BIMERR
RENOVATION 4.0

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ACRONYMS

Acronym	Meaning
API	Application Programming Interface
BCVTB	Building Controls Virtual Test Bed
BEP	Building Energy Performance
BIF	BIMERR Interoperability Framework
BIMERR	BIM-based holistic tools for Energy-driven Renovation of existing Residences
BIM	Building Information Modelling
BSD	Building Surface Detailed
CFD	Computational Fluid Dynamics
CSV	Comma Separated Values
EMS	Energy Management System
EPBD	Energy Performance of Building Directive
EPW	EnergyPlus Weather file
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
FSD	Fenestration Surface Detailed
GID	Global Identifier
HTTP	Hypertext Transfer Protocol
HVAC	Heating Ventilation and Air Conditioning
IDD	Input Data Dictionary
IDF	Input Data File
IFC	Industry Foundation Classes
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
obXML	Life Cycle Assessment
PRUBS	Life Cycle Costing
RenoDSS	Renovation Decision Support System
RDD	Report Data Dictionary

EXECUTIVE SUMMARY

This Deliverable addresses the topic of how the Energy Key Performance Indicators (KPIs), defined in D3.3, are to be computed and communicated to the Renovation Decision Support System (RenoDSS). The calculation of these KPIs is a key part of the process towards the identification of the best renovation scenarios according to stakeholders' preferences. Unified building and occupant behaviour data models, based on the Industry Foundation Classes (IFC) and the occupant behaviour eXtensible Markup Language (obXML) standards, respectively, provide data for extracting relevant information for the setup of Building Energy Performance (BEP) simulations. Interfaces, aimed at generating respective inputs and invoking relevant external simulation engines (e.g. EnergyPlus), and ways of post-processing the results, are investigated so that the predefined Energy KPIs can be computed.

This Deliverable consists the first version of the BEP[1] module documentation, where results of a survey on existing BEP simulation methodologies, the BEP simulation engine's selection, delivered data pre-processing, mapping and post-processing functionalities, the technology stacks that the BEP module builds upon, the API that is exposed to RenoDSS, installation instructions and usage walkthrough, are reported.

Since this work reflects the activities that have been undertaken for the initial release of the module, it adheres to certain assumptions/restrictions and does not fully implement all the fine-grained functionalities that will be issued in the BEP module's final version (e.g. a more efficient integration with the RenoDSS that is still under development). The final documentation of the BEP module, anticipated to be released on M30 of the BIMERR project implementation, shall focus on enhancing the module performance based on the feedback acquired during the BIMERR integration, pre-validation and validation activities, introducing a set of already planned extensions and new functionalities.

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[1] Although the shortened form of the Building Energy Modelling module should be BEM, in literature, the BEM abbreviation is frequently referred to Building Energy Management systems. Hence, from this point forward, the Building Energy Performance (BEP) term is adopted.

1. INTRODUCTION

1.1 SCOPE AND OBJECTIVES OF THE DELIVERABLE

This deliverable aims at reporting on the work conducted up to M20 on the BEP module, being developed in the context of T7.3 – *Building Energy Performance Modelling Module* [1]. In alignment with the BIMERR architecture [2], the BEP module is considered as a sub-component of the BIMERR's Renovation Decision Support System, RenoDSS. In principle, RenoDSS provides to the renovation designer an accurate estimation of the Energy, Cost, Life Cycle Assessment trade-offs of various alternative renovation scenarios, based on the available renovation options in terms of materials and components.

The BEP module is responsible for the performance evaluation of the renovation measures in terms of specific Energy KPIs calculation that have been defined and documented in D3.3 – *BIMERR evaluation methodology* [3]. The BEP module's core functionalities are to map the IFC [4] data to proper Input Data Format (IDF) files that are used to execute BEP simulations and combine them with obXML data for occupancy [5] to enable the RenoDSS users to explore various what-if scenarios, quickly run simulations to estimate the energy performance and fine-tune the interventions in order to explore the benefits.

The need for the aforementioned functionalities stems from the fact that within BIMERR, Industry Foundation Classes (IFC) files are used to streamline and expedite the collection of the building static information (building elements, materials and their thermal properties, HVAC components, to name but a few), while obXML files capture the dynamic data (schedules and thermal comfort preferences). Since a wide range of BEP simulation methodologies exists, a survey on existing BEP calculation methodologies that exploit both IFC and obXML data to automate the BEP input data files' generation, and the selection of the BEP simulation engine that best fits the BIMERR case-studies, has been the preliminary objective of this deliverable.

The main aim of this deliverable is to provide a comprehensive overview and documentation of the Building Energy Performance modelling module, and as a "Demonstrator" type deliverable, to report on the actual service that has been developed and delivered.

1.2 RELATION TO OTHER TASKS/DELIVERABLES

Table 1 depicts the relations of this document to other deliverables within the BIMERR project, that should be considered along with this document for further understanding of its contents.

Table 1 Relation to other BIMERR project's deliverables

Del. Number	Deliverable Title	Relations and Contribution
D3.1 [6]	Stakeholder requirements for the BIMERR system	Analysis of the end-user requirements in order to create the necessary inputs for defining the different components of the BIMERR, along with a thorough description of the business scenarios, use cases and system requirements tailored to the project's goals and therefore setting the skeleton for the BIMERR framework.
D3.3 [3]	BIMERR evaluation methodology	The evaluation methodology is designed based on well-established international methodologies and protocols, reviewing the state of the art and relevant BIM projects, as well as relevant renovation works and expertise of the BIMERR constructor partners. The energy KPIs are documented here.
D3.5 [2]	BIMERR system architecture 1st version	The first version of the BIMERR architecture is delivered. The structural view, describing the core components of the system in the form of software modules, and the dynamic view, which presents the already defined use cases with the corresponding sequence diagrams are described highlighting the data exchange and interoperability requirements of each tool.
D4.2 [7]	BIMERR Ontology and Data Model 1	The initial BIMERR ontology and data model structure is developed to address the various semantic interoperability challenges for BIM-related data in an efficient manner.

Functionalities that are introduced in this document will be deployed to also address the aspects relevant to the scope of T7.5 – *Decision Support System Engine and UI & Module Integration* [1], where continuous integration of all WP7 components and testing are anticipated to ensure that functional and non-functional requirements of the Renovation Decision Support System are met.

1.3 STRUCTURE OF THE DOCUMENT

To address the aspects relevant to the scope of T7.3, Section 1 introduces the work performed and the scope of this deliverable, along with its relevance to other BIMERR tasks and the deliverable's structure.

As a short introduction to the BIMERR BEP module requirements, (1) a survey on existing methodologies and widely used simulation engines towards selecting the BEP simulation engine that best fits the BIMERR objectives, (2) a summary of the BIMERR Energy KPIs, and the inputs/outputs formats of the selected engine, are reported in Section 2.

Section 3 summarizes the technical work that has been conducted up to M20 within T7.3. Having concluded to the BEP module architecture, a transformation process that converts the data obtained from the IFC to the BEP simulation engine's input data file is required; rules embedded in the "Input Data File Generator", responsible for that transformation process, are presented in Section 3.1. Establishing a link between the BEP input data file and the occupant behaviour data model (obXML), so that dynamic schedules can be incorporated in the simulation, is of paramount importance towards increasing the energy performance estimation accuracy. This functionality, which we refer to as co-simulation, is briefly introduced in Section 3.2.

Beyond a wide variety of the BEP simulation output data and files, particular results are relevant and need to be further processed to estimate the Energy KPIs. Such data post-processing functionalities are reported in Section 3.3.

The remaining parts of Section 3 presents the integration plans in RenoDSS, the technology stack, assumptions, restrictions, installation instructions and licensing that have been considered in the first release of the BEP module.

Finally, in Section 4, conclusions are provided along with the release plan for the 2nd iteration of the BIMERR BEP module.

2. ENERGY KPIS AND BEP SIMULATION ENGINE SELECTION

According to the BIMERR architecture [2], the BEP module is invoked by the RenoDSS tool to evaluate the as-is thermal behaviour of a building (baseline) and estimate the energy performance of certain renovation scenarios, that are candidate to be applied. To deliver its scope, the BEP module retrieves information from the RenoDSS management module (i.e. IFC, obXML and EPW files) transforms them to proper simulation input data files and launches respective simulation tools (or engines) to calculate predefined KPIs.

Towards achieving the data retrieval, transformation, and appropriate simulation tools execution, the following points for discussion have arisen: Which are the KPIs that will be calculated for the ranking of different renovation scenarios? Since simulation of numerous different renovation scenarios will be requested, which is the BEP simulation engine that strikes a balance between accuracy and computational complexity? Do the simulation outputs require any post-processing before being communicated back to RenoDSS? In the following paragraphs, after a prompt to the energy KPIs that have been analyzed in D3.3 [3], these questions are answered.

2.1 ENERGY KEY PERFORMANCE INDICATORS

D3.3 has focused on the definition of the BIMERR Key Performance Indicators that are to be used in BIMERR to evaluate the performance of candidate renovation measures and is strongly linked to this deliverable. For the sake of completeness, a summary of the Energy KPIs that the BEP module must be capable to calculate is listed Table 2.

Table 2 List of Energy Key Performance Indicators according to the BIMERR evaluation methodology [3]

KPI	Name	Definition/Description	Units
EN1	Total primary energy consumption	Primary energy consumption refers to the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process	kWh/m^2/year
EN2	PENRT Primary energy non-renewable total	The primary energy content of all non-renewable resources (crude oil, coal, etc.).	kWh/m^2/year

EN3	Electric energy consumption	The building's total electric energy consumed for the operation of HVAC systems, lighting, and appliances	kWh/m^2/year
EN4	Natural gas energy consumption	The building's total natural gas energy consumed for the operation of HVAC systems and appliances	kWh/m^2/year
EN5	District heating energy consumption	The building's total district heating energy consumed for the operation of HVAC systems and domestic hot water equipment	kWh/m^2/year
EN6	Other fuel types consumption	The building's total energy consumed, generated by other resources, e.g. diesel, biomass energy consumption	kWh/m^2/year
EN7	Peak heating load and heating load profile	The heating power profile for a specific period in Watts and its maximum/peak value	Watts
EN8	Peak cooling load and cooling load profile	The cooling power profile for a specific period in Watts and its maximum/peak value	Watts
EN9	Heating and cooling energy demand	The sum of heating and cooling loads required to maintain the thermal comfort conditions to all the conditioned building's spaces	kWh/m^2/year
EN10	Peak electricity load and electricity load profile	The electricity power profile for a specific period in Watts and its maximum/peak value	Watts
EN11	PV electric energy generation	The electric energy generated by photovoltaic panels installed on the building's envelope	kWh/m^2/year
EN12	Solar thermal energy generation	The thermal energy generated by solar thermal panels installed in the building	kWh/m^2/year

2.2 BEP SIMULATION METHODOLOGIES AND ENGINES

The evaluation of the Energy KPIs is a complex, multi-parametric problem, being solved by different methods that fall under two main categories: quasi-steady state and dynamic methods.

The monthly-based calculation methodology described in ISO 13790:2008 [8] standard is a prime example of a quasi-steady state method, adapted by many EU member states to form at a national level an accepted calculation methodology for computing energy performance, in the context of activities for the implementation of the Energy Performance of Buildings Directive (EPBD) [9]. As part of that standard, the accuracy of the calculation methodology that it adopts is analysed, indicating certain scenarios where deviations from reality are acceptable in an annual basis, but on a monthly scale these deviations are significant. The sensitivity to input data is also reported: uncertainties in the estimation of thermal properties or other input parameters can contaminate the results, and the propagation of these errors can yield sizable deviations in the end results. For this reason, in many cases, the calculation methodology is used to establish an ordering relation, that allows for meaningful comparisons of different retrofitting scenarios (and thus establishing the rating system used in many countries), but with lesser expectations with regards to prediction of real performance.

Within BIMERR, The BEP module aims to enhance the Decision Support System by providing an accurate estimation of post-renovation building energy consumption, taking into account structural and geometrical properties of the building, materials, heating/cooling system and other relevant energy loads, and most importantly information about the actual usage patterns of these loads based on the resident behavioural patterns and comfort preferences within the home (obXML data, generated by the PRUBS component), whose nature is strictly dynamic. In other words, dynamic effects matter, and the temporal resolution of a month that the steady-state methods imply is not sufficient.

Dynamic methods follow a more granular approach, using smaller time steps which are comparable to the time scale of time-varying physical effects that are being modelled, e.g. the conductive and convective heat transfer from building thermal masses or the dynamic effects of the HVAC system's operation. In their highest granularity, dynamic methods touch upon the Computational Fluid Dynamics (CFD) topic. CFD for whole building energy performance simulation can be helpful as a quasi-qualitative tool for understanding fundamental flow structures. However, their computational complexity (in terms of simulation runtime) and the requested domain expertise are almost prohibitive for use in energy renovation studies, where several candidate renovation scenarios need to be simulated within a reasonable timescale and on the basis of realistic assumptions. Accordingly, the use of CFD calculation methodologies is mostly restricted in the design phases of a building life cycle.

Other dynamic methods introduce the thermal zones concept, where the building is divided into spaces (thermal zones), each with a uniform temperature, humidity etc. The 3D thermal zones-type methods have gained ground in the BEP simulation domain, being used in many envisaged and practical use scenarios, as it keeps accuracy and computational complexity in balance. Beyond a wide range of existing thermal zones-type BEP simulation engines, DeST [10], EnergyPlus [11], eQUEST, ESP-r, IES-VE [12], TRNSYS [13], and Modelica [14], are the most frequently used, but all are suffering from two major drawbacks: (1) their input data files' preparation is a very time-consuming process due to the difficulty to collect relevant information, often requiring more time than it is available due to project's deadlines, and (2) it is a non-standardized process that produces BEP simulation models whose results can significantly vary from one modeler to another according to their experience.

Within BIMERR, IFC and obXML files are used to streamline and expedite the collection of such information, while our BEP approach intend to introduce a methodology to automatically translate IFC to BEP simulation input data, making the BEP simulation modelling process much more expedient and less vulnerable to modelling errors. The topic of automated data translation between BIM and thermal simulation input data has received considerable attention as of late [15, 16, 17, 18, 19], where studies have shown that EnergyPlus and Modelica consist the most frequent used engines. Furthermore, within the EBC-Annex 66 [20] project, an overview of the thermal zones-type engines capabilities to implement stochastics occupant behaviour models, provided through the obXML entities, has been performed, indicating the EnergyPlus flexibility on capturing such data in three different ways, briefly presented in Section 2.3.

Due to our bias for the implementation of an open-source BEP simulation engine, EnergyPlus has been selected; robust Modelica libraries are commercial, while a free open-source library of Modelica models for BEP simulation is under development, as part of IBPSA Project-1 workplan[2].

2.3 BEP Simulation – EnergyPlus

EnergyPlus is a software released by the U.S. Department of Energy. EnergyPlus follows the thermal zoning, spatial-discretization, paradigm, where the building is divided into

[2] https://ibpsa.github.io/project1/index.html

spaces (thermal zones), representing nodes with averaged values of thermal parameters. The energy conservation differential equation and the mass conservation differential equation hold for each zone and are solved to evaluate the evolution in time of the zonal thermal parameters.

The main input file is the Input Data File (IDF), an ASCII file which contains information about the building and the HVAC system to be simulated. The EnergyPlus input data are structured into classes. For each class, fields are defined, which describe the characteristics of the class objects. Objects are the instances of a class. All the available classes are listed into the Input Data Dictionary (IDD)[3]. The EnergyPlus Weather file (EPW)[4] is a Comma Separated Value (CSV) format file containing the hourly or sub-hourly weather data needed by the simulation program.

Concerning the obXML data insertion, there are three main groups of IDD classes, whose objects could be used to incorporate occupant behaviour data: (1) Energy Management System (EMS) classes that allow custom functions to overwrite the occupants' presence and actions data (schedules) at each simulation timestep; (2) Building Controls Virtual Test Bed (BCVTB) API classes that enable the co-simulation of EnergyPlus with an external tool, where the occupant behaviour modelling functions are simulated; and (3) Function Mockup Units (FMUs) classes that enable the aforementioned co-simulation in a more efficient manner.

Beyond a wide variety of EnergyPlus output variables, particular variables can be reported depending on the actual simulation problem described in the IDF. The Report Data Dictionary (RDD)[5] is a text file listing those variables available for reporting during the simulation of a certain IDF. Selecting an output variable from that list, an object of the Output:Variable class is defined and imported in the initial IