BIO4EEB

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D4.9 – BIO4EEB application in virtual demo cases (1st version)

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SEN – Sensitive, limited under the conditions of the grant agreement
Classified R-UE/EU-R – EU RESTRICTED under the commission Decision No2015/444
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Document history

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Executive Summary

This deliverable presents the initial findings of Task 4.3 Demonstration in Virtual Demo Cases in WP4. This task aims to evaluate renovation strategies using BIO4EEB solutions for typical European residential buildings. The goal is to create and analyse virtual demo cases and provide support for real demo cases, enhancing the replicability and applicability of BIO4EEB solutions across Europe.

In the methodology section, we detail our approach to selecting virtual demo cases that represent prevalent residential building types and climatic zones in Europe: a single-family house in Hungary (Continental climate), a terraced house in Belgium (Marine climate), and a multi-family house in Italy (Mediterranean climate). We identified key performance indicators (KPIs) such as energy demand, Predicted Mean Vote (PMV), and Predicted Percentage of Dissatisfied (PPD) to assess the impact of renovation strategies. PMV and PPD specifically measure aspect of thermal comfort as described in ISO 7730 (International Organization for Standardization, 2005). PMV represents the average thermal sensation vote of a large group of people exposed to the same environment, considering factors such as air temperature and velocity, relative humidity, mean radiant temperature, clothing insulation level and metabolic relate. PPD predicts the percentage of individuals that would be dissatisfied with particular thermal environment. For each demo case, we evaluated approximately 6,000 intervention scenarios, integrating BIO4EEB solutions into building components while considering variables like shading, orientation, and occupant behavior. This comprehensive approach allowed us to predict the impact of these interventions on energy performance and occupant comfort effectively.

In the data collection and analysis section, we describe how data for the base cases and renovation scenarios were gathered from reliable sources such as the TABULA WebTool, national statistical agencies, and technical literature to ensure accurate representation of building characteristics and material properties. We defined material properties and construction assemblies based on existing conditions and the potential improvements offered by BIO4EEB solutions. Data validation involved cross-referencing multiple sources and performing consistency checks to enhance the credibility of our findings. The collected data encompassed envelope characteristics, occupancy schedules, climate data, and specifics of BIO4EEB solutions like thermal conductivity and density.

In the simulation results and evaluation section, we showcase the outcomes of our simulations, demonstrating that refurbishing building envelopes—particularly walls, roofs, and floors—with BIO4EEB solutions significantly improves energy efficiency and occupant comfort across different climates and building types. Envelope characteristics such as U-values and solar heat gain coefficients emerged as the most influential factors affecting energy demand and thermal comfort. We developed surrogate models using linear regression to approximate the relationships between input variables and KPIs, enabling quick predictions of building performance without extensive computations. The models exhibited high predictive accuracy, with coefficients of determination (R^2) above 0.9 for energy and heating demand, confirming the effectiveness of BIO4EEB solutions in enhancing the energy performance of buildings.

Disclaimer

Abbreviations and Acronyms

Abbreviation	Description
EU	European Union
IEE	Intelligent Energy Europe
KPI	Key performance indicator
MFH	Multi-family house
nZEB	Nearly zero energy building
PMV	Predicted mean vote
PPD	Percentage of dissatisfied
R^2	Coefficient of determination
SFH	Single-family house
SHGC	Solar heat gain coefficient
TH	Terraced house

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1 Introduction

1.1 Goals and objectives

The primary goal of Task 4 in WP4 is to evaluate renovation strategies using the BIO4EEB solutions for typical European residential buildings by creating and analyzing virtual demo cases, as well as provide support and suggestions for real demo cases on the application of BIO4EEB solutions. This will be achieved, by creating virtual demo cases, carefully selected from the main geo-clusters within the EU to ensure they accurately represent the diverse building stock in terms of characteristics, size, and age. By focusing on representative buildings, we aim to enhance the replicability and applicability of our solutions across various real-world scenarios, ultimately contributing to the overarching project goals.

To achieve this, we have established several key objectives for this deliverable:

1. **Define Minimum Data Requirements**: We will identify and establish the essential data needed to perform concept-level calculations for each virtual demo case. This ensures that our models are built on a solid foundation of relevant and accurate information.

2. **Develop Data Infrastructure**: Where gaps in the required data are identified, we will deploy additional data infrastructure to collect the necessary information. This step guarantees the reliability and comprehensiveness of our simulation models.

3. **Create Dynamic Simulation Models**: Using the collected data, we will develop comprehensive energy and comfort simulation models for each demo case. These models will serve as the basis for assessing the current performance and potential improvements of each building type.

4. **Apply Renovation Scenarios**: Based on the developed technical solutions, we will create renovation scenarios aimed at improving the performance of the virtual demo buildings. These scenarios will integrate the various technological solutions developed within the project to evaluate their effectiveness and applicability to each demo case.

5. **Assess Key Performance Indicators (KPIs)**: Once the as-built simulation models are established, we will evaluate selected key performance indicators to identify areas that require improvement and to rate renovation scenarios using BIO4EEB products. This assessment is crucial for targeting the most impactful renovation opportunities

6. **Validate partners decisions :** Based on the outcome of evaluation of developed simulation models for virtual demo cases, we will focus on validating decisions for partners working on real demonstration cases, while offering decision support if and when it is needed..

The task will be documented in two specific deliverables. This deliverable will discuss out current progress in all the above mentioned objectives, however for some we will have initial results. Final deliverable due in M48 will contain the final results of the virtual demos, as well as the decision support method for the real demo cases.

Outcomes of this task will help in comparing newly developed BIO4EEB solutions with their existing market counterparts, as well as validating the performance improvements these new solutions will be able to bring to the demonstration projects, both real and virtual.

1.2 Geographical focus of virtual and real demo cases

The BIO4EEB project consortium has strategically selected both real and virtual demo cases to ensure comprehensive coverage of the European residential building stock. This selection process prioritizes geographical diversity, encompassing the main climate zones and a wide range of building typologies prevalent across the EU. By doing so, the project aims to evaluate and confirm the applicability of developed solutions in various environmental and architectural contexts, thereby enhancing the replicability and impact of the outcomes.

Real Demo Cases

Five real demo cases have been chosen to represent three dominant climate zones—Continental, Mediterranean, and Oceanic—and five distinct building typologies. These real-world sites provide robust testing conditions for different solution configurations, whether applied as refurbishments or integrated into new constructions. The selected real demo cases are as follows:

1. **Lithuania:** A two-family house refurbishment located in a Continental climate zone. This site focuses on enhancing energy efficiency in residential buildings.
2. **Spain:** A historical/protected single-family residential refurbishment situated in a Mediterranean climate. This case emphasizes envelope renovations while preserving architectural heritage, since the buildling is listed in the Catalogue of Elements or Artistic, Historical, Envrionmental, and Heritage Interest in Mallorca.
3. **Germany:** An office building now used for housing, situated in Marine climate erected in the post-war era. This case emphasizes the envelope renovations of post-war housing stock.
4. **Czech Republic:** A semi-detached residential refurbishment located in a Continental climate. This site targets energy performance improvements in pre-war housing stock.
5. **France:**.Part of a grand refurbishment project of former railway maintenance halls, in Oceanic climate. The demo consists of an experimental zone made of offices and workspaces. This site targets the evaluation of facade renovation in office settings.

These real demo cases not only cover a broad spectrum of building types and environmental conditions but also facilitate the comparison of conventional and BIO4EEB technologies, providing valuable insights into their performance and applicability.

Virtual Demo Cases

Complementing the real demo cases, three virtual demo cases have been selected to cover additional popular building typologies and climate zones within Europe. These virtual cases serve as a test-bed for assessing various technological solutions and their potential environmental, economic, and social impacts. The virtual demo cases are:

1. **Hungary (Middle European Continental Climate);**
2. **Belgium (Oceanic Climate);**
3. **Italy (Mediterranean Climate)**.

Comprehensive Coverage and High Replicability

Together, the real and virtual demo cases cover the main residential building types across the dominant climate regions in Europe. This comprehensive geographical and typological coverage ensures that the project's solutions are tested under diverse conditions, enhancing their robustness and adaptability. By relying on the TABULA-Episcope building typology, the selected demo cases embody some of the most

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common characteristics of European residential buildings, thereby maximizing the replicability potential of the developed solutions.

Moreover, the integration of both real and virtual demo cases allows for extensive evaluation and fine-tuning of the simulation models. This dual approach ensures that the project can address a wide range of energy performance challenges and provide actionable, scalable renovation strategies applicable to various real-world scenarios.

In summary, the geographical focus of the virtual and real demo cases within the BIO4EEB project is designed to capture the diversity of the European residential building stock. This strategic selection facilitates the thorough assessment of innovative renovation technologies, ensuring their effectiveness and scalability across different climates and building types, ultimately contributing to significant energy efficiency improvements in the EU's housing sector.

2 Methodology

2.1 Virtual demo case selection

The virtual demo cases were chosen to complement the real demo sites, filling in gaps and ensuring coverage of the most common residential building types and climate conditions across Europe. The selection process was guided by the following criteria:

1. **Geographical Diversity:**
   - Virtual demo cases were selected from major geo-clusters within the EU to capture the climatic and regional variations that influence building performance and renovation needs. This includes regions with Middle European Continental, Oceanic, and Mediterranean climates (as described in the previous chapter).
2. **Building Typologies:**
   - The selected virtual cases represent prevalent residential building types, such as single-family houses (SFHs), terraced houses (THs), and multi-family houses (MFHs). This ensures that the models reflect the diversity and common characteristics of the European housing stock.
3. **Age and Construction Period:**
   - Buildings from different construction periods, ranging from the early 20th century to more recent constructions, were included. This allows the assessment of renovation solutions across various building technologies and materials.
4. **Data Availability and Reliability:**
   - Virtual demo cases were chosen based on the availability of reliable and comprehensive data. Where data gaps existed, additional data infrastructure was deployed to ensure the accuracy and completeness of the simulation models.

Selected Virtual Demo Cases:

Hungary (Continental Climate):

Representing the "Kádár-cube" type SFHs typically built between the 1950s and 1980s. This virtual case focuses on affordable renovation options for a significant portion of Hungary's residential stock, which remains largely unrefurbished ("FEOL - A Kádár-kockák népszerűsége ma is töretlen," n.d.; Fodor and Somogyi, 2016).

Belgium (Marine Climate):

Featuring a typical THs constructed between 1920 and 1970. This case assesses energy-saving potentials and solution applicability in dense urban settings, considering the influence of neighboring buildings.

Italy (Mediterranean Climate):

Initially, the project planned to model an apartment block (AB) with detailed geometry to be provided by our Italian partner FOCCHI. However, after FOCCHI left the project, we adapted by selecting a multifamily house (MFH) built between 1961 and 1975, for which detailed geometrical data were available.

Despite this change – by selecting MFH - we ensured that the replicability potential remains similar, maintaining the validity of our virtual demo case selection. This virtual demo case evaluates the impact of BIO4EEB technologies on cooling demand in large residential buildings with gas central heating systems. The goal is to demonstrate the effectiveness of BIO4EEB solutions in improving energy efficiency and occupant comfort in Mediterranean climates.

2.2 KPIs Selection

The selection of KPIs for our evaluation was approached through a comprehensive two-fold methodology to ensure a thorough and relevant assessment of renovation scenarios. First step was based on a more comprehensive assessment of the KPIs looking at the possible benefits achieved using BIO4EEB solutions (Figure 1). Initially, we examined the extensive list of approximately 80 KPIs outlined in Deliverable D2.4, which covers technical, environmental, and economic aspects. Given the wide range of these indicators, it was crucial to prioritize those that closely align with our project's objectives and the specific capabilities of our dynamic energy modeling tools. By identifying the KPIs that overlap between D2.4 and our modeling capabilities, we ensured that our evaluation framework remains both comprehensive and manageable. KPI cards were a final product of the methodology, which are comprehensive documents that include all necessary information for understanding and estimation of the KPIs that are part of final KPI repository. They are a crucial source of information containing all relevant data for KPIs assessment to be used for decision making process regarding the application of BIO4EEB products in real and virtual demo cases. The KPI cards are also an essential source for effective representation and integration of BIO4EEB products into the BIO4EEB platform.

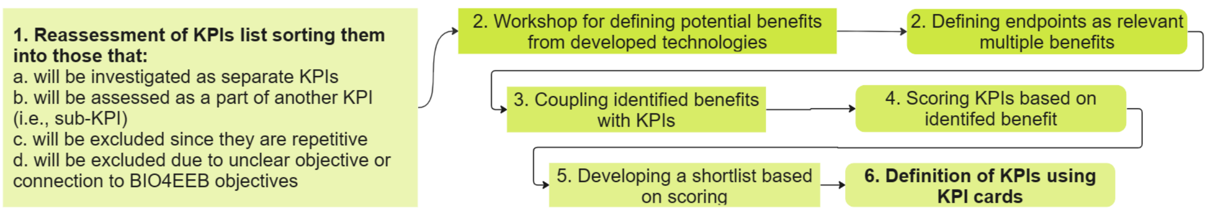

Figure 1- Methodology for core KPIs definition

Based on the second stage of the KPIs definition process in Figure 1, (i.e. the workshop held during the 3rd General Assembly with the participation of both the consortium and the Advisory Board of the project), the following **benefits** were expected from the application of the BIO4EEB products:

1. Competitive performance to conventional solutions;
2. Contribution to occupant comfort improvement;
3. Reducing environmental impact of building envelope;
4. Contribution to boosting nZEB market;
5. Contribution to expansion of sustainable building market;
6. Increasing financial returns for stakeholders.

	Expected benefits	KPI category	KPI
1	Competitive performance to conventional solutions	Technical performance of solutions	Solution performance competitiveness index
		Efficiency of building envelope integration	Time reduction
			Installation speed
			People dislocating
2	Contribution to occupant comfort improvement	Well-being improvement	Thermal comfort
			Indoor air quality
			Occupant satisfaction
3	Reducing environmental impact of building envelope	Life cycle assessment (LCA) of building envelope	Embodied energy
			Embodied carbon
4	Contribution to boosting nZEB market	Component level energy efficiency	Building envelope efficiency
			U-value competitivness of building envelope
		Building level energy efficiency	Energy demand/consumption
5	Contribution to expansion of sustainable building materials market	Social aspect	Client satisfaction score
		Technical aspect	Solution level adaptability
		Economic aspect	Payback period
6	Increasing financial returns for stakeholders	Financial viability	Net present value
		Building user benefit	Operating cost reduction

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Figure 2 the identified KPIs associated with specific benefits are represented. For each KPI, the comprehensive KPI card is provided, an example is shown in Figure 3. After definition of KPI cards repository which addresses main benefits correlated with the application of the BIO4EEB solution, we evaluated which KPIs could be effectively measured using our dynamic energy model. This step was essential to ensure that the selected indicators are not only relevant but also quantifiable within the constraints of our analytical tools. Integrating these KPIs with our modeling software allows for accurate and iterative evaluations of various renovation scenarios. Additionally, our KPI selection was guided by the specific goals defined in the Grant Agreement (GA).

	Expected benefits	KPI category	KPI
1	Competitive performance to conventional solutions	Technical performance of solutions	Solution performance competitiveness index
		Efficiency of building envelope integration	Time reduction
			Installation speed
			People dislocating
2	Contribution to occupant comfort improvement	Well-being improvement	Thermal comfort
			Indoor air quality
			Occupant satisfaction
3	Reducing environmental impact of building envelope	Life cycle assessment (LCA) of building envelope	Embodied energy
			Embodied carbon
4	Contribution to boosting nZEB market	Component level energy efficiency	Building envelope efficiency
			U-value competitivness of building envelope
		Building level energy efficiency	Energy demand/consumption
5	Contribution to expansion of sustainable building materials market	Social aspect	Client satisfaction score
		Technical aspect	Solution level adaptability
		Economic aspect	Payback period
6	Increasing financial returns for stakeholders	Financial viability	Net present value
		Building user benefit	Operating cost reduction

Figure 2 Categorization of the KPIs based on identified benefits

Expected benefits	KPI category	KPI	Sub-KPI	(Sub-)KPI estimation process	Data source + provider	Unit of measurement	Addressed goals from DoA
Contribution to boosting nZEB market	Building level energy efficiency	**Energy demand/consumption**	for heating for cooling for lighting for DHW	Demo case specific yearly energy demand/consumption per floor area after application of BIO4EEB solutions based on **simulation/energy bills. Building energy modelling -> energy demand, energy bills - energy consumption.**	Demo site data/simulation + DO	kWh/m2	•Reduction of EU's total energy consumption (5-6%) and CO2 emissions(5%). •At least a 5% reduction of the energy spent during the whole LC of a building.

Figure 3 Example of a KPI card

Key objectives influencing our selection include achieving energy savings between 50% and 80% through the implementation of the Plug and Play envelope combined with high-insulation materials, ensuring that renovation solutions within the BIO4EEB project generate at least a 20% reduction in CO_2 emissions compared to standard renovation packages, and contributing to a 5-6% decrease in the EU's total energy consumption and a 5% reduction in CO_2 emissions. Further goals include reducing embodied energy and CO_2 emissions by at least 30%, using XPS/EPS as references and PLA as counterparts—for instance, achieving a 65% and 36% reduction in windows compared to PVC—improving insulation properties by at least 20%, such as a 65% enhancement in window frame insulation, lowering energy spending throughout the building's lifecycle by at least 5%, and decreasing envelope thermal losses by 40% compared to traditional solutions.

To guide the selection process, a set of quantifiable targets and corresponding measures have been established. These targets, which address energy efficiency, emissions reduction, and material performance, are summarized in the table below:

Objective	Target/Measure
Achieve significant energy savings through Plug & Play envelope	50–80% reduction in energy use
Reduce CO_2 emissions compared to standard renovation packages	≥20% reduction in CO_2 emissions (BIO4EEB vs. standard packages)
Contribute to EU-wide energy and emissions reductions	5–6% decrease in EU total energy use and 5% reduction in CO_2
Lower embodied energy and CO_2 emissions in materials/components	≥30% reduction (XPS/EPS reference; PLA counterpart, e.g. 65% and 36% reduction in windows vs. PVC)
Increase insulation effectiveness	≥20% improvement (e.g., 65% enhancement in window frame insulation)
Reduce lifecycle energy costs	≥5% reduction in total building lifecycle energy expenditure
Decrease envelope thermal losses compared to traditional methods	40% reduction in thermal losses

To effectively measure and achieve these KPIs, selecting a robust simulation engine capable of iterative analyses was imperative. For the development of renovation scenarios we selected an approach utilizing parametric software tools offering advanced capabilities for dynamic energy modeling and providing essential outputs for KPI evaluation, including detailed energy consumption profiles, assessments of thermal performance metrics, quantifications of CO_2 emissions, comprehensive lifecycle assessment data, measurements of insulation efficiency, economic evaluations through cost-benefit analyses, and

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the ability to perform multiple simulation iterations for scenario testing, optimization, and validation purposes.

Ultimately, we selected Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD), and energy demand for heating and cooling at each floor as our primary KPIs. PMV and PPD were chosen because they provide a robust assessment of thermal comfort, which is crucial for ensuring occupant satisfaction and well-being in renovated buildings. These indicators allow us to quantify the effectiveness of insulation and HVAC improvements in creating a comfortable indoor environment. Additionally, energy demand for heating and cooling at each floor was selected to provide a detailed understanding of energy performance across different building levels, enabling targeted interventions and optimization of energy use. This granular approach ensures that our renovation strategies not only meet energy efficiency targets but also enhance overall building performance and occupant comfort.

By leveraging this dual approach—aligning the extensive KPI framework from D2.4 with the analytical strengths of our dynamic energy modeling tools—we have established a focused and effective set of KPIs. This strategic selection ensures that our evaluations are both comprehensive and aligned with the project's sustainability and performance objectives, thereby facilitating informed decision-making and successful project outcomes.

2.3 Development and Simulation of renovation scenarios

For the renovation scenarios, we collected all available BIO4EEB solutions to incorporate into our models. In creating these scenarios, for adjustable solutions like insulation thickness, we begin by determining the optimal thickness needed to achieve the advanced renovation U-values for specific building components, based on project goals and alignment with renovation scenarios in the TABULA Webtool ("TABULA WebTool," n.d.). For elements with fixed properties, such as window components, we utilize the material properties provided by the solution developers.

Moreover, we focused on integrating applicable BIO4EEB solutions into relevant building components, as detailed in the accompanying Table 1. It is important to note that mechanical properties are not evaluated in this phase; users are advised to consult the product data sheets available on the platform to ensure compliance with required mechanical specifications.

Solution Name	Partner	Floor	Roof	Wall	Window
Block Façade module	GOYER			+	
Fair Façade module	GOYER			+	
BioPUR spray	INDRESMAT	+	+	+	
PLA foam	AIMPLAS	+	+	+	
Posidonia core panel	SOPHIA & STARCELL	+	+	+	
KLIMA-PUR w/ solar control	INDRESMAT				+
KLIMA-PUR w/o solar control	INDRESMAT				+

Table 1 Potential application of BIO4EEB solutions.

To see how other aspects influence energy end use and comfort in the virtual demo cases, apart of purely physical aspects mentioned above, we also looked at other aspects specified in Figure 4, including:

- **Shading use**

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We defined three types of shading:

1. **No Shading**: There is no shading device on the building.
2. **Shading Controlled by Indoor Temperature**: Shading is applied whenever the indoor temperature exceeds the setpoint temperature.
3. **Shading Based on Irradiance**: Shading is applied whenever solar irradiance exceeds a specified level.

- Orientation

It has been shown that building orientation can significantly influence energy use. Since we are evaluating general buildings, it is crucial to assess the effect of BIO4EEB solutions in both **East-West** and **North-South** orientations. This is important because the placement of openings can significantly affect the building's energy performance.

- Behaviour types.

  In recent years, new occupant behavior patterns have emerged. The COVID-19 pandemic in 2020 significantly changed occupant behaviors, having a profound effect on residential energy use. With the widespread adoption of home offices, people are using significantly more energy in their homes than before. Therefore, it is important to consider two occupant behavior scenarios:

1. **Work-from-Home Scenario**: Most people work from home during weekdays.
2. **Traditional Scenario**: People are at work during weekdays and at home on weekends.

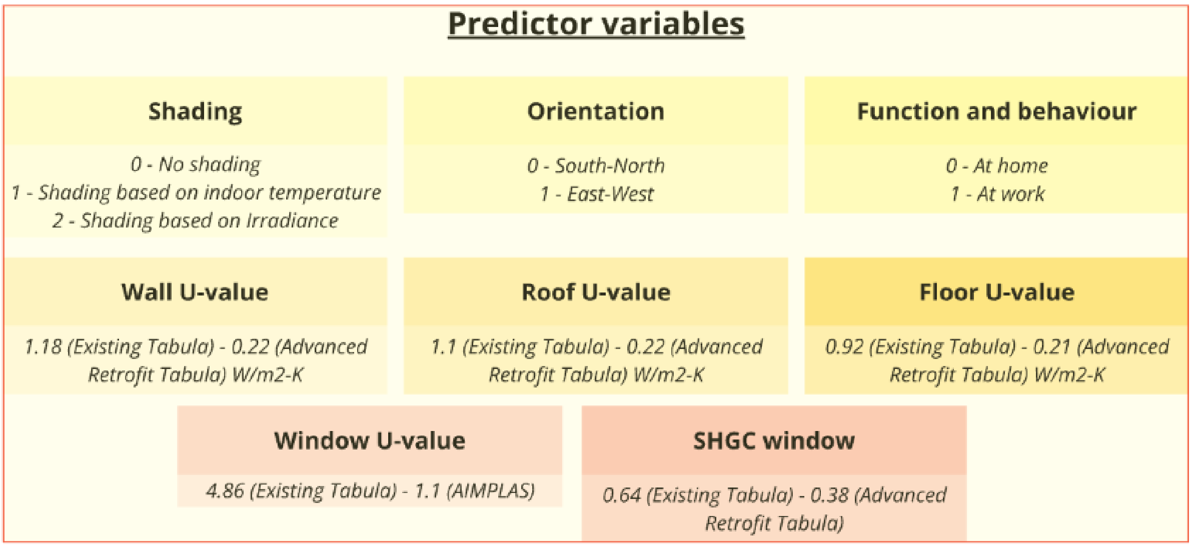

Figure 4 Data input for energy simulations

Creation of renovation scenarios.

When creating the renovation scenarios, we had two primary goals in mind: first, to support the development of the BIO4EEB Platform and simulation tool; and second, to aid the development of real demo cases by applying lessons learned from the virtual demo cases. To accomplish this, we created all possible permutations of the solutions. Naturally, some solutions are mutually exclusive—for instance, if a building adopts one wall solution, it cannot simultaneously have another wall solution. By excluding combinations that are mutually exclusive, we ended up with and initial set of 6,000 renovation scenarios for each virtual demo case.

2.4 Development of simulation models

The development of detailed simulation models was a critical step in evaluating the energy performance and thermal comfort implications of various renovation scenarios using BIO4EEB solutions. These models allowed us to predict the impact of different interventions on the virtual demo cases, facilitating the optimization of renovation strategies to enhance energy efficiency and occupant comfort. By simulating a large number of scenarios, we aimed to capture the variability in building performance due to different materials, climatic conditions, and user behaviors.

To effectively handle the complexity and scale of our simulations, we selected Rhino in combination with Grasshopper, its visual programming language. We utilized the Honeybee plugin for environmental analysis and energy simulation. This suite of tools offered several advantages:

- **Iterative Simulation Capability:** Grasshopper's parametric design environment allowed us to rapidly iterate through thousands of scenarios, adjusting parameters such as material properties and occupancy schedules with ease.

- **Integration with EnergyPlus:** Honeybee facilitate simulations using EnergyPlus, a highly respected and validated energy simulation engine known for its accuracy.

- **Flexibility and Adaptability:** The visual scripting nature of Grasshopper enabled us to modify simulation parameters quickly, which was particularly useful given that we did not have all the information from the BIO4EEB solutions at the outset.

- **Handling Large Datasets:** The software's capacity to manage large numbers of scenarios made it possible to simulate approximately 6,000 renovation scenarios per virtual demo case efficiently.

By leveraging these tools, we were able to create flexible, accurate, and scalable simulation models that could accommodate updates and refinements as more data became available.

Geometry

The base geometries for the virtual demo cases were developed using multiple sources that provided typical building configurations for the selected climatic zones:

- **Hungary:** We modeled a typical " Kádár-cube", a common SFH type built between the 1950s and 1980s (“Egy kispesti Kádár-kocka újrakondicionálása,” n.d.; “FEOL - A Kádár-kockák népszerűsége ma is töretlen,” n.d.). It corresponds to HU.N.SFH.02.Bel80 building type in Tabula Webtool (“TABULA WebTool,” n.d.).
- **Belgium:** In case of the terraced house geometry, the one proposed in (Toparlar et al., 2018) was adopted to represent typical terraced houses in an urban setting. It corresponds to BE.N.TH.01.Gen building type in Tabula Webtool (“TABULA WebTool,” n.d.).
- **Italy:** Due to the availability of detailed geometrical data, we modeled a MFH according to data provided in (Dipasquale et al., 2019), instead of an apartment building. Despite the change, the replicability potential remained similar, ensuring the validity of our simulations. It corresponds to IT.MidClim.MFH.05Gen building type in Tabula Webtool (“TABULA WebTool,” n.d.).

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The geometries were constructed in Rhino as shown in Figure 5, ensuring precise representation of building dimensions, orientations, and spatial configurations relevant to energy performance.

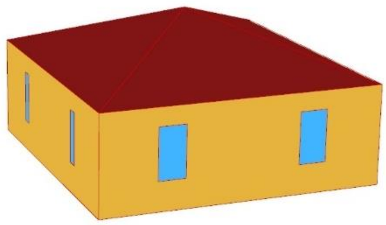	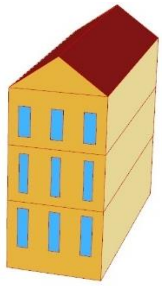	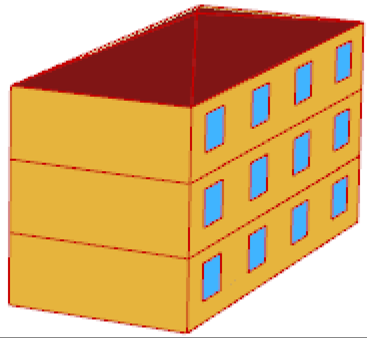
a) SFH in Hungary	b) TH in Belgium	c) MFH in Italy

Figure 5 Models of the simulated buildings

Zoning

For zoning, we implemented a floor-by-floor zoning, where each floor of the buildings was defined as a separate thermal zone to capture variations in energy use and thermal behavior between levels. Aligned with this, the hungarian house, being a 1 story house has only 1 zone, while the other houses, both being 3 story houses have 3 separate thermal zones (Figure 5).

This zoning approach was crucial for accurately modeling heat transfer, solar gains, and occupant comfort throughout the buildings.

Material and Construction Definitions

The material properties and construction assemblies were defined based on:

- **Baseline Data:**
  We used the TABULA WebTool data to define the existing conditions of building components, such as walls, roofs, floors and windows. This is further described in Section 3.
- **Renovation Scenarios:**
  For the renovation scenarios, we incorporated data from the TABULA renovation options (Advanced Refurbishment), adjusting material properties to reflect improved insulation levels based on the usual renovation scenarios present per countries for the specific building types.
- **BIO4EEB Solutions:**
  Material properties and performance characteristics of the BIO4EEB solutions were obtained directly from the solution providers. This included thermal conductivity, density, specific heat capacity, and other relevant parameters. The thicknesses of the thermal insulation was adjusted to reflect Advanced Refurbishment requirements for reaching U-value of components.

By aligning our material definitions with reliable data sources and project-specific information, we ensured that the simulations accurately reflected both the existing conditions and the proposed renovations.

Infiltration rate

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It has been decided to use 3 set of values for infiltration rate considering following assumptions:

a) If ratio of sum of the U-values after retrofit and existing state is in range of 0.45-0.30, infiltration rate is equal to 0.0003 m^3/sm^2;

b) If ratio of sum of the U-values after retrofit and existing state is lower than 0.30, infiltration rate is equal to 0.0001 m^3/sm^2;

c) **Otherwise it is 0.0006 m^3/sm^2.**

Climate Data

We employed Meteonorm weather files corresponding to each specific climatic zone of the virtual demo cases. The current scenarios utilize only the current weather files.
In future work, we plan to incorporate weather files for the years 2030 and 2050 to assess how climate change may impact building performance and the effectiveness of renovation measures, and the BIO4EEB solutions.

Occupancy Schedules and Internal Gains

Occupancy patterns significantly influence energy consumption and thermal comfort. We defined two primary occupancy schedules to reflect different user archetypes:

- **At-Home Scenario:**

  This schedule assumes occupants are at home throughout the day, reflecting the increased prevalence of remote work and home-based activities, especially following the COVID-19 pandemic.

- **At-Work Scenario:**

  This schedule represents traditional occupancy patterns where occupants are away during typical working hours on weekdays and at home during evenings and weekends.

These schedules influenced internal heat gains from occupants, equipment, and lighting, thereby affecting the heating and cooling demands.

HVAC Systems

In this phase of the project, we focused on calculating the heating and cooling energy demand rather than modeling specific HVAC systems.

- **Demand Calculations:**

  The simulations calculated the energy required to maintain thermal comfort based on setpoint temperatures without simulating the performance of actual HVAC equipment.
- **Future Work:**

  Modeling of HVAC systems, including efficiency and control strategies, will be addressed in subsequent phases of the project.

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By focusing on demand, we established a baseline for energy needs that can later be coupled with HVAC system models to assess total energy consumption.

Simulation Control Parameters

- **Time Steps:**
  Simulations were conducted on an hourly basis over a full calendar year to capture seasonal variations and daily fluctuations in energy demand.

Shading Devices and Controls

Shading strategies were incorporated to assess their impact on thermal comfort and energy use:

- **No Shading:**
  Represents buildings without any shading devices. Only overhangs (depending on building types) are present to provide shading, but shading is assumed to be always off.
- **Shading Controlled by Indoor Temperature and Irradiance:**
  Shading devices are activated when indoor temperatures exceed 24°C and if the solar radiation on the window is higher than 400 W/m2.
- **Shading Based on Irradiance:**
  Shading is applied when solar irradiance on the facade exceeds 150 W/m2, mitigating overheating during peak solar exposure.

These scenarios allowed us to evaluate the effectiveness of different shading controls in reducing cooling loads and enhancing occupant comfort.

Data Storage and Organization

Simulation outputs were systematically stored and organized for efficient analysis:

- **Data Format:** Results were exported in CSV format, facilitating compatibility with data analysis tools and the surrogate model.
- **Centralized Database:** Data was consolidated into a centralized database, enabling comprehensive analysis across all scenarios.
- **Quality Assurance:** Quality control measures were implemented to ensure the reliability of simulation results:
- **Error Checking:** Scripts included checks for simulation errors or incomplete runs, prompting reviews and reruns as necessary.
- **Validation of Results:** Preliminary results were compared against expected trends and benchmarks to identify any anomalies.

2.5 Surrogate model

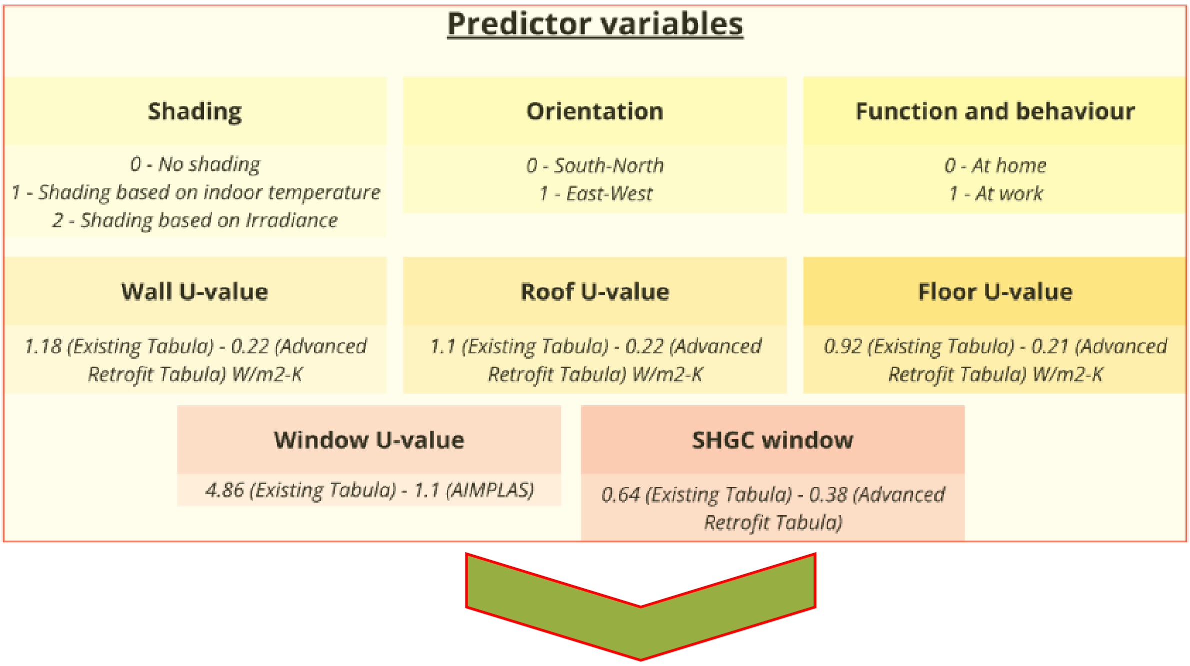
This surrogate model serves as a simplified mathematical representation of the complex simulation models discussed in Section 4 by approximating the relationships between various input parameters and KPIs, it enables swift predictions of building performance outcomes, streamlining the decision-making process for stakeholders without necessitating extensive computational resources. The development of various models, among which are regression techniques have been recognized as a helpful tools to forecast the heat demand of buildings among others. These tools are primarily used to support early design stages regarding insulating envelopes (Marta and Belinda, 2017).

The primary aim of the surrogate model was twofold. Firstly, it was designed to allow real demo cases to adopt the results and calculations derived from our virtual demo cases and validate their decisions based on these results, effectively bridging the gap between simulated environments and real-world applications. This adaptability ensures that insights gained from extensive simulations can be applied to actual buildings, facilitating practical renovations and energy efficiency improvements. Secondly, the surrogate model serves to inform solution developers, especially since not all BIO4EEB solutions are finalized. By providing predictive insights based on existing data, developers can better understand and validate the potential impact of their solutions, refining their approaches during the development processes.

By enhancing efficiency and accessibility, the surrogate model accelerates project timelines and supports a broad range of stakeholders, including those who may not possess specialized expertise in building simulations. It plays an integral role in supporting the development of the BIO4EEB platform, offering quick assessments of BIO4EEB solutions across diverse configurations. This enables stakeholders to explore various renovation options interactively, promoting informed decision-making and facilitating the adoption of BIO4EEB technologies in real-world settings.

The initial surrogate models were constructed using the extensive dataset generated from the detailed energy simulations of approximately 6,000 renovation scenarios for each virtual demo case. This dataset encompassed a wide array of building configurations, material properties, operational settings, and climatic conditions, providing a rich foundation for model development.

The initial step involved data collection and preparation. Simulation results were extracted and organized into structured datasets. Input variables, such as physical properties (e.g., U-values of building components), operational parameters (e.g., shading use, orientation), and occupant behaviors, were identified as features, while the KPIs served as target variables (Figure 6). The predictor variables were based on two extremes of a specific input to incorporate the broadest range of the response variables. To ensure the integrity and reliability of the model, the dataset underwent thorough cleaning to address missing values, inconsistencies, and outliers. Normalization techniques were applied where necessary to facilitate efficient model training and improve convergence. Subsequently, a correlation analysis was performed to identify the most influential input variables affecting each target KPI.



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Response variables

	Energy demand *whole building [kWh/m2]*	
Cooling_GF *cooling demand for ground floor [kWh/m2]*	**Cooling_FF** *cooling demand for first floor [kWh/m2]*	**Cooling_SF** *cooling demand for second floor [kWh/m2]*
Heating_GF *heating demand for ground floor [kWh/m2]*	**Heating_FF** *heating demand for first floor [kWh/m2]*	**Heating_SF** *heating demand for second floor [kWh/m2]*
PMV_GF *predicted mean vote for ground floor [%]*	**PMV_FF** *predicted mean vote for first floor [%]*	**PMV_SF** *predicted mean vote for second floor [%]*
PPD_GF *predicted percentage of dissatisfied for ground floor [%]*	**PPD_FF** *predicted percentage of dissatisfied for first floor [%]*	**PPD_SF** *predicted percentage of dissatisfied for second floor [%]*

Figure 6 Predictor and response variables of the surrogate model

Pearson correlation coefficients were calculated between input features and target variables to assess the strength and direction of linear relationships (example given in Figure 7). This step was conducted to ensure that the models concentrated on variables with substantial impact on building performance.

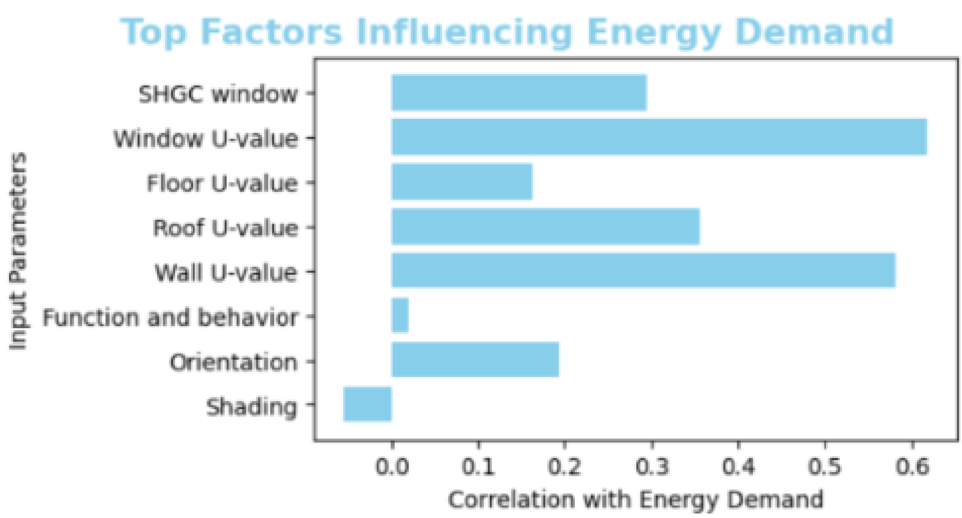

Figure 7 Pearson correlation coefficient results for energy demand as response variable

Linear regression was chosen as the modeling technique due to its simplicity, transparency, and effectiveness in capturing linear relationships inherent in the data. Separate linear regression models were developed for each target KPI, including total energy demand, heating and cooling demands for each floor, and thermal comfort metrics such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD).

The model development process entailed splitting the dataset into training and testing subsets, typically using 80% of the data for training and reserving 20% for testing. The linear regression models were trained on the training dataset using the selected features. Model performance was then evaluated using the coefficient of determination (R^2) on both training and testing datasets to assess predictive accuracy and generalizability. The resulting coefficients were employed to formulate predictive equations for each KPI, providing explicit mathematical relationships between inputs and outputs.

Validation of the surrogate models was conducted by comparing the predicted values against actual simulation results in the testing dataset. Scatter plots were utilized to visualize the agreement between predicted and actual values, with high R^2 values indicating strong model performance and reliability in predictions.

2.6 Application to real demo cases

Building upon the methodologies and surrogate models developed for the virtual demo cases, the BIO4EEB project extends its findings to five real demo cases across Europe. These cases—located in Lithuania, Spain, Germany, the Czech Republic, and France—represent a diverse range of climatic conditions, building typologies, and renovation needs. The application of the surrogate models to these real-world scenarios bridges the gap between theoretical simulations and practical implementations, enabling stakeholders to validate and refine renovation strategies using BIO4EEB solutions.

As described in section 5.6, the surrogate models are designed to predict KPIs such as energy demand and thermal comfort based on input variables like material properties, building orientation, shading devices, and occupant behavior. The Excel datasheet will be provided to the real demo-owners as a Plug&Play tool based on the findings of the virtual demo cases simulations. For the baseline scenario only shading, orientation and function and behavior are requested as an input from a user, after which based on material properties of a building without renovation KPI results are provided. For the renovation scenarios larger dataset is required as shown in Table 2. Consequently using the surrogate model the possible/increase in specific KPI is communicated with the user. The tool offers comparison of up to three case scenarios (Figure 8). This enables them to explore different renovation scenarios, identify the most effective strategies, and make informed decisions that align with their specific goals and constraints.

Table 2 Predictor variables required by the user of the tool

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Notation for predictor variable in the equation	Predictor variable
x_1	Shading (can be 0/1/2)
x_2	Orientation (can be 0/1)
x_3	Function and behaviour (can be
x_4	Wall U-value
x_5	Roof U-value
x_6	Floor U-value
x_7	Window U-value
x_8	SHGC of window

	Surrogate models:	Retrofit cases:						
		Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
Energy demand:	**ED** = 43.503-2.332×x_1+12.885×x_2+1.284×x_3+55.855×x_4+36.513×x_5+20.821×x_6+14.140×x_7+27.993×x_8	203.42	202.37	216.31	Decrease in KPI [%]	2.19	6.36	6.33
Cooling demand GF:	**CD_GF** = 21.595-3.349×x_1+10.140×x_2-11.209×x_3+5.385×x_4-0.689×x_5+0.314×x_6+0.242×x_7+18.220×x_8	35.31	20.75	45.45		4.65	24.34	20.54
Cooling demand FF:	**CD_FF** = 40.659-4.577×x_1+12.821×x_2-15.193×x_3+1.208×x_4-2.321×x_5-5.671×x_6-0.914×x_7+24.522×x_8	44.44	24.67	57.26		5.64	27.12	17.53
Cooling demand SF:	**CD_SF** = 35.962-3.418×x_1+9.507×x_2-11.070×x_3+1.057×x_4+8.371×x_5-3.067×x_6-0.30×x_7+18.963×x_8	53.29	38.80	62.80		2.58	13.71	10.53
Heating demand GF:	**HD_GF** = -33.398+1.325×x_1+1.804×x_2+32.577×x_3+46.099×x_4+15.236×x_5+17.140×x_6+11.064×x_7+2.893×x_8	66.28	100.18	68.08		10.74	10.76	12.56
Heating demand FF:	**HD_FF** = -35.135+1.303×x_1+2.022×x_2+31.796×x_3+47.462×x_4+16.148×x_5+19.049×x_6+10.981×x_7+2.522×x_8	67.00	100.10	69.02		13.41	13.07	14.92
Heating demand SF:	**HD_SF** = -62.852+1.719*x_1+2.362*x_2+36.240*x_3+66.354*x_4+72.793*x_5+34.698*x_6+21.347*x_7+16.861*x_8	180.27	218.23	182.63		-6.17	-3.76	-5.39
PMV GF:	**PMV GF** = 74.328-0.460×x_1-3.895×x_2+3.086×x_3-19.504×x_4+1.832×x_5+1.771×x_6-1.257×x_7+14.997×x_8	76.59	79.21	72.69	Increase in KPI [%]	24.38	34.74	41.25
PMV FF:	**PMV FF** = 71.539+0.722×x_1-5.477×x_2+6.697×x_3-18.519×x_4+1.737×x_5+2.551×x_6-0.643×x_7+8.635×x_8	73.57	80.99	68.09		25.02	36.64	48.93
PMV SF:	**PMF SF** = 65.680-0.222×x_1-4.991×x_2+0.943×x_3-13.135×x_4-11.060×x_5+2.747×x_6-0.497×x_7+7.973×x_8	55.44	56.17	50.45		25.47	26.12	35.12
PPD GF:	**PPD GF** = 70.787-0.622×x_1-4.285×x_2+2.366×x_3-17.577×x_4+1.484×x_5+1.332×x_6-1.1×x_7+16.085×x_8	74.20	75.94	69.91		22.80	32.65	40.37
PPD FF:	**PPD FF** = 68.039+0.608×x_1-6.063×x_2+6.004×x_3-17.002×x_4+1.416×x_5+2.106×x_6-0.607×x_7+10.899×x_8	71.31	77.92	65.25		24.68	34.29	47.57
PPD SF:	**PPD SF** = 64.662-0.168×x_1-4.982×x_2+0.915×x_3-13.002×x_4-11.062×x_5+2.570×x_6-0.435×x_7+6.517×x_8	53.66	54.41	48.68		26.07	26.73	34.74

Figure 8 Representation of the Excel tool for real demo case owners

In practice, applying the surrogate models to real demo cases will involve several key steps:

1. **Data Collection and Customization**: Detailed information about each building's characteristics—such as geometric configurations, existing material properties, and occupancy patterns—will be collected. This data will be used to customize the input variables in the surrogate models, ensuring that predictions are tailored to the unique conditions of each building.
2. **Scenario Analysis**: Multiple renovation scenarios incorporating BIO4EEB solutions will be simulated using the surrogate models. Stakeholders can quickly compare the predicted outcomes of different options, considering factors like energy savings, improvements in occupant comfort, and cost-effectiveness.
3. **Optimization of Renovation Strategies**: By identifying the most impactful variables through the surrogate models, stakeholders can prioritize specific interventions. For example, the models may reveal that insulation applied at the upper floors of the low-rise building could more significantly impact the heating demand than on the ground floor, guiding the focus of renovation efforts.
4. **Integration into Validation Processes**: The surrogate models will facilitate data-driven validation by providing clear, quantitative predictions of performance outcomes. This supports stakeholders in selecting renovation strategies that maximize benefits while meeting practical considerations such as budget and timelines.

Furthermore, the insights gained from applying the surrogate models to real demo cases will inform and help validate design choices in the ongoing development of BIO4EEB solutions. Solution developers can use the predictive capabilities of the models to understand how their products perform in various contexts, guiding refinements and innovations. As more data becomes available from real-world applications, the models themselves can be validated and enhanced, improving their predictive accuracy and expanding their applicability.

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As this part is currently underway, reporting on how this was actually applied at all the demo cases will be part of the following deliverable.

3 Data collection and analysis

In Section 6. the actual data collected and used for the simulations will be described and provided, as well as how this data was handled during simulation.

3.1 Data collection processes

A part of the data used for the development of simulation models providing analysis of virtual demo-cases was collected from the web pages of the Intelligent Energy Europe (IEE) Project TABULA (2009 - 2012), "Typology Approach for Building Stock Energy Assessment" ("TABULA WebTool," n.d.).
During the European IEE project, TABULA typologies of residential buildings were created for several European countries. Each national typology is presented as a matrix in which model buildings are grouped according to their size, age, and other parameters. The main matrix offers an overview of the dwelling types included in the housing typology. All dwelling types are characterised by a few parameters that are not immediately visible in the main matrix.

These model buildings are described in detail for each country in "Building Typology Brochures," published in the respective national languages. The national brochures include a two-page spread for each model building, graphically displaying information on energy consumption and the impact of implemented energy saving measures. An example is provided for Belgium in Figure 9.

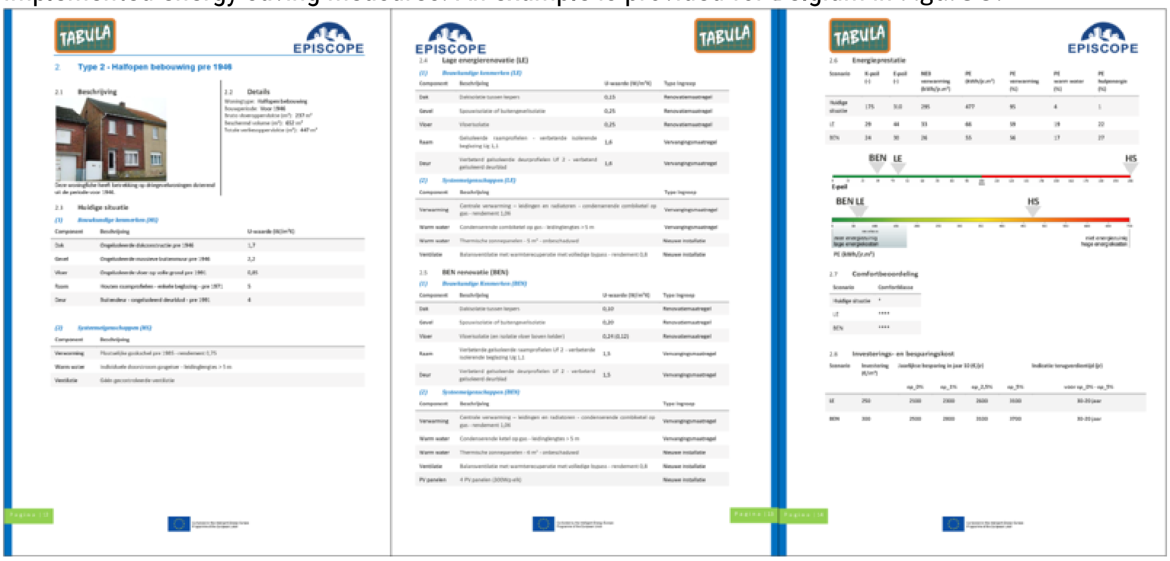

Figure 9 Example of Building Typology Brochure

The software tool "TABULA Webtool" allows online calculations for model buildings from all countries, enabling the input of various combinations of measures on the building envelope along with measures on heating and hot water systems. The core of TABULA Webtool is a simple and transparent reference procedure for calculating energy demand, energy consumption, and evaluating the type of energy used (primary energy, carbon dioxide, costs).
In addition to the reference calculation used for comparison between countries, it is important to consider typical levels of actual consumption and calibrate the calculated energy consumption – with

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the goal of enabling realistic assessments of energy savings and heating costs. Based on residential building typology, building stock models have been developed for several countries, allowing for projections of actual national building stock consumption and energy-saving potential.

To exchange valid information between countries uniform definitions were necessary. Therefore, in Table 9 the following common definitions and data structure were developed:

Table 3 Common definitions and data structure for TABULA data collection

1	**Parameters for Classification**	
	1 Country	country identification
	2 Region	> **national** > **country region, if necessary**
	3 Construction Year Class	for each country definition of periods: from {year} … to … {year}
	4 Building Size Class	**categories:** > **single family house** > **terraced house** > **multi-family house** > **apartment block**
	5 Additional Parameter	optional/for example: > **semi-detached / end terraced house** > **mid-terraced house** > **tower building** > **half-timbered building** > **panel building** > **etc.**
2	**Reference area**	floor area based on internal dimensions
3	**Calculation method building**	calculation of energy need for space heating: > **seasonal method according to EN ISO 13790** > **one-zone model**
4	**Boundary conditions**	to be defined by each partner for his country > **external temperature** > **solar radiation** standard values: > **room temperature** > **air exchange rate** > **internal heat gains** > **values for red. factors solar radiation (shading, …)**
5	**Thermal envelope**	external dimensions
6	**U-values**	to be provided by each partner
7	**Consideration of thermal bridging**	categories (impact on building thermal performance) > **low** > **medium** > **high**
8	**Calculation method supply system**	balance type: EN 15316, level B tabular values for subsystems

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		determined by applying national procedures/standards: > **heat generation>energy expenditure factors** > **heat storage: annual losses in kWh/m²a** > **heat distribution (including heat emission): annual losses in kWh/m²a)** > **auxiliary energy: annual electric consumption in kWh/(m2.a)** > **(for space heating systems and DHW systems each)**
9	**Delivered energy/fuel**	reference to gross calorific value

<u>Data collection in Hungary</u>

The Hungarian housing typology was developed by a team of professors and associates at the Budapest University of Technology and Economics.

This typology identifies 15 distinct types of buildings, ranging from small, traditional family houses to modern high-rise residential buildings. The classification of Hungary's residential building stock is based on technological changes over time and includes the following periods:

- Built before 1944;
- Built between 1944-1979;
- Built between 1980-1989;
- Built between 1990-2005;
- Built after 2006 (Tamás et al., 2014).

The traditional building method in Hungary is typically one-storey family house with an empty attic In Budapest, the capital, multi-storey residential blocks in the eclectic style are prominent, though they are less common in other parts of the country. A significant portion of Hungary's building stock dates to before the 1950s. Moreover, during the communist period (i.e., after 1945) substantial number of uniform one- and multi-storey family houses were built in villages and suburbs so called "Kádár-cube" ("Cubic houses"). Their name is associated with the square-shaped floor plan and characterised by poor energy performance due to absence of the thermal insulation (Tamás et al., 2014). Hence, the choice of virtual demo case with the characteristic of the "Kádár-cube" is responding to a substantial part of the building stock in the country.

<u>Data collection in Belgium</u>

The Belgian housing typology is a set of building types related to the Belgian housing stock, organised within a specific system and for which a set of characteristics with relevance to the energy consumption for building operations is defined.

Several government authorities collect statistical data about the Belgian building stock. The following <u>general data</u> sources containing basic data about residential buildings (dwelling type, surface area, construction year, frequency, condition of the buildings, etc.) in Belgium were explored:

- Land registry statistics for the building stock
- NIS statistics containing data from building permit procedures
- NIS General Socio-economic Survey 2001
- NIS General Population and Housing Censuses of 1981 and 1991

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The collected data enabled to divide the Belgian housing stock into classes defined through:
- Dwelling types (detached, semi-detached, terrace houses, apartments)
- Construction periods
- Dwelling surface area
- Heating system
- Energy carriers

The data sources were also used to define dwelling frequencies for the different dwelling classes. Consequently, these data sources were used to compose the main matrix of the housing typologies. This main matrix is then the collection of various dwelling types (detached, semi-detached, terraced houses, multi-family dwellings and apartment blocks) across various constructions periods. The matrix also specifies the dwelling frequencies, i.e. the number of dwellings as a fraction of the total Belgian housing stock. Based on the assessment of distribution of different building typologies in Belgium, the TH built before 1945 present substantial portion (Figure 10). Hence in the case of virtual demo cases this building type is assessed. Because TABULA project is nearly 15 years old it is obvious that some data need to be updated. This comment is valid especially for the dwelling frequencies data.

BELGIUM	freestanding			semi-detached			terraced			flats		
<1945	5,95%	20,29%	269.771	8,26%	41,56%	375.000	16,90%	66,12%	766.884	6,86%	27,15%	311.066
1946-1970	6,82%	23,26%	309.263	6,08%	30,57%	275.838	5,35%	20,95%	242.952	6,32%	25,03%	286.826
1971-1990	9,84%	33,58%	446.481	3,48%	17,52%	158.123	1,93%	7,56%	87.706	4,96%	19,65%	225.136
1991-2007	6,70%	22,87%	304.057	2,06%	10,35%	93.345	1,37%	5,37%	62.307	7,12%	28,18%	322.897
total	29,30%	100%	1.329.572	19,88%	100%	902.306	25,56%	100%	1.159.849	25,25%	100%	1.145.925
FLANDERS	freestanding			semi-detached			terraced			flats		
<1945	4,76%	14,75%	125.772	5,58%	27,33%	147.381	13,97%	57,50%	368.916	4,27%	18,55%	112.769
1945-1970	8,19%	25,38%	216.419	7,54%	36,94%	199.174	6,18%	25,46%	163.328	5,57%	24,21%	147.202
1971-1990	11,42%	35,38%	301.722	4,50%	22,03%	118.810	2,48%	10,20%	65.452	4,68%	20,33%	123.631
1990-2007	7,90%	24,49%	208.790	2,79%	13,69%	73.827	1,66%	6,84%	43.858	8,50%	36,92%	224.471
total	32,28%	100,00%	852.703	20,41%	100%	539.192	24,29%	100%	641.554	23,02%	100%	608.074
WALLOON REG.	freestanding			semi-detached			terraced			flats		
<1945	9,60%	35,23%	142.105	14,96%	60,81%	221.483	21,14%	68,03%	313.027	6,65%	38,94%	98.524
1945-1970	6,10%	22,38%	90.267	4,69%	19,09%	69.517	3,99%	12,84%	59.075	3,49%	20,40%	51.614
1971-1990	7,83%	28,75%	115.961	3,05%	12,38%	45.103	2,89%	9,31%	42.850	2,90%	17,00%	43.006
1990-2007	3,71%	13,63%	54.991	1,90%	7,72%	28.123	3,05%	9,81%	45.150	4,04%	23,67%	59.886
total	27,24%	100%	403.325	24,60%	100%	364.226	31,07%	100%	460.102	17,09%	100%	253.030
BCR	freestanding			semi-detached			terraced			flats		
<1945	0,45%	33,18%	1.894	1,46%	39,97%	6.136	20,27%	77,52%	84.941	27,12%	39,41%	113.636
1946-1970	0,62%	45,15%	2.577	1,71%	46,56%	7.147	4,90%	18,75%	20.549	24,27%	35,27%	101.699
1971-1990	0,18%	13,23%	755	0,27%	7,46%	1.146	0,48%	1,83%	2.000	9,41%	13,67%	39.409
1991-2007	0,11%	8,44%	482	0,22%	6,00%	921	0,50%	1,90%	2.077	8,03%	11,66%	33.627
total	1,36%	100%	5.708	3,66%	100%	15.350	26,15%	100%	109.567	68,82%	100%	288.370

*Figure 10 Residential building stock in Belgium with respective distribution of building typologies according to SuFiQuad project (*IEE TABULA-Typology Approach for Building Stock Energy Assessment*, 2011)*

A few targeted surveys and inspections have been conducted in Belgium from the 1990s up to the present days with particular focus on the housing quality and the energy-efficiency of the dwellings. These surveys, mainly organized on a regional level and thus separately for the Flanders, Brussels or Walloon region, reveal data about the dwelling condition, the level of insulation of the building envelope and the type of heating systems installed. It is worth mentioning, however, that these available surveys and studies in most cases provided rather qualitative than quantitative results. Therefore, the acquired data had to be completed with data from other sources such as Energy Advice Procedure (EAP) and Energy Performance Certificate databases.

Data collection in Italy

The residential Italian building stock was characterized through the definition of the types of building construction elements and the types of building systems.
The types of Italian building construction elements were identified through the experience (e.g. advices from experts of the sector), with the support of scientific-technical literature, statistical data and technical standards.
According to the year of construction and number of apartments in the building, the building stock of Italy can be characterised as shown in Figure 11. The following specifications define the criteria of classification of the building construction elements and their thermos-physical parameters:

- Massive structures are typical for the Italian housing stock
- The traditional materials which constitute the building components are usually solid or hollow bricks and concrete
- The construction period is related to the thermal insulation level of the building envelope components and corresponding standards and regulations.
- It is worth highlighting the following features of the housing stock:
    - Insulation materials have not been used until 1976 when the first thermal regulation came into force.
    - The typical thermal transmittance of walls from the period 1976-1991 is approximately U_{wall} = 0,8 $W/m^2.K$
    - The typical thermal transmittance of walls from the period 1991-2005 is approximately U_{wall} = 0,6 $W/m^2.K$
    - The thermal transmittance of walls from the period 2005 onwards is defined by the decree N°192/2005 later integrated with N° 311/2006 and with 59/2009. The most significant advancement in the new national regulations was adopted in July 2009, when a new ministerial decree with the National Guidelines on Energy Certification on Buildings entered into force The typical value is approximately U_{wall} = 0,34 $W/m^2.K$

Taking into account above-listed characteristics of the Italian building stock, choice of MFH built between 1961 and 1975 for virtual demo case would correspond to a representative residential building type with great potential of replicability.

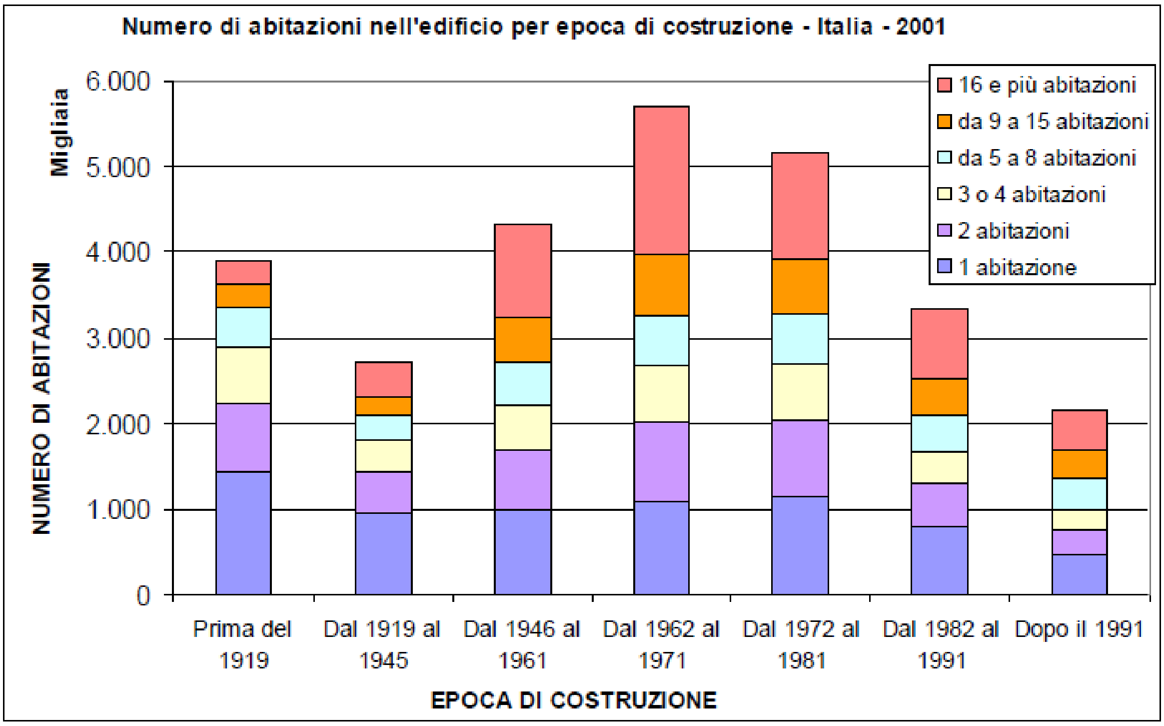

Figure 11 Characteristics of Italian building stock with respect to construction periods and number of flats in the residential building (Corrado et al., 2014)

3.2 Data requirements for base cases

The detailed description of the predictor variables has been provided in the previous sections. Hence, in this section solely envelope characteristics of the virtual demo cases will be provided, which have been based on the Tabula Webtool data ("TABULA WebTool," n.d.). In the section **Hiba! A hivatkozási forrás nem található.** detailed description of the data collection

processes is presented. The base cases are corresponding to the envelope characteristics for the buildings without any renovation measures applied (i.e., Existing state in Tabula Webtool):

- **Hungary** - The existing envelope characteristics of a typical unrenovated SFH from the period of 1945-1979 is given in Table 4 regarding walls, roof and floors. Characteristics of the existing windows are given in Table 4.
- **Belgium** - The existing envelope characteristics of a typical unrenovated TH from the period until 1945 is given in Table 4 regarding walls, roof and floors. Characteristics of the existing windows are given in Table 4.
- **Italy** - The existing envelope characteristics of a typical unrenovated MFH from the period of 1961-1975 is given in Table 4 regarding walls, roof and floors. Characteristics of the existing windows are given in Table 4.

Table 4 Demo buildings' base case wall, roof and floor characteristics

Component	Layers	Thickness [m]	Thermal conductivity [W/m-K]	Density [kg/m^3]	Specific heat [J/kg-K]	U-value [W/m^{2}K]
HUNGARY						

Wall	External plaster	0.02	0.9	1800	1000	**1.41**
	Solid brick	0.38	0.75	1920	800	
	Internal plaster	0.02	0.7	1400	1000	
	Total thickness:	0.42				
Roof	Clay tiles	0.06	0.8	1890	880	**1.26**
	Wooden planks	0.025	0.18	560	2500	
	Timber batten cavity	0.035	0.13			
	Wooden planks	0.025	0.18	560	2500	
	Internal plaster	0.02	0.7	1400	1000	
	Total thickness:	0.165				
Floor	Wooden flooring	0.03	0.12	1200	540	**1.04**
	Concrete	0.08	1.2	2200	840	
	Reinforced concrete	0.1	1.55	2400	840	
	Gravel	0.15	0.36	1840	840	
	Total thickness:	0.36				
BELGIUM						
Wall	External plaster	0.02	0.9	1800	1000	**2.22**
	Brick	0.2	0.8	2050	900	
	Internal plaster	0.02	0.7	1400	1000	
	Total thickness:	0.24				
Roof	Clay tiles	0.12	0.8	1890	880	**1.79**
	Timber batten cavity	0.035	0.13			
	Total thickness:	0.155				
Floor	Cement flooring	0.015	0.9	2100	840	**1.54**
	Screed	0.07	0.41	2200	1000	
	Reinforced concrete	0.25	1.55	2400	840	
	Internal plaster	0.02	0.7	1400	1000	
	Total thickness:	0.355				
Ground Floor	Cement flooring	0.015	0.9	2100	840	**1.64**
	Screed	0.07	0.41	2200	1000	
	Unreinforced concrete	0.15	1.13	2000	840	
	Sand bed	0.05	0.4	1800	840	
	Total thickness:	0.285				
ITALY						
Wall	External plaster	0.02	0.9	1800	1000	**1.18**
	Hollow brick 1	0.12	0.39	800	1000	
	Air cavity	0.08				
	Hollow brick 2	0.06	0.3	800	790	
	Internal plaster	0.02	0.7	1400	1000	
	Total thickness:	0.3				

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Roof	Terracotta tiles	0.02	0.8	1890	880	**1.1**
	Timber batten cavity	0.05	0.13			
	Concrete	0.04	1.4	2240	840	
	Brick and concrete slab	0.2	0.68	1150	1000	
	Internal plaster	0.02	0.7	1400	1000	
	Total thickness:	0.33				
Floor	Wooden flooring	0.02	0.12	1200	540	**0.92**
	Subfloor	0.04	0.7	800	800	
	Screed	0.04	0.41	2200	1000	
	Brick and concrete slab	0.25	0.54	1150	1000	
	Internal plaster	0.02	0.7	1400	1000	
	Total thickness:	0.37				

Table 5 Demo buildings' base case windows characteristics

Demo case	Description	SHGC [-]	Tvis [-]	U-value [W/m²K]
HUNGARY	Single glazing with box type wooden frame	0.64	0.65	**3.01**
BELGIUM	Single glazing with wooden frame	0.64	0.65	**5.00**
ITALY	Single glazing with wooden frame	0.64	0.65	**4.86**

3.3 Data requirements for renovation scenarios and BIO4EEB solutions

In regards to the refurbishment simulations following steps were conducted for evaluation of the BIO4EEB solutions:

1. The envelope data presented in Table 6, based on advanced refurbishment scenarios from the TABULA Webtool ("TABULA WebTool," n.d.), were simulated using glass wool as the primary insulation material. In the case of windows, the characteristics of those adopted for advanced refurbishment are given in Table 7. Glass wool was chosen as the representative material for the "business-as-usual" scenario due to its widespread use in the European thermal insulation market, where it accounts for approximately one-third of the total market share (IAL, 2023; Pavel and Blagoeva, n.d.). Adopted characteristics of the glass wool are:
    a. Thermal conductivity: 0.04 W/m-K;
    b. Density: 200 kg/m³;
    c. Specific heat: 670 J/kg-K.

Table 6 Demo buildings' advanced refurbishment wall, roof and floor characteristics

Component	Glass wool thickness [m]	Existing state U-value [W/m-K]	Advanced refurbishment U-value [W/m-K]
	HUNGARY		

Wall	0.16	1.41	0.21
Roof	0.28	1.26	0.20
Floor	No changes for advanced refurbishment based on Tabula Webtool [2]		
BELGIUM			
Wall	0.14	2.22	0.40
Roof	0.26	1.79	0.39
Floor	0.08	1.54	0.37
Ground floor	No changes for advanced refurbishment based on Tabula Webtool [2]		
ITALY			
Wall	0.13	1.18	0.22
Roof	0.15	1.1	0.22
Floor	0.15	0.92	0.21

Table 7 Demo buildings' base case windows characteristics

Demo case	Description	SHGC [-]	Tvis [-]	U-value [W/m²K]
HUNGARY	Triple glazing, low-e coating and argon gas filling	0.38	0.47	**1.00**
BELGIUM	Double glazed, argon filled, low E, insulated frame	0.38	0.47	**1.60**
ITALY	Low-e triple glazing, argon filled, wood frame	0.38	0.47	**1.73**

2. Using the U-values for the Advanced refurbishment case scenarios, the thickness of the BIO4EEB solutions is determined. The Posidonia core panel is available in fixed thicknesses of either 10 cm or 20 cm, while all other solutions are considered flexible in terms of their potential thickness. The characteristics of the BIO4EEB products were provided by their respective developers:
    a. BioPUR spray + KlimaPUR windows – Indresmat;
    b. PLA foam – Aimplas;
    c. Posidonia core panel – Sophia and Starcell.

It is important to note that due to the varying technology readiness levels of these solutions, the provided characteristics may evolve. Any updates will be addressed in the second version of this deliverable. Currently, facade modules developed by Goyer have not been included in the simulations because of insufficient data. These modules, however, will also be incorporated into the next version of the deliverable. For window solutions, two types developed by Indresmat have been characterized based on their currently available properties. These are applied as refurbishment options in line with the provided data.

Table 8 Demo buildings' base case windows characteristics

Component/BIO4EEB product	BIO4EEB product				
	Thickness [m]	Thermal conductivity [W/m-K]	Density [kg/m³]	Specific heat [J/kg-K]	U-value [W/m²K]
HUNGARY					

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Wall/BioPUR spray	0.07	0.022	40	1600	0.27
Wall/PLA foam	0.09	0.027	30	1400	0.26
Wall/Posidonia	0.10	0.038	100	1200	0.31
Roof/BioPUR spray	0.08	0.022	40	1600	0.23
Roof/PLA foam	0.10	0.027	30	1400	0.23
Roof/Posidonia	0.10	0.038	100	1200	0.30
BELGIUM					
Wall/BioPUR spray	0.07	0.022	40	1600	0.29
Wall/PLA foam	0.09	0.027	30	1400	0.28
Wall/Posidonia	0.10	0.038	100	1200	0.34
Roof/BioPUR spray	0.08	0.022	40	1600	0.27
Roof/PLA foam	0.10	0.027	30	1400	0.24
Roof/Posidonia	0.10	0.038	100	1200	0.31
Floor/BioPUR spray	0.08	0.022	40	1600	0.26
Floor/PLA foam	0.10	0.027	30	1400	0.23
Floor/Posidonia	0.10	0.038	100	1200	0.31
ITALY					
	0.07	0.022	40	1600	0.25
Wall/PLA foam	0.09	0.027	30	1400	0.24
Wall/Posidonia	0.10	0.038	100	1200	0.30
Roof/BioPUR spray	0.08	0.022	40	1600	0.22
Roof/PLA foam	0.10	0.027	30	1400	0.22
Roof/Posidonia	0.10	0.038	100	1200	0.29
Floor/BioPUR spray	0.08	0.022	40	1600	0.22
Floor/PLA foam	0.10	0.027	30	1400	0.22
Floor/Posidonia	0.10	0.038	100	1200	0.29

Table 9 Demo buildings' base case windows characteristics

Product	**Description**	**SHGC [-]**	**Tvis [-]**	**U-value [W/m²K]**
KlimaPUR W1	Low emissive glass+solar control	0.40	0.69	**1.10**
KlimaPUR W2	Low emissive glass	0.60	0.81	**1.20**

.

3.4 Data quality and validation

Ensuring the quality and reliability of input data is essential for the accuracy of our simulation models and the validity of our results. As detailed in Section 3.3, our primary data sources were reputable and authoritative, predominantly the TABULA WebTool ("TABULA WebTool," n.d.), which offers comprehensive building typologies across Europe.

Where the TABULA data did not fully meet our requirements, we supplemented it with additional information from other reliable sources. For instance:

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- Belgium: We incorporated data from national statistical agencies, regional housing surveys, and Energy Performance Certificate databases (Section 3.3). These sources provided detailed insights into dwelling frequencies, construction elements, and energy efficiency measures specific to the Belgian housing stock.
- Italy: Supplementary information was gathered from scientific and technical literature, statistical data, and national technical standards, as discussed in Section 3.3. This helped define the types of building construction elements and systems prevalent during different construction periods.

To validate the collected data, we performed basic checks to identify and address any inconsistencies or anomalies:

- Outlier Detection: We reviewed key parameters such as U-values, material properties, and building dimensions to identify values that deviated significantly from expected ranges based on known building characteristics and standards. Any anomalies were investigated and corrected as necessary.
- Cross-Referencing: Data from supplementary sources were cross-checked against TABULA data to ensure consistency. Discrepancies were resolved by consulting the most reliable sources available.

By relying on reputable sources and implementing these validation steps, we aimed to enhance the credibility of our findings and support the project's objectives effectively. This approach ensured that our simulation models were built on a solid foundation of accurate and reliable data, contributing to the overall quality of the project outcomes.

3.5 User archetypes

To accurately simulate a building's energy performance, specialized software must closely replicate occupant behavior. Assessing how user behavior impacts heating performance is essential for constructing precise energy models. In our second deliverable, we will implement comprehensive user archetypes developed in D2.3 for each virtual demo case.

These archetypes include detailed characteristics such as occupancy patterns, lighting usage, shading practices, window operation, equipment use, and thermostat adjustment habits, all of which will enhance the accuracy of our modeling.

4 Simulation results and evaluation

The simulation results are based on 6,000 case scenarios, incorporating a range of predictor variables detailed in Sections 2 and 3. For each demonstration case, Excel sheets containing 6,000 individual simulations are imported into Python. There, an analysis is conducted to calculate the Pearson correlation coefficient for each KPI considering predictor variables (Figure 6). Following this, a multiple linear regression model is developed for each KPI using 80% of the simulations as training data. The model's accuracy is then evaluated using the remaining 20% as test data. In the subsequent sections, the surrogate models created for each demo case will be presented, along with the respective coefficients of determination (R^2) and correlation matrices. Upon examining the surrogate models, it was observed that their accuracy decreases as the total number of interventions is reduced. This highlights the need for an expanded dataset to improve the predictive capability of the models. For example, scenarios with only a single component intervention (e.g., floor refurbishment alone) account for less than 1% of the simulations for each component, resulting in lower model reliability. To address this, the surrogate models will be updated by incorporating a greater variety of scenarios, enabling more robust and accurate predictions.

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While some of the predictor variables have negligible influence on the KPIs, in this version of the deliverable all predictor variables are used to develop surrogate models.

4.1 Hungary

As the first step in the results analysis, the Pearson correlation coefficients were determined for each KPI to assess the magnitude of influence of the predictor variables. Envelope characteristics, such as the U-values of building components and the SHGC of windows, emerged as the most significant predictors for energy and heating demand (Figure 12). For heating demand, functional and behavioural factors exhibited a greater impact compared to their influence on overall energy demand. Conversely, for cooling demand, the floor U-value was identified as the most influential parameter among the envelope characteristics. In contrast, roof and wall U-values demonstrated the strongest impact on thermal comfort-related KPIs (Figure 13). The energy simulation results for the " Kádár-cube" residential building in Hungary indicate that refurbishing the floor, walls, and roof is the most effective strategy for simultaneously improving energy efficiency and occupant comfort.

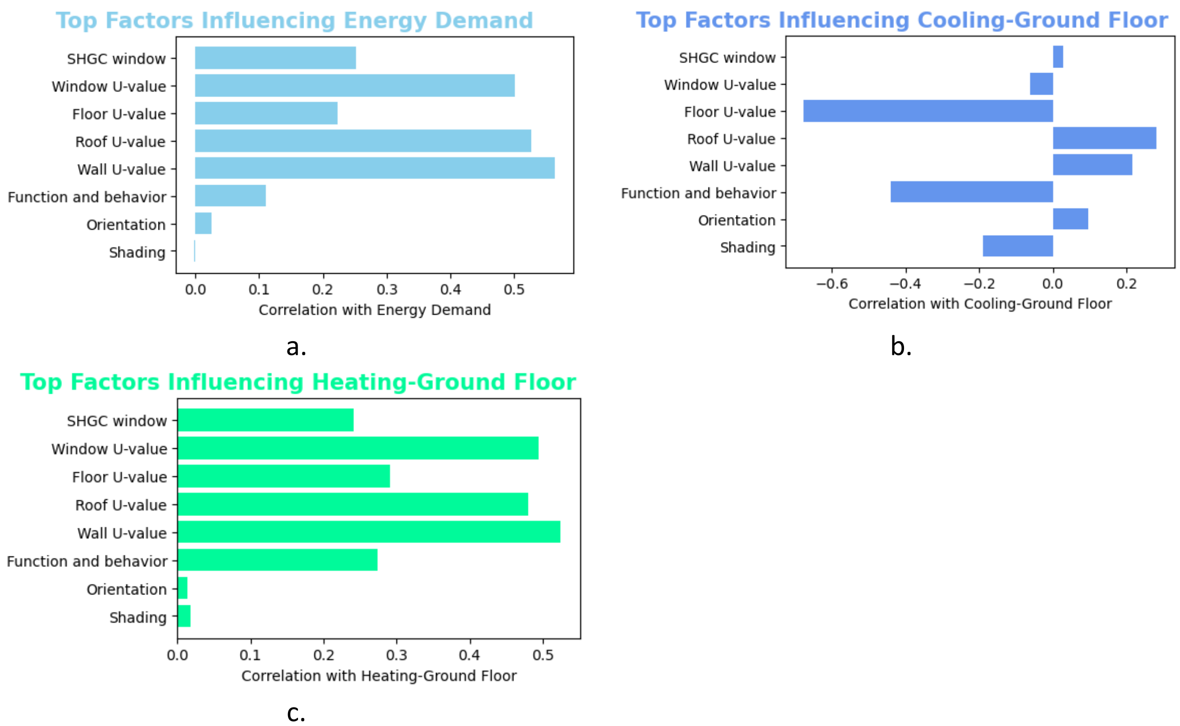


Figure 12 Correlation matrix of the predictor variables with the energy demand related KPIs including a. overall energy demand; b. cooling and c. heating demand for Hungarian demo case

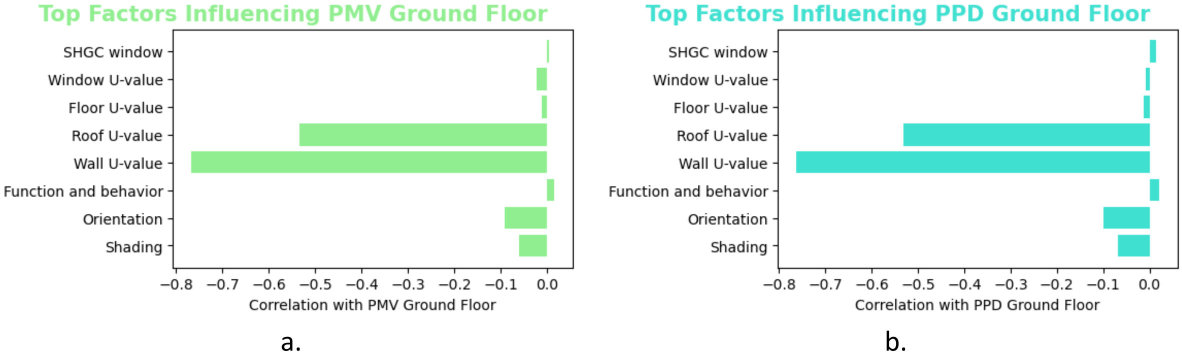


Figure 13 Correlation matrix of the predictor variables with the comfort related KPIs including a. PMV and b. PPD for Hungarian demo case

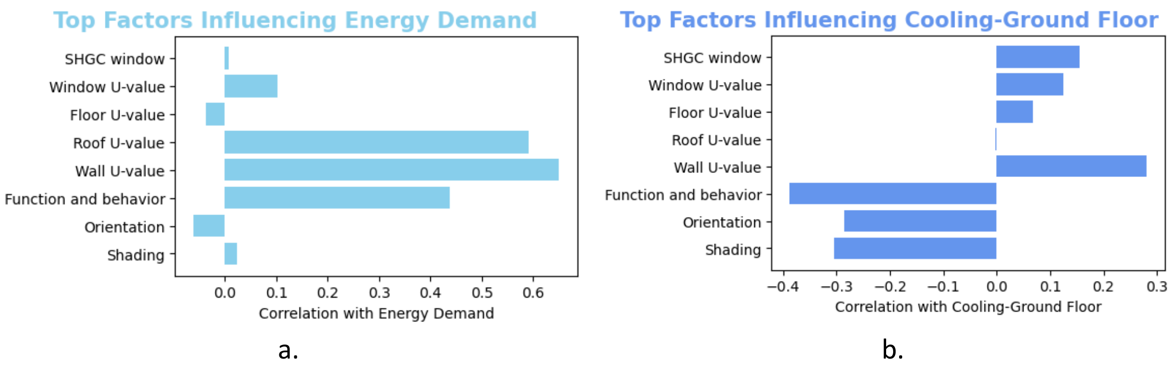
Taking into account the coefficient of determination for both test and training data, the surrogate models based on multiple linear regression for each KPI are shown in Table 12. The predictor variable notations are consistent with those presented in Table 2. The surrogate models are most successful in predicting heating and energy demand (R^2 above 0.9), while for cooling demand and thermal comfort KPIs, the accuracy is lower but still above 0.8.

Table 10 Surrogate models for Hungarian virtual demo case

KPI [unit]	**Surrogate model**	**R^2 (training data)**	**R^2 (test data)**
Energy demand [kWh/m²]	$27.391 + 0.028x_1 + 3.681x_2 + 18.205x_3 + 66.780x_4 + 104.017x_5 + 47.038x_6 + 52.215x_7 - 38.890x_8$	0.9138	0.9089
Cooling demand [kWh/m²]	$27.481 - 2.071x_1 + 1.810x_2 - 7.860x_3 + 4.260x_4 + 6.111x_5 - 15.804x_6 - 1.253x_7 + 8.307x_8$	0.8334	0.8372
Heating demand [kWh/m²]	$-54.988 + 2.099x_1 + 1.872x_2 + 45.837x_3 + 63.912x_4 + 97.905x_5 + 62.842x_6 + 53.467x_7 - 47.200x_8$	0.9150	0.9082
PMV [%]	$78.774 - 0.830x_1 - 2.104x_2 + 0.354x_3 - 19.480x_4 - 15.070x_5 - 0.428x_6 - 0.520x_7 + 2.831x_8$	0.8880	0.8836
PPD [%]	$74.599 - 0.875x_1 - 2.106x_2 + 0.445x_3 - 17.978x_4 - 13.932x_5 - 0.452x_6 - 0.302x_7 + 2.884x_8$	0.8812	0.8767

4.2 Belgium

Envelope characteristics, specifically roof and wall U-values emerged as the most significant predictor variables for energy and heating demand (Figure 14). In contrast, for cooling demand, the floor U-value and window's characteristics were identified as influential parameters among the envelope characteristics. Regarding thermal comfort-related KPIs, roof and wall U-values demonstrated the strongest impact (Figure 15). The energy simulation results for the TH in Belgium constructed prior to World War II, suggest that refurbishing the walls and roof is the most effective strategy for simultaneously enhancing energy efficiency and occupant comfort..



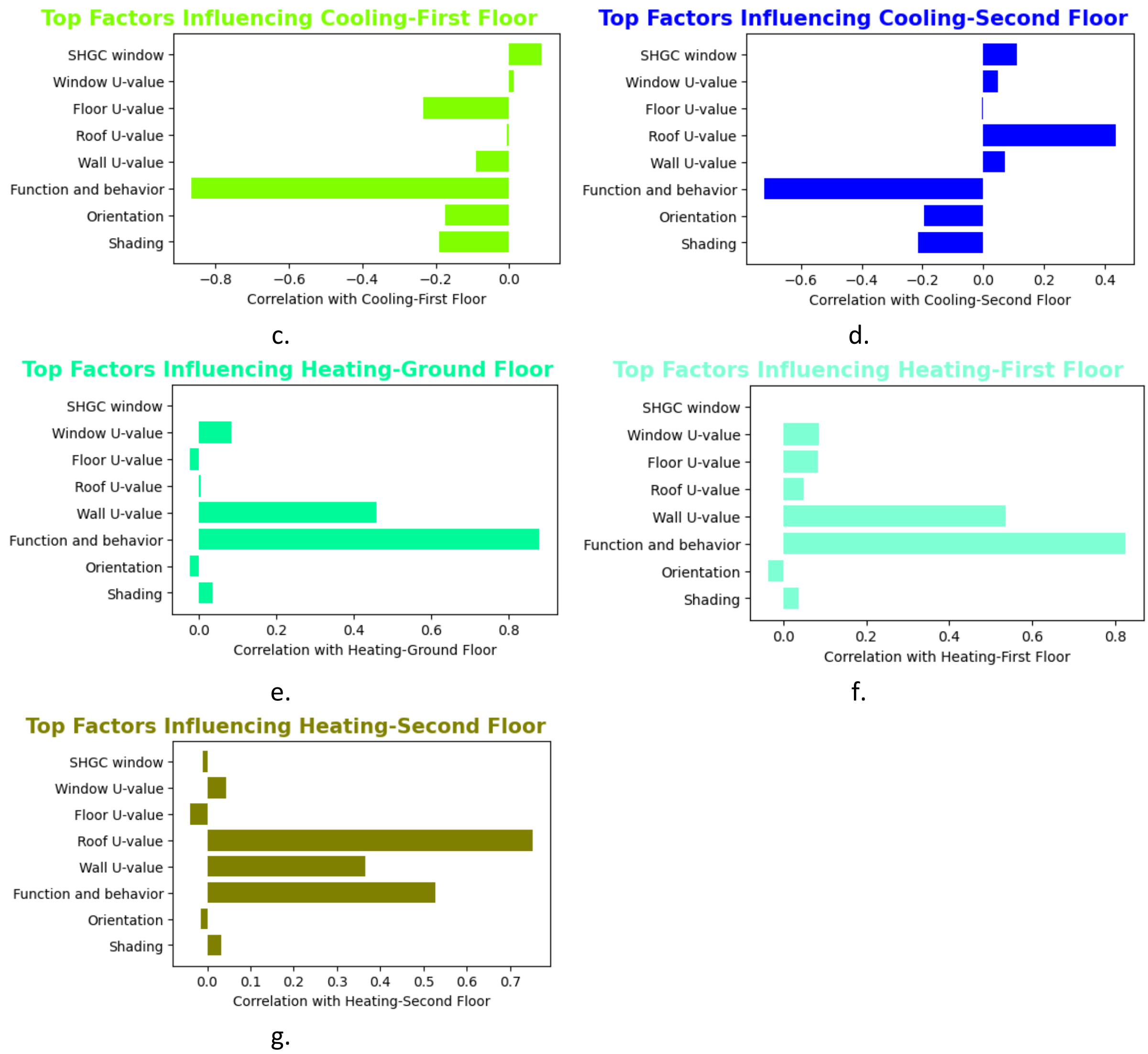
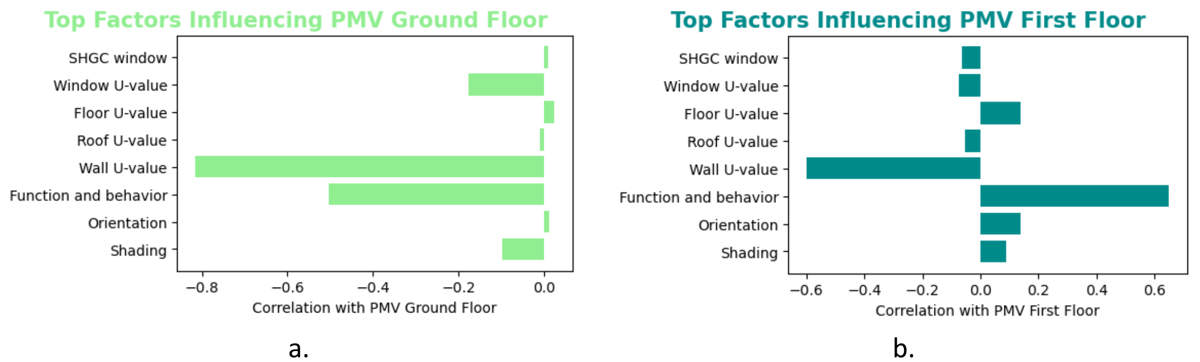
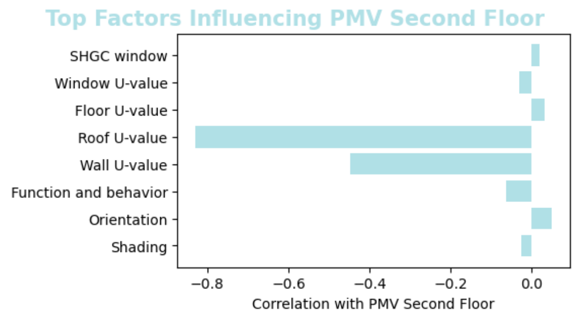


Figure 14 Correlation matrix of the predictor variables with the energy demand related KPIs including a. overall energy demand; cooling for b. ground, c. first and d. second floor and heating for e. ground, f. first and g. second floor for Belgian demo case





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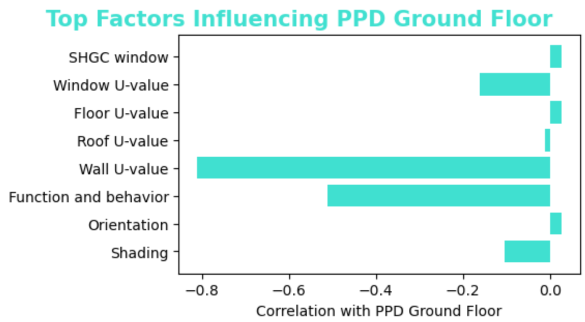

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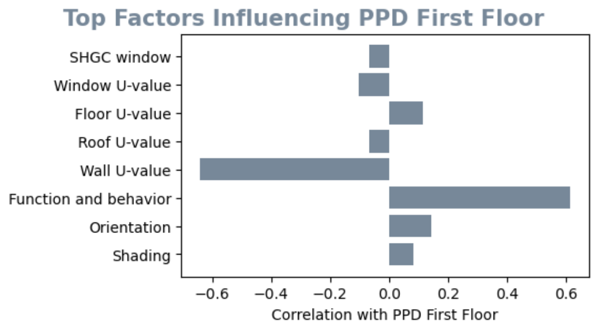
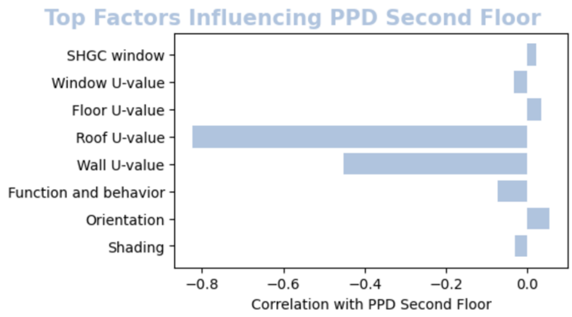


e.



f.

Figure 15 Correlation matrix of the predictor variables with the comfort related KPIs including PMV for a. ground, b. first and c. second floor and PPD for d. ground, e. first and f. second floor for Belgian demo case

Taking into account the coefficient of determination for both test and training data, the surrogate models based on multiple linear regression for each KPI are shown in Table 11. The predictor variable notations are consistent with those presented in Table 2. The surrogate models are most successful in predicting heating and energy demand (R^2 above 0.9), while for cooling demand and thermal comfort KPIs, the accuracy is lower with the exception of PMV and PPD fro ground floor. The cooling demand for ground floor is associated with the lowest accuracy, which will be further investigated.

Table 11 Surrogate models for Belgium virtual demo case

KPI [unit]	**Surrogate model**	**R^2 (training data)**	**R^2 (test data)**
Energy demand [kWh/m²]	$90.578 + 0.553x_1 - 2.403x_2 + 17.387x_3 + 10.593x_4 + 19.553x_5 - 1.434x_6 + 1.574x_7 - 10.868x_8$	0.9824	0.9810
Cooling demand ground floor [kWh/m²]	$0.21 - 0.166x_1 - 0.261x_2 - 0.349x_3 + 0.15x_4 + 0x_5 + 0.069x_6 + 0017x_7 + 0.556x_8$	0.4355	0.4337
Cooling demand first floor [kWh/m²]	$14.123 - 1.491x_1 - 2.257x_2 - 11.328x_3 - 0.507x_4 - 0.086x_5 - 3.016x_6 - 0.15x_7 + 6.908x_8$	0.8878	0.8858
Cooling demand second floor [kWh/m²]	$2.45 - 0.504x_1 - 0.756x_2 - 2.809x_3 + 0.114x_4 + 1.432x_5 - 0.001x_6 - 0.004x_7 + 2.083x_8$	0.8110	0.8067
Heating demand ground floor [kWh/m²]	$21.843 + 1.175x_1 - 1.253x_2 + 46.703x_3 + 10.04x_4 + 0.245x_5 - 1.245x_6 + 1.75x_7 - 13.685x_8$	0.9972	0.9972

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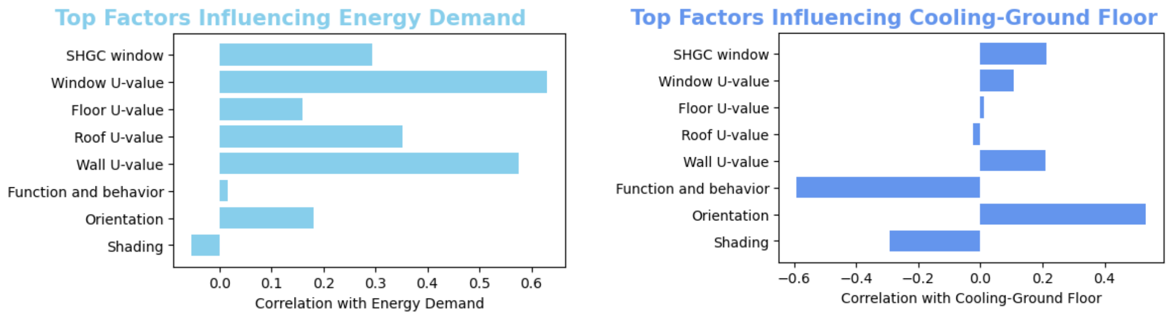
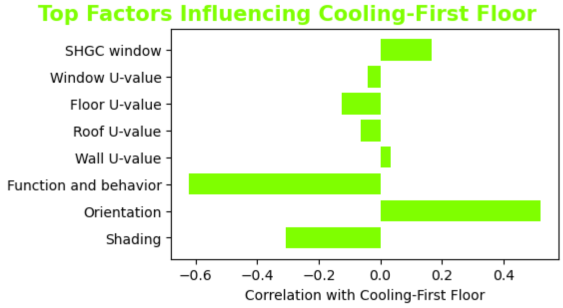
Heating demand first floor [kWh/m²]	$3.6 + 0.9x_1 + 1.44x_2 + 32.82x_3 + 8.8x_4 + 1.645x_5 + 3.305x_6 + 1.359x_7 - 10.55x_8$	0.9905	0.9910
Heating demand second floor [kWh/m²]	$65.829 + 1.743x_1 - 1.241x_2 + 46.384x_3 + 13227x_4 + 55.423x_5 - 3.414x_6 + 1.749x_7 - 17.917x_8$	0.9844	0.9827
PMV ground floor [%]	$84.505 - 1.141x_1 + 0.24x_2 - 9.531x_3 - 6.385x_4 - 0.198x_5 + 0.473x_6 - 1.358x_7 + 11.397x_8$	0.9715	0.9700
PMV first floor [%]	$72.359 + 1.052x_1 + 2.621x_2 + 12.469x_3 - 4.752x_4 - 0.786x_5 + 2.592x_6 - 0.351x_7 - 3.353x_8$	0.8379	0.8316
PMV second floor [%]	$69.272 - 0.421x_1 + 1163x_2 - 1.589x_3 - 4.58x_4 - 17.022x_5 + 0.849x_6 - 0.402x_7 + 5.481x_8$	0.8981	0.9028
PPD ground floor [%]	$80.988 - 1.222x_1 + 0.515x_2 - 9.69x_3 - 6.354x_4 - 0.224x_5 + 0.505x_6 - 1.298x_7 + 12.38x_8$	0.9720	0.9701
PPD first floor [%]	$71.605 + 0.97x_1 + 2.723x_2 + 11.716x_3 - 5.049x_4 - 1.008x_5 + 2.105x_6 - 0.541x_7 + 2.228x_8$	0.8458	0.8396
PPD second floor [%]	$67.491 - 0.475x_1 + 1.234x_2 - 1.775x_3 - 7.055x_4 - 16.256x_5 + 0.878x_6 - 0.425x_7 + 5.83x_8$	0.8948	0.8977

4.3 Italy

Envelope characteristics (i.e., U-values and SHGC of the windows) were found to be the most influential predictor variables for energy demand (Figure 16). A similar trend was observed in the case of heating, with the addition of function and occupant behavior as influential factors. However, for cooling, the envelope characteristics had a lesser influence. Regarding the comfort-related KPIs, only the wall U-value, among the envelope-related variables, had a significant effect on both PMV and PPD results for the ground and first floors (Figure 17). Additionally, for the second floor, the roof's U-value also showed a substantial influence. Thus, according to the energy simulation results for the MFH in Italy (built between 1961 and 1975), refurbishing the wall and roof is the most influential strategy for achieving both increased energy efficiency and occupant comfort.



a. b.



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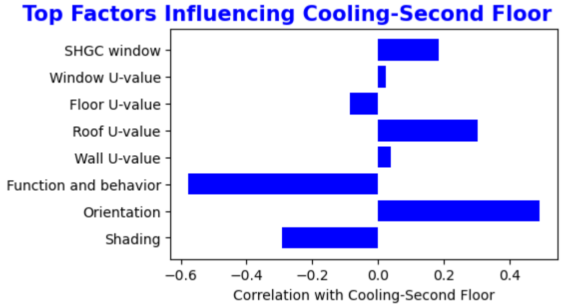

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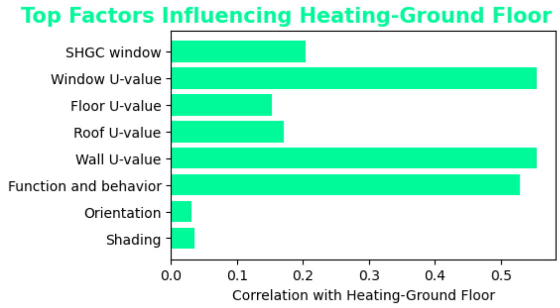

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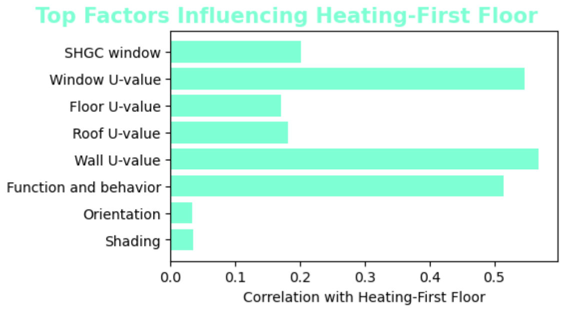

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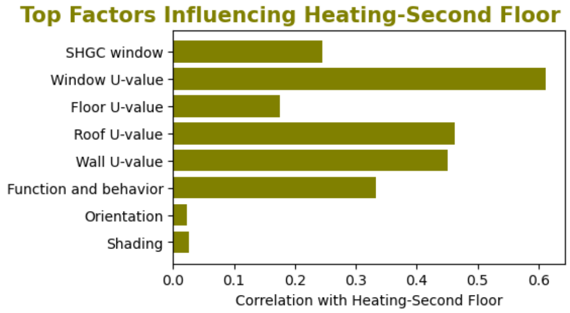
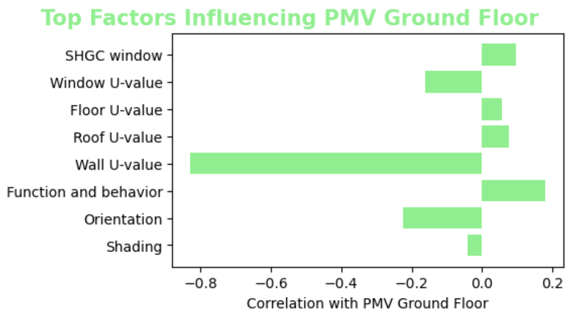
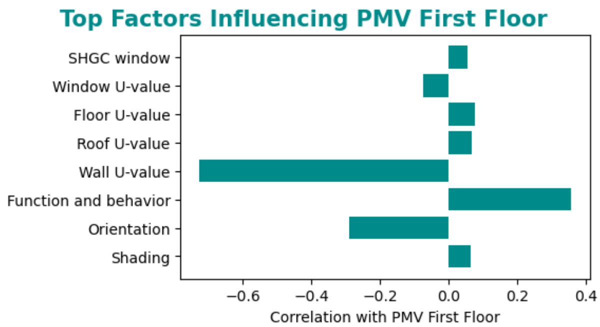


g.

Figure 16 Correlation matrix of the predictor variables with the energy demand related KPIs including a. overall energy demand; cooling for b. ground, c. first and d. second floor and heating for e. ground, f. first and g. second floor for Italian demo case



a.



b.

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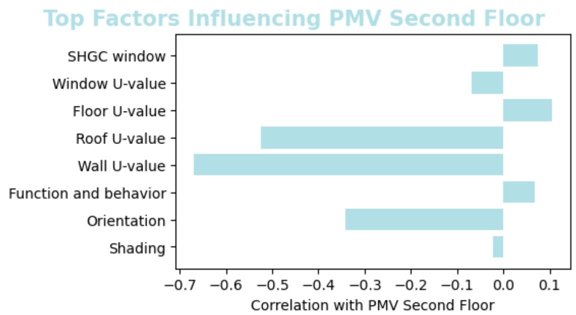

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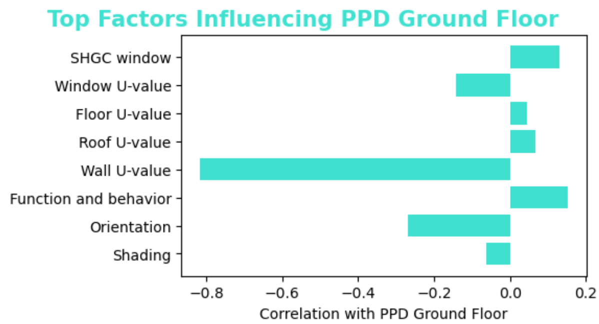

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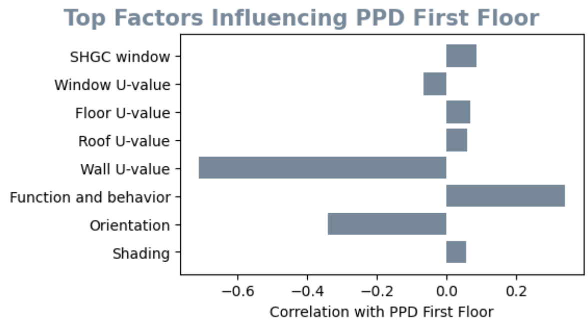
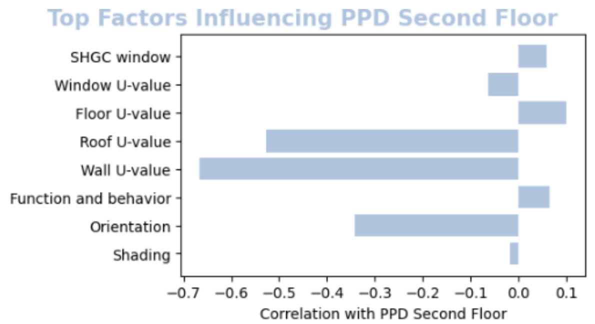


e.



f.

Figure 17 Correlation matrix of the predictor variables with the comfort related KPIs including PMV for a. ground, b. first and c. second floor and PPD for d. ground, e. first and f. second floor for Italian demo case

Taking into account the coefficient of determination for both test and training data, the surrogate models based on multiple linear regression for each KPI are shown in Table 12. The predictor variable notations are consistent with those presented in Table 2. The surrogate models are most successful in predicting heating and energy demand (R^2 above 0.9), while for cooling demand and thermal comfort KPIs, the accuracy is lower but still satisfactory.

Table 12 Surrogate models for Italian virtual demo case

KPI [unit]	**Surrogate model**	**R^2 (training data)**	**R^2 (test data)**
Energy demand [kWh/m²]	$43.503 - 2.332x_1 + 12.885x_2 + 1.284x_3 + 55.855x_4 + 36.513x_5 + 20.821x_6 + 14.140x_7 + 27.993x_8$	0.9192	0.9198
Cooling demand ground floor [kWh/m²]	$21.595 - 3.349x_1 + 10.140x_2 - 11.209x_3 + 5.385x_4 - 0.689x_5 + 0.314x_6 + 0.242x_7 + 18.220x_8$	0.8099	0.8181
Cooling demand first floor [kWh/m²]	$40.659 - 4.577x_1 + 12.821x_2 - 15.193x_3 + 1.208x_4 - 2.321x_5 - 5.671x_6 - 0.914x_7 + 24.522x_8$	0.8132	0.8144
Cooling demand second floor [kWh/m²]	$35.962 - 3.418x_1 + 9.507x_2 - 11.070x_3 + 1.057x_4 + 8.371x_5 - 3.067x_6 - 0.300x_7 + 18.963x_8$	0.7994	0.8012
Heating demand ground floor [kWh/m²]	$-33.398 + 1.325x_1 + 1.804x_2 + 32.577x_3 + 46.099x_4 + 15.236x_5 + 17.140x_6 + 11.064x_7 + 2.893x_8$	0.9512	0.9499

Heating demand first floor [kWh/m²]	$-35.135 + 1.303x_1 + 2.022x_2 + 31.796x_3 + 47.462x_4 + 16.148x_5 + 19.049x_6 + 10.981x_7 + 2.522x_8$	0.9529	0.9515
Heating demand second floor [kWh/m²]	$-62.852 + 1.719x_1 + 2.362x_2 + 36.240x_3 + 66.354x_4 + 72.793x_5 + 34.698x_6 + 21.347x_7 + 16.861x_8$	0.9382	0.9354
PMV ground floor [%]	$74.328 - 0.460x_1 - 3.895x_2 + 3.086x_3 - 19.504x_4 + 1.832x_5 + 1.771x_6 - 1.257x_7 + 14.997x_8$	0.8354	0.8310
PMV first floor [%]	$71.539 + 0.722x_1 - 5.477x_2 + 6.697x_3 - 18.519x_4 + 1.737x_5 + 2.551x_6 - 0.643x_7 + 8.635x_8$	0.7706	0.7593
PMV second floor [%]	$65.680 - 0.222x_1 - 4.991x_2 + 0.943x_3 - 13.135x_4 - 11.060x_5 + 2.747x_6 - 0.497x_7 + 7.973x_8$	0.8721	0.8658
PPD ground floor [%]	$70.787 - 0.622x_1 - 4.285x_2 + 2.366x_3 - 17.577x_4 + 1.484x_5 + 1.332x_6 - 1.100x_7 + 16.085x_8$	0.8304	0.8260
PPD first floor [%]	$68.039 + 0.608x_1 - 6.063x_2 + 6.004x_3 - 17.002x_4 + 1.416x_5 + 2.106x_6 - 0.607x_7 + 10.899x_8$	0.7680	0.7568
PPD second floor [%]	$64.662 - 0.168x_1 - 4.982x_2 + 0.915x_3 - 13.002x_4 - 11.062x_5 + 2.570x_6 - 0.435x_7 + 6.517x_8$	0.8662	0.8611

5 Conclusion

This deliverable presents the initial findings of Task 4 in WP4 of the BIO4EEB project, focusing on evaluating renovation strategies using BIO4EEB solutions through virtual demo cases.

The comprehensive approach involved selecting representative virtual demo cases, defining relevant KPIs, developing detailed simulation models, and creating surrogate models to predict building performance. Simulating approximately 6,000 renovation scenarios per virtual demo case provided valuable insights into the impact of BIO4EEB solutions on energy demand and occupant comfort.
The results underscore the significance of refurbishing building envelopes—particularly walls, roofs, and floors—in achieving substantial energy efficiency gains and enhancing thermal comfort.
The surrogate models developed exhibit high predictive accuracy, enabling rapid assessment of KPIs based on various input variables. This facilitates informed decision-making for stakeholders specifically in real-demo cases, bridging the gap between complex simulations and practical applications. By providing accessible tools for real demo case owners, progress in T4.3 supports the selection of optimal renovation strategies tailored to specific building characteristics and user needs.

Overall, the deliverable highlights the potential of BIO4EEB solutions to contribute significantly to energy savings, CO_2 emission reductions, and improvements in occupant comfort. The methodologies and tools developed lay a strong foundation for achieving the project's overarching goals and advancing sustainable building practices in Europe.

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6 Future work

In our next deliverable, due at the end of Month 48, we will build upon our methodologies and initial results by updating our simulation models with the latest data from BIO4EEB solutions. We will also incorporate future climate projections to assess long-term performance metrics more effectively. To create tailored occupant behavior profiles for the demo cases, we will consider country-specific user archetypes.

We will further refine the surrogate models by expanding the range of scenarios and enhancing their predictive capabilities. Lastly, we will integrate our simulation outputs with the BIO4EEB platform developed in Task 3.7, ensuring seamless accessibility and usability for stakeholders.

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Annexes

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