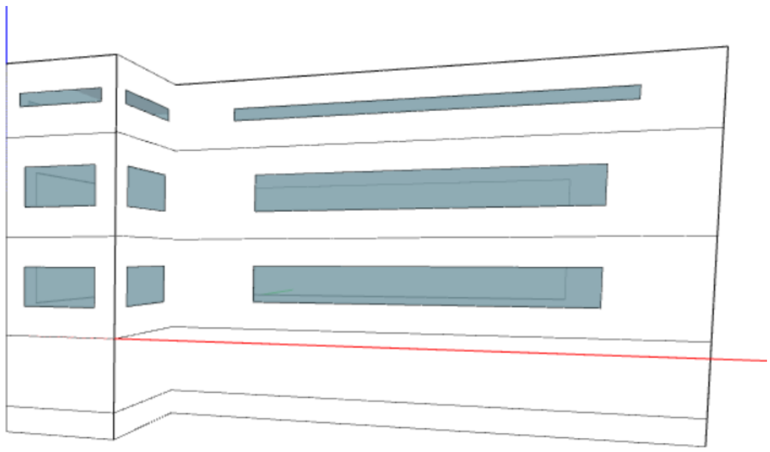


Figure 30. Simplified Geometry from the Questionnaire results – Building 1, Greece

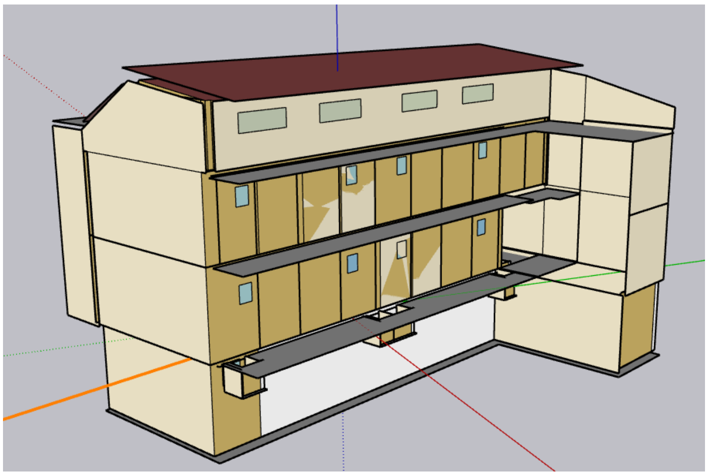


Figure 31. Building Geometry extraction – Building 1, Greece

The Spain pilot comprises several independent buildings in a typical Spanish neighbourhood. Each of the buildings is eight stories high and hosts 32 apartments, a reception, and an underground parking lot. These Residential units were built in 2006, and they cover a total area of 6,500 m2. Each building has a total area of 4,500 m2 with each apartment of an approximate area of 90 m2. These buildings are situated in a Semi-arid (Steppe) climate typical for that part of Spain (Figure 32).

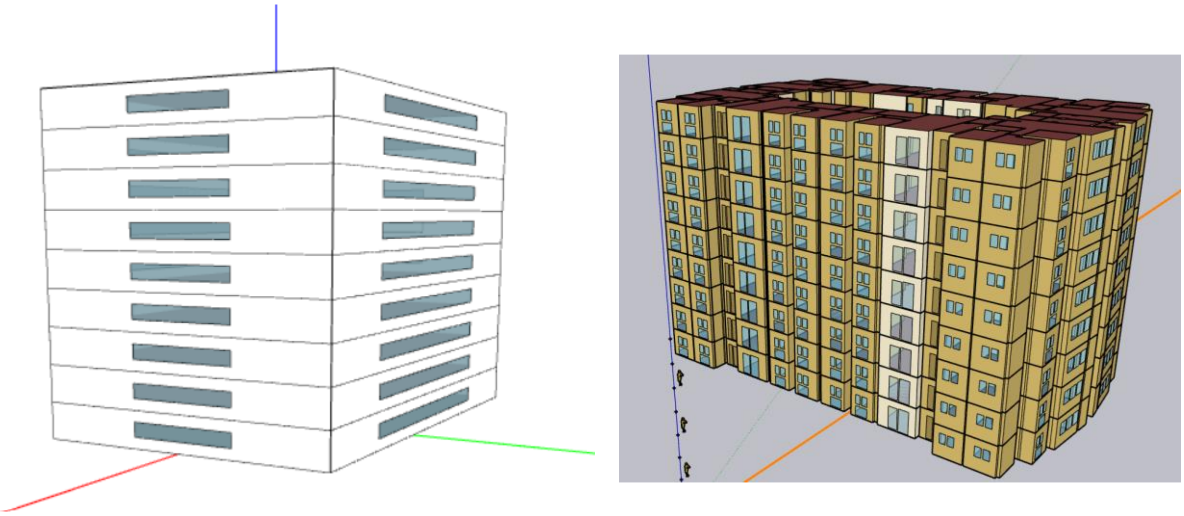


Figure 32. Simplified Geometry from the Questionnaire results – Building 1,2,6,7 – Spain(left), Building Geometry extraction – Building 1,2,6,7, Spain

For each building, building operators were initially asked to complete the questionnaire and generate energy simulation models using the developed software platform. A detailed inspection was subsequently conducted, which included laser scans and thorough material surveys to capture accurate data on the building geometry, materials, and HVAC systems. This information was then used to generate refined energy simulation models. Finally, building energy performance was simulated based on both the questionnaire-driven models and the detailed models, with simulated energy consumption per year and per square meter extracted for comparative analysis. Results of the Validation

The results indicate a significant variance in accuracy between the simplified and detailed models across different buildings, with deviations ranging from 3.28% to 40.57%. On average, the simplified models overestimate yearly energy use by approximately 20% compared to the detailed models.

Where available, the inclusion of calibrated models using sensor data shows improved alignment with the detailed simulations. For instance, in the case of the German building, the calibrated model predicts an energy use of 130.84 kWh/m², which is much closer to the detailed model value (125.93 kWh/m²) than the simplified model (141.95 kWh/m²), reducing the deviation from 12.72% to just 3.9%. This suggests that calibration using sensor data can significantly enhance model accuracy.

Overall, the findings highlight that while simplified models are useful for quick assessments, incorporating real sensor data leads to more reliable estimations of energy performance.

4 Gained Knowledge by KTU

The aim of this chapter is to summarize the knowledge and competences acquired by Kaunas University of Technology (KTU) during the activities related to the development of digital twins, assessment of the energy efficiency of buildings, and testing of data collection methodologies, in cooperation with international partners.

4.1 Hands-on experience with Contecht GmbH

4.1.1 Evaluation of BIM-to-BEPS Toolchains

The first knowledge domain addressed by the KTU researchers concerned the analysis and comparison of existing toolchains used to transfer BIM models into BEPS environments. In practice, energy simulation rarely relies on native BIM files alone; instead, workflows commonly involve multi-step conversion and simplification processes. KTU evaluated two well-documented conversion chains: Revit – SketchUp – EnergyPlus and Revit – TRNSYS. These workflows involve intermediate applications such as Euclid, Green Building Studio, and custom-developed IFC parsers. Through stepwise reproduction and documentation of these chains, the KTU team gained detailed insight into the stages where errors, data loss, or misalignment typically occur.

For example, in the Revit–SketchUp–EnergyPlus procedure, KTU researchers observed common issues such as: loss of original element naming conventions during IDF export; geometric inaccuracies and surface misalignments; manual input requirements for HVAC schedules, internal loads, and weather data; misinterpretation of material layers and thermal resistance properties.

Similarly, the TRNSYS workflow revealed challenges in translating volumetric data and required substantial manual input for missing thermal specifications. While TRNSYS offers flexibility in configuring Type56 models, the conversion from IFC files was found to be non-trivial due to inconsistencies in exported geometry, the absence of thermal boundary definitions, and the need to restructure material libraries manually.

These findings demonstrated to the KTU researchers that while BIM–BEPS toolchains are technically available; their usability depends heavily on manual oversight. Therefore, full automation of this process remains an open research challenge.

4.1.2 Assessment of IFC Data Exchange and Semantic Fidelity

A major area of technical knowledge acquired during the research concerned the (IFC) schema — the dominant open standard used to represent BIM data across disciplines. Through extensive literature review and experimental workflows, the KTU team deepened their understanding of the semantic structure of IFC files, with special focus on: IfcSpaceBoundary and spatial hierarchy logic; thermal and physical descriptors under IfcMaterialLayerSet; the relationship between 1st and 2nd level space boundaries and their implications for energy modelling.

KTU examined methods for generating 2nd level space boundaries within IFC, which are necessary to accurately simulate thermal zones. The team reviewed algorithms such as Common Boundary Intersection Projection (CBIP) (Lilis et al., 2021) and investigated automated systems for checking geometric and semantic consistency of space definitions (e.g., Mediavilla et al., 2023). Researchers also explored how these representations affect simulation accuracy, especially when curved geometries or unconnected zones are involved.

This work contributed to a refined understanding of why IFC models, although semantically rich, are often incompatible with direct simulation inputs. For example, while the schema theoretically supports thermal descriptors via IfcThermalMaterialProperties, in practice, these are rarely included or standardized across BIM authoring tools.

Furthermore, the KTU team explored the potential of Model View Definitions (MVDs) to streamline data exchange. In particular, the MVD for building energy performance simulation proposed by Pinheiro et al. (2018) was studied as a means of filtering only relevant subsets of the IFC schema for BEPS purposes. The team recognized that the success of MVD-based workflows depends not only on technical compatibility but also on widespread implementation within authoring tools and downstream simulators — a gap still unresolved in current practice.

4.1.3 Definition of Minimum Information Requirements for BEPS

Another key area of contribution was the systematic identification of minimum data requirements needed to perform reliable energy simulations using BIM-originated models. Based on toolchain testing and semantic IFC analysis, the KTU team compiled a list of essential model components, which include accurate geometric descriptions of walls, floors, ceilings, windows, and external doors; thermal properties such as U-values, thermal resistance (R-values), solar heat gain coefficients, and visible light transmittance; HVAC system layout and control logic (where available); thermal zones with assigned usage, occupancy schedules, and internal load profiles.

To support the identification and validation of these attributes, the KTU team implemented a rules-based checking routine using DynamoBIM, a visual programming tool compatible with Revit. The routine systematically assessed model completeness by checking whether critical parameters were present for each building element. When missing, values were replaced by documented defaults and flagged for further data entry through Requests for Information (RFIs).

This procedural knowledge not only improved the fidelity of exported simulation models but also formed the basis for a generic validation protocol applicable to other projects involving BIM-to-BEPS workflows. Moreover, it highlighted the need for early coordination between architects, engineers, and energy modelers to ensure simulation-ready model creation from the outset of the design process.

4.1.4 Methodological Integration and Generalization

Lastly, the KTU team synthesized the above findings into a generalized methodological framework for aligning BIM practices with energy performance simulation needs. This framework included: guidelines for the preparation of BIM models intended for export to BEPS tools; recommendations for geometric simplification practices, depending on simulation objectives; a flowchart for selecting suitable conversion tools based on model type, complexity, and simulation platform; criteria for evaluating data loss and corrective actions at each stage of the translation process.

Through this work, the KTU researchers developed the capacity to bridge the conceptual gap between design-phase BIM and operational-phase BEPS, especially in renovation scenarios where thermal modelling of existing buildings requires hybrid data sources (e.g., point clouds, thermal imaging).

Furthermore, the research confirmed that while IFC and gbXML are critical enablers for data interoperability, they alone are insufficient. Effective BEPS workflows require toolchains that support error-tolerant geometric parsing, robust metadata mapping, and interactive user feedback — features that remain unevenly supported across current platforms.

4.2 KTU Acquired Knowledge from Vercel Dashboard Use Case Development (Shayan Saket Internship)

As part of the knowledge exchange activities at Kaunas University of Technology (KTU), an internship was organized for Shayan Saket, a Contecht representative and co-author of this study. The internship focused on the development of interactive, web-based data visualization solutions for the built environment using **Vercel dashboard** and served as a practical example of digital tool implementation in real-world conditions.

The internship was carried out according to a detailed plan developed by the KTU team. The plan structured the work into five progressive stages—requirements definition, interface mock-ups, data source configuration, dashboard development, and testing—which ensured a systematic approach to both technical knowledge acquisition and tool implementation. The outcomes of the internship are accessible via the demonstration platform: https://sensor-lyart.vercel.app.

4.2.1 System Architecture for Wi-Fi-Based Occupancy Detection and Visualization

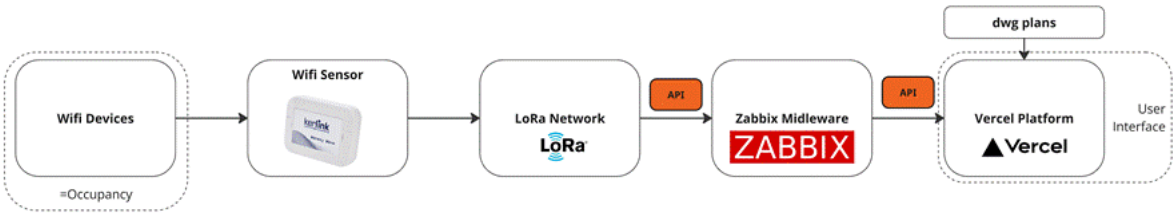


Figure 33. IoT-based Occupancy Detection and Visualization System

Occupancy was interpreted as the number of detected Wi-Fi devices, with calibration and validation performed against the actual number of occupants in the building, using data from the Kaunas University of Technology Academic Information System (AIS), class timetables, and other relevant sources. The data was collected via a LoRa-based infrastructure and integrated into the Zabbix middleware platform for monitoring and analysis. For real-time visualization and public-facing dashboards, a web application was developed and deployed using the **Vercel** cloud platform. Vercel enabled seamless integration with modern frontend technologies and provided automated deployment from version control, allowing rapid updates, and ensuring high availability of the occupancy information through a globally distributed content delivery network.

For Wi-Fi-based occupancy detection, **Kerlink Wanesy Wave** sensors (Fig. 34) were deployed throughout the building. These LoRaWAN-compatible devices passively detected Wi-Fi signals emitted by mobile devices, enabling the estimation of occupancy levels without requiring user interaction.

Figure 34. Kerlink Wanesy Wave sensor[14]

The collected data was transmitted via a LoRa-based infrastructure and integrated into the Zabbix middleware platform for centralized monitoring, analysis, and cross-validation with institutional data sources such as the Kaunas University of Technology Academic Information System (AIS) and class schedules.

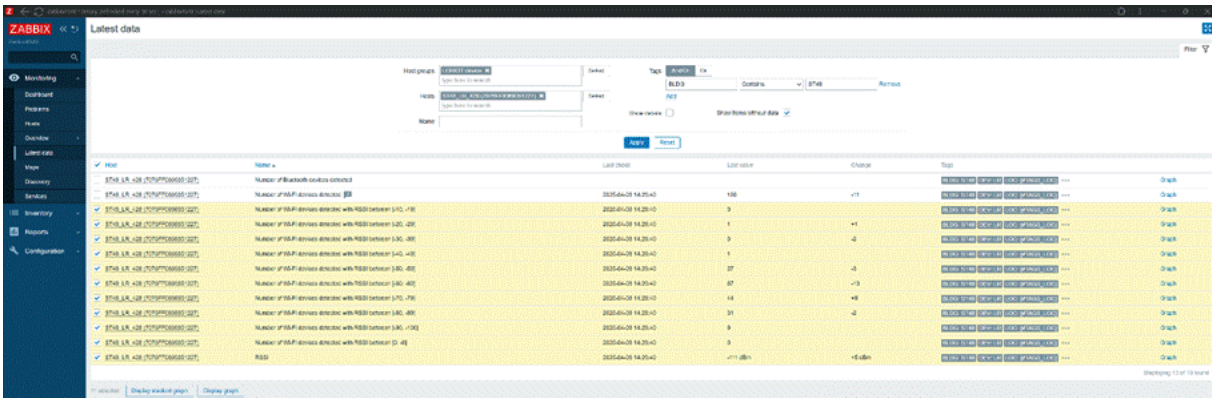


Figure 35. WiFi detechted devices data in Zabbix middleware

[14] https://www.kerlink.com/product/wanesy-wave/

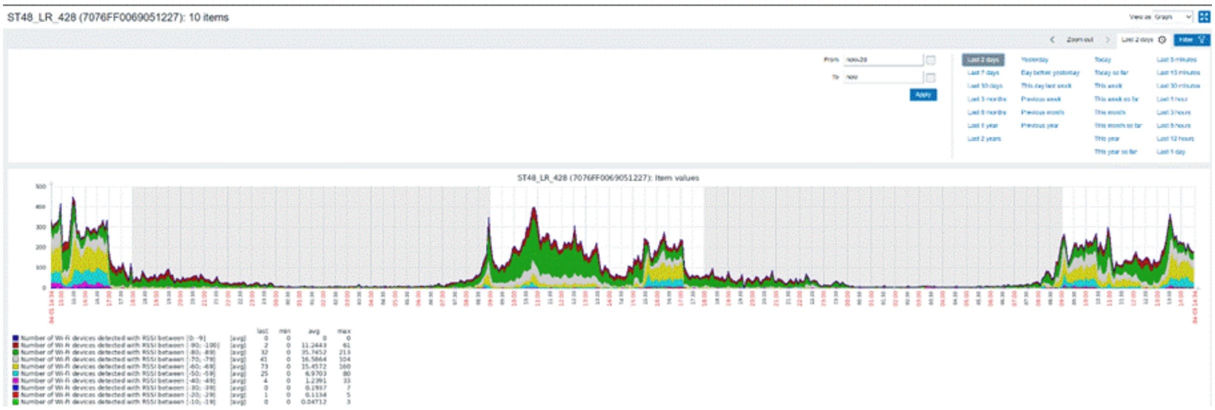


Figure 36. Time series stacked data representation

4.2.2 Use Case Definition and Stakeholder Requirements

KTU researchers, in collaboration with Shayan Saket, began by identifying specific use cases for Vercel dashboard within the context of smart buildings and energy-aware environments. These included indoor localization and occupancy monitoring; environmental metric tracking (e.g., temperature, humidity, air quality); energy consumption overview and system-level interactivity.

Stakeholder consultations enabled the team to define the expectations regarding interactivity, interface responsiveness, data granularity, and integration methods. Through this work, the KTU team strengthened their methodology for user-cantered interface design and formalized an approach to use case-driven tool adaptation.

The main deliverable from this phase was a comprehensive document outlining key scenarios, technical and functional requirements, and preliminary data modelling considerations.

4.2.3 Visual Mockup and UI/UX Design with Vercel dashboard

Building on the identified use cases, the team focused on creating layout prototypes using Vercel dashboard, a feature-rich and extensible visualization tool. During this phase, the intern and supervising team members explored the limits of Dashboard in representing complex spatial data (Fig. 37).

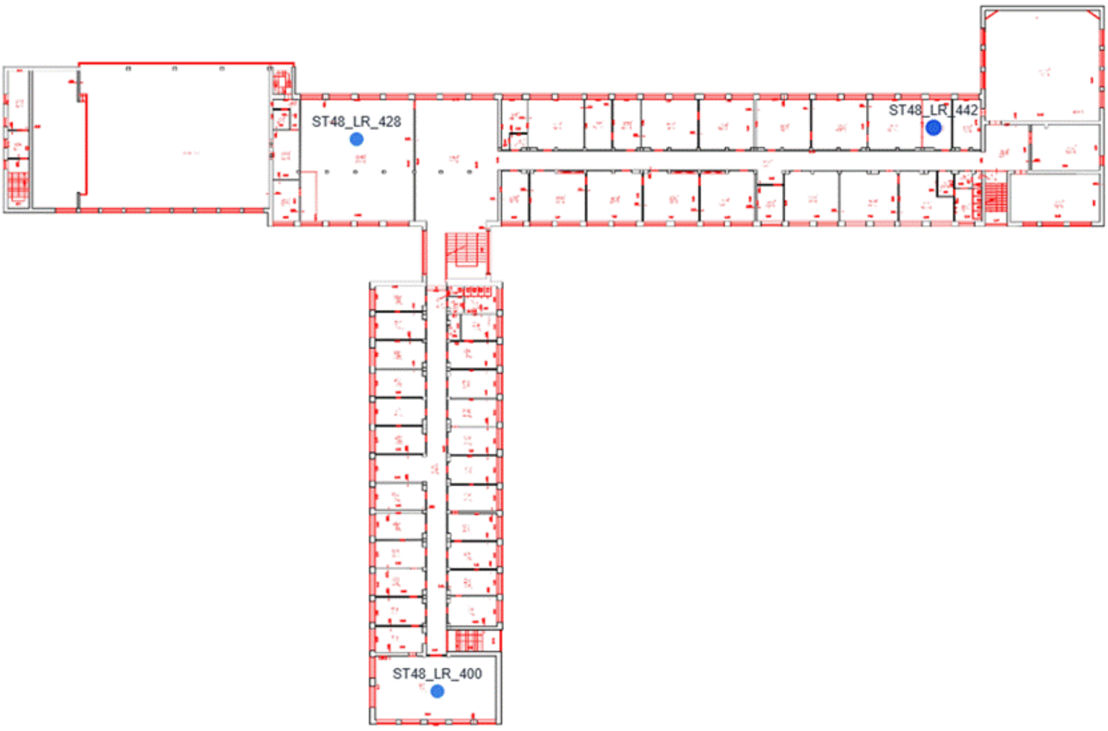


Figure 37. Floor plan

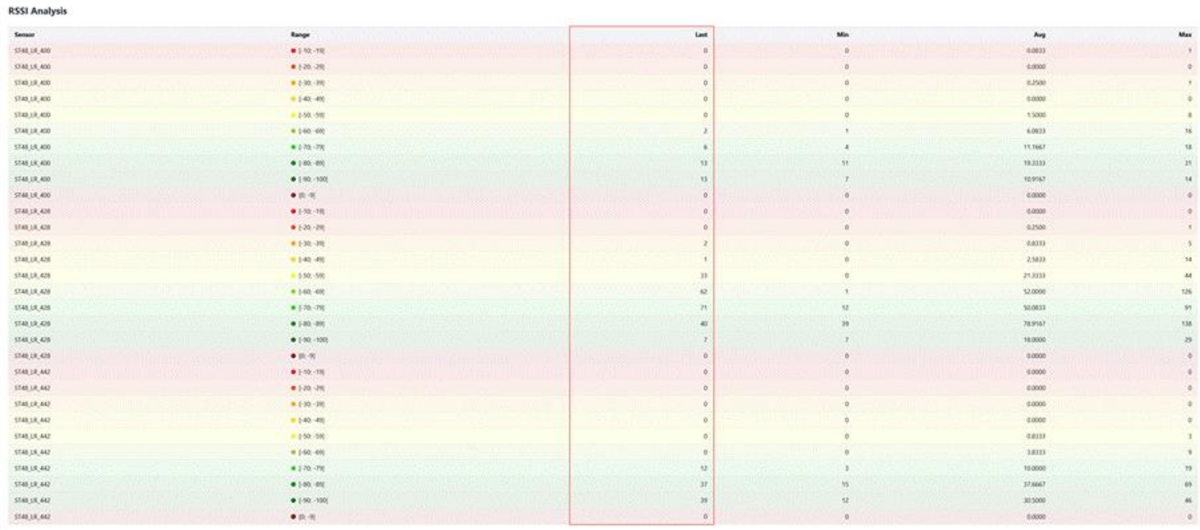
- The mock-ups included:
- Interactive floor plans with real-time object positions.
- Clickable elements and contextual tooltips.
- Dynamic filtering capabilities based on time or spatial parameters.

This activity deepened the KTU team's understanding of visual data storytelling, UI layout responsiveness, and real-time feedback mechanisms, all of which are essential in high-stakes facility monitoring and building operation scenarios.

4.2.4 Data Source Configuration and Stream Integration

A critical component of the project involved the integration of real-time or simulated data streams with Vercel dashboard. To this end, the KTU team investigated best practices for formatting data using MQTT brokers; applying filters to incoming data streams; structuring data for visualization widgets.

The process required a thorough comprehension of data pipelines, asynchronous messaging protocols, and schema validation. As a result, KTU researchers developed new competencies in sensor integration and live data visualization workflows (Fig.38), particularly in the context of Internet of Things (IoT)-driven infrastructure.



RSSI Analysis

Sensor	Range	Last	Min	Avg	Max
ST48_LR_400	[-10; -19]	0	0	0.0833	1
ST48_LR_400	[-20; -29]	0	0	0.0000	0
ST48_LR_400	[-30; -39]	0	0	0.2500	1
ST48_LR_400	[-40; -49]	0	0	0.0000	0
ST48_LR_400	[-50; -59]	0	0	1.5000	8
ST48_LR_400	[-60; -69]	2	1	6.0833	16
ST48_LR_400	[-70; -79]	6	4	11.1667	18
ST48_LR_400	[-80; -89]	13	11	19.3333	21
ST48_LR_400	[-90; -100]	13	7	10.9167	14
ST48_LR_400	[0; -9]	0	0	0.0000	0
ST48_LR_428	[-10; -19]	0	0	0.0000	0
ST48_LR_428	[-20; -29]	0	0	0.2500	1
ST48_LR_428	[-30; -39]	2	0	0.8333	5
ST48_LR_428	[-40; -49]	1	0	2.5833	14
ST48_LR_428	[-50; -59]	33	0	21.3333	44
ST48_LR_428	[-60; -69]	62	1	52.0000	126
ST48_LR_428	[-70; -79]	71	12	50.0833	91
ST48_LR_428	[-80; -89]	40	39	78.9167	138
ST48_LR_428	[-90; -100]	7	7	18.0000	29
ST48_LR_428	[0; -9]	0	0	0.0000	0
ST48_LR_442	[-10; -19]	0	0	0.0000	0
ST48_LR_442	[-20; -29]	0	0	0.0000	0
ST48_LR_442	[-30; -39]	0	0	0.0000	0
ST48_LR_442	[-40; -49]	0	0	0.0000	0
ST48_LR_442	[-50; -59]	0	0	0.8333	3
ST48_LR_442	[-60; -69]	0	0	3.8333	9
ST48_LR_442	[-70; -79]	12	3	10.0000	19
ST48_LR_442	[-80; -89]	37	15	37.6667	69
ST48_LR_442	[-90; -100]	39	12	30.5000	46
ST48_LR_442	[0; -9]	0	0	0.0000	0

Figure 38. RSSI Analysis

4.2.5 Dashboard Implementation and Interactivity Enhancement

Following the preparation of data and UI mock-up's, the team proceeded with implementing fully functional dashboards. These dashboards included:

- Real-time object movement on Canvas floor plans.
- Highlighted zones and alert logic.
- Linked dashboards for multi-perspective analysis.

This stage highlighted the capacity of **Vercel dashboard** as an interactive simulation and control interface and helped the KTU team gain experience in applying Dashboard beyond standard metric dashboards—leveraging it instead for spatial and contextual data visualization within a building.

4.2.6 System Testing and Usability Evaluation

The final phase consisted of testing the solution in terms of usability across devices (desktop and mobile); data refresh rates and real-time consistency; error handling in dynamic visualizations.

The iterative testing process helped the team refine their understanding of human-cantered dashboard design, especially for non-technical users in the building management or facility monitoring domains.

The result was a publicly accessible web-based prototype, available at https://sensor-lyart.vercel.app , which serves as both a demonstrator and learning tool for further projects involving spatial data visualization in the built environment.

4.2.7 Summary of Acquired Competencies

The internship and associated development process enabled the KTU team to acquire valuable skills across multiple layers of digital solution design, including competency areas listed below (Table 7):

Table 7.Gained competencies and their description

Competency Area	Description
Use Case Modeling	Practical experience in translating building management challenges into software requirements
UI/UX Design	Familiarity with responsive dashboard layouts and user interaction principles
Real-Time Data Integration	Knowledge of MQTT data streams and filtering for visualization purposes
Grafana Canvas Customization	Skills in implementing advanced Canvas features for spatial use cases
System Testing and Optimization	Usability-focused validation of dashboards across devices and user profiles

This practical implementation case reinforced several key insights relevant to the wider BIM–BEPS integration domain:

Effective visualization of real-time performance data requires not only technical tooling (e.g., Vercel), but also contextual knowledge of building operations and user needs.

Interactive dashboards can act as bridges between passive monitoring and active decision-making in building energy and comfort management.

Real-time localization and environmental feedback provide a valuable complement to model-based simulation, supporting hybrid workflows that combine digital twins and operational analytics.

4.3 In-Depth Gained Knowledge from Scientific Research

The preparation and authorship of the scientific publication "Exploratory Analysis of Interoperability Issues in Building Energy Performance Simulation within the Digital Twin Framework" which was submitted to the "Journal of Building Engineering" with comprehensive practical knowledge in advanced topics related to energy modelling, digital twin architectures, and interoperability issues. The study's interdisciplinary nature required engaging deeply with simulation software, data exchange formats, standards analysis, and error diagnostics—transforming theoretical knowledge into applied skills.

4.3.1 Understanding Digital Twin Integration in Building Energy Performance Simulation

The paper demanded an advanced understanding of the differences between traditional BIM-based modelling and dynamic digital twin environments, especially regarding how real-time data and lifecycle management are integrated. Through the process, KTU gained this knowledge:

- A detailed understanding of the ISO/IEC 30173:2023 standard for defining digital twins and how real-time data synchronization plays a critical role in simulation based on ISO/IEC TR 30172:2023, ISO/IEC 20924:2024.
- The ability to distinguish between static BIM representations and adaptive digital twins that support real-time simulation and optimization in the Use stage.
- Experience applying the DIKW (Data–Information–Knowledge–Wisdom) pyramid, particularly how sensor data evolves into simulation-ready knowledge in digital twin systems.

A more in-depth understanding of the underlying interoperability issues that hinder the seamless integration of the BIM-to-BEPS workflow within the Digital Twin architecture.

4.3.2 Advanced Energy Simulation Workflows

While authoring the paper, authors worked extensively with different BIM-to-BEPS pipelines, including the combinations:

- Autodesk Revit → SketchUp → EnergyPlus
- Autodesk Revit → TRNSYS

This involved the creation of ad-hoc test models and hands-on manipulation of intermediary file formats like IFC, IDF and gbXML. She acquired knowledge in:

- Mapping BIM components (e.g., IfcWall, IfcWindow, IfcSlab) to simulation-relevant objects in EnergyPlus.
- Understanding how GUI-based tools (e.g., OpenStudio, DesignBuilder) interact with simulation engines (e.g., EnergyPlus, TRNSYS).
- Applying white-box and gray-box modeling strategies and understanding when each is most appropriate.
- Examination and finalization of the model after the import to the simulation engine.

4.3.3 Diagnosing and Categorizing Interoperability Issues

A significant focus of the paper was identifying interoperability issues at every stage of the BIM-to-BEPS process. Young scientists became proficient in:

Detecting errors such as geometric discrepancies (volumes, areas) in IFC-to-IDF transitions, incomplete transfer of thermal properties and other semantic data, building systems data omissions, and operational schedule inaccuracies. Identified interoperability problems were categorized into syntactic, semantic, and visualization levels.

Table 8. Categorization of Interoperability Issues Identified by co-authors

Interoperability Issues Level	Description	Typical Errors Observed	Software Combination Affected
Syntactic level	Refers to describing the exact format of the information to be exchanged	Missing geometry attributes, undefined HVAC parameters, need for manual interventions to support compatibility with simulation tool libraries	Revit → IDF → EnergyPlus
Semantic level	Mismatch in meaning between data elements and the relationships that form the logic of BIM and simulation models	Misclassified spaces, loss of HVAC component behavior, incomplete transfer of thermal properties, loss of semantic information	Revit → IFC → TRNSYS
Visualization level	Inaccurate representation of 3D geometry or spaces	Inverted surfaces, misaligned walls, unenclosed thermal zones, redundant objects	Revit → SketchUp → EnergyPlus

Table 9. BIM Element Mapping to Energy Simulation Inputs

BIM Element / IFC Entity	Simulation Role in BEPS Tools	Observed Interoperability Challenge
IfcWall, IfcSlab, IfcRoof	Defines thermal envelope (geometry + material properties)	Incomplete U-values, R-values; surface connection errors
IfcWindow, IfcDoor	Heat gains/losses, natural lighting	Missing solar gain coefficients, incorrect orientation
IfcZone, IfcSpace	Assigns thermal zones and occupancy	Mismatch in zone boundaries; unlinked HVAC data
IfcSystem, IfcBoiler, etc.	HVAC configuration	Omitted or incorrect HVAC components in export
IfcSchedule, IfcTimeSeries	Operation and usage patterns	Schedule lost in export or misinterpreted by the simulation tool

4.3.4 Standards-Based Analysis and Graph Theory Applications

The methodological part of the study required mapping over 150 ISO standards from domains such as BIM, digital twins, and building sustainability. Authors developed the ability to perform qualitative and quantitative analyses of standards, including the responsible ISO Committee, interoperability mechanisms embedded in the standard to guide BIM-to-BEPS process, definition of interoperability levels, visualize connections between standards using network graphs in Gephi, and assess whether interoperability connections were weak or strong.

4.3.5 Interdisciplinary Collaboration and Scientific Writing

The research process involved collaboration with partners from Germany (Contecht GmbH, TU Berlin), Cyprus (Frederick University), and various KTU faculties. researchers improved her ability to:

- Navigate international collaboration within Horizon Europe frameworks
- Respond to reviewer comments and adapt content for high-impact journals
- Align scientific contributions with policy-relevant goals such as EPBD compliance and EU sustainability directives

Table 10. Interoperability Issue Types Across Software Steps

Step in Workflow	Syntactic Issues	Visualization Issues	Semantic Issues
BIM Export (IFC / gbXML)	✓		✓
Intermediary Tool Usage (e.g., SketchUp)		✓	✓
BEPS Tool Import (e.g., EnergyPlus)	✓	✓	✓
Simulation Result Interpretation			✓

4.3.6 Summary of Knowledge Acquired by KTU

Table 11. Summary of knowledge acquired by KTU

Knowledge Area	Skill / Understanding Gained
Digital Twin Simulation Architecture	Static data, dynamic data flow, synchronization logic, DIKW pyramid, reference architecture
Intermediary Tool Usage (e.g., SketchUp)	Model import using Euclid plugin, model checking for errors and applying necessary fixes
BIM-to-BEPS Pipeline	Software combinations, file formats, mapping schema
Interoperability Diagnostics	Error categories, IFC validation, Dynamo routines, model preparation to mitigate possible interoperability errors

Simulation Tools	Hands-on use of EnergyPlus, TRNSYS, SketchUp, OpenStudio
Standards Analysis	ISO mapping, committee structure, interoperability frameworks
Graph Visualization	Network analysis using Gephi to evaluate standard interconnectivity
Research Design & Experimentation	Custom model creation, methodology framing, result validation
Academic Writing & Collaboration	Manuscript structuring, international coordination, Horizon deliverables

5 Conclusions

This study presents an integrated methodology for enhancing building performance simulation by leveraging the synergies between BIM and BEPS. Recognizing the limitations of conventional approaches—which often suffer from fragmented data, manual processing, and lack of interoperability—the proposed methodology harnesses automated data acquisition, dynamic calibration, and advanced digital twin integration to produce more robust and agile energy models. The work is anchored by a dual approach: first, by simplifying the data collection process through a minimalistic questionnaire that informs initial model generation; and second, by enriching these models with high-fidelity BIM data acquired via state-of-the-art surveying techniques and subsequent refinement using real-time sensor data.

A critical achievement of the project is the development of a systematic conversion process that reliably translates user-provided inputs into detailed EnergyPlus IDFs. By standardizing the acquisition of key parameters—including geometric details, construction materials, and HVAC characteristics—and embedding default values where direct measurements are unavailable, the workflow minimizes manual intervention while preserving data integrity. This automation, complemented using open standards such as IFC and gbXML, significantly enhances interoperability across various software applications used in the architectural, engineering, and construction sectors. Consequently, stakeholders can now exchange complex datasets with higher confidence and reduced need for intermediary corrections.

The methodology also demonstrates the value of integrating dynamic data—captured from IoT sensor networks—into the simulation framework. As evidenced by the case studies across multiple European countries, calibration using sensor data markedly improves model accuracy. For instance, in the German pilot building, sensor-calibrated models reduced the deviation in predicted energy consumption from over 12% to less than 4% when compared with detailed simulation benchmarks. These findings underscore the potential of digital twins in maintaining real-time alignment between simulated models and evolving building operational conditions, thereby enabling proactive management and enhanced predictive capabilities.

Beyond the technical robustness of the conversion workflow, the report emphasizes the necessity of stakeholder collaboration. The methodology's design supports integrated communication among architects, engineers, energy modelers, and facility managers. This collaborative framework is instrumental not only for validating model performance but also for ensuring that the simulation outputs remain meaningful and actionable for building operators. In a rapidly evolving performance landscape, where non-energy metrics like thermal comfort, water usage, and acoustic quality are increasingly important, the ability to synchronize insights from diverse domains is essential.

Validation through real-world case studies—spanning diverse climates and building types in the Netherlands, Germany, Greece, and Spain—highlights the flexible applicability of the approach. Although the simplified questionnaire-based models tend to overestimate energy consumption by approximately 20% on average when compared to detailed models, the integration of sensor calibration data bridges this gap considerably. The variance in accuracy across buildings, with deviations ranging from as low as 3.28% to as high as 40.57%, suggests that while the simplified models are useful for preliminary assessments, incorporating detailed site-specific data yields more reliable forecasts. These insights advocate for a hybrid modeling framework that begins with minimalistic approaches and evolves toward enriched, data-driven simulations as further information becomes available.

Despite the evident advancements, several technical and practical limitations remain. The report identifies challenges in managing the complexity of BIM-to-BEM conversions, particularly when dealing with the intricate geometric and operational details inherent in established building stocks. Proprietary data formats, the inherent complexity of IFC schemas, and issues related to data loss or misinterpretation during model transfers pose significant hurdles. Moreover, limited access to comprehensive as-built data—often exacerbated by operational constraints and discontinuities in information management—underscores the need for more unified data exchange protocols in the industry.

Looking ahead, future research should explore enhanced methodologies for seamless multi-source data integration and real-time simulation updates. The potential for advanced machine learning algorithms to predict and adjust simulation parameters in the absence of complete datasets is particularly promising. Additionally, further development of crowd-sourced data collection applications, such as the BIM-SPEED Inhabitants App highlighted in this study, could enable continuous feedback loops that keep the digital twin representations dynamically aligned with real-world conditions. These innovations have the potential to significantly decrease reliance on resource-intensive manual inspections and move toward more autonomous, high-accuracy building performance management systems.

In summary, the integrative framework presented herein marks a significant step forward in bridging the gap between traditional energy simulation practices and modern, data-centric approaches. It lays out a robust pathway from preliminary data collection through to detailed BIM-based model enrichment, validated by extensive case studies. By highlighting both the strengths and current limitations of the approach, this report provides a comprehensive foundation for future developments in building performance simulation and underscores the critical role of dynamic data integration in achieving truly adaptive, efficient, and sustainable building management.

6 References

- Dong, B., Yan, D., Li, Z., & Wang, C. (2018). A framework for integrating building performance simulation and multi-objective optimization for energy performance design decision support. *Automation in Construction*, 89, 205–218.
- Grieves, M. (2014). Digital Twin: Manufacturing Excellence through Virtual Factory Replication. *White paper*, Florida Institute of Technology.
- Johra, H., & Heiselberg, P. (2022). Energy renovation of buildings – A review of envelope and HVAC system measures with a focus on interactions. *Energy and Buildings*, 256, 111726.
- Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmström, J. (2021). Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 9, 59522–59535.
- Klein, L., Kwak, J., Kavulya, G., Jazizadeh, F., Becerik-Gerber, B., & Varakantham, P. (2020). Coordinating occupant behavior for building energy and comfort management using multi-agent systems. *Automation in Construction*, 110, 102939.
- Mastrolembo Ventura, S., Gervasio, H., & Habert, G. (2023). BIM-based LCA for early design stages: Parametric tools and workflows. *Journal of Cleaner Production*, 402, 136898.
- Nguyen, H. T., Reiter, S., & Rigo, P. (2022). Integration of indoor environmental quality and energy consumption in early design decision-making. *Building and Environment*, 208, 108584.
- Qi, H., Mourshed, M., & Loveday, D. L. (2023). A Digital Twin approach to predicting and optimizing energy use in smart buildings. *Applied Energy*, 342, 120936.
- Salvalai, G., Sesana, M. M., & Vitaliti, M. C. (2021). Towards the decarbonization of the building stock: The role of LCA in BIM-based performance analysis. *Sustainable Cities and Society*, 74, 103132.
- Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction*, 38, 109–127.
- Zanni, M. A., Soebarto, V., & Williamson, T. (2019). A framework for BIM-enabled whole-of-life building sustainability assessment. *Renewable and Sustainable Energy Reviews*, 103, 564–579.

- Asl, M. R., Zarrinmehr, S., Bergin, M., & Yan, W. (2015). BPOpt: A framework for BIM-based performance optimization. *Energy and Buildings*, 108, 401–412.
- Attia, S., Hamdy, M., O'Brien, W., & Carlucci, S. (2018). Integrating performance simulation and multi-criteria decision-making in early design support: A review. *Automation in Construction*, 96, 44–59.
- Fang, Y., Wang, J., & Cho, Y. K. (2020). Building energy compliance checking using a BIM-enabled knowledge-based system. *Advanced Engineering Informatics*, 44, 101087.
- Santos, R., Costa, A. A., Silvestre, J. D., & Mateus, R. (2021). BIM-based building performance assessment: From evaluation to improvement. *Advanced Engineering Informatics*, 48, 101316.
- Pang, Z., Zhang, J., & Wu, P. (2023). Machine learning-enhanced energy modeling in BIM environments: Frameworks and applications. *Advanced Engineering Informatics*, 56, 102151.
- Schlenger, J., Yeung, T., Vilgertshofer, S., Martinez, J., Sacks, R., Borrmann, A., 2022. A Comprehensive Data Schema for Digital Twin Construction, in: Proceedings of the 29th EG-ICE International Workshop on Intelligent Computing in Engineering. Presented at the The 29th EG-ICE International Workshop on Intelligent Computing in Engineering, EG-ICE, pp. 34–44. https://doi.org/10.7146/aul.455.c194
- ISO 10303-11:2004(en), Industrial automation systems and integration — Product data representation and exchange — Part 11: Description methods: The EXPRESS language reference manual [WWW Document], n.d. URL https://www.iso.org/obp/ui/en/#iso:std:iso:10303:-11:ed-2:v1:en (accessed 9.10.24).
- Borrmann, A., Schlenger, J., Bus, N., Sacks, R., 2024. AEC Digital Twin Data - Why Structure Matters, in: Skatulla, S., Beushausen, H. (Eds.), Advances in Information Technology in Civil and Building Engineering, Lecture Notes in Civil Engineering. Springer International Publishing, Cham, pp. 651–669. https://doi.org/10.1007/978-3-031-35399-4_46.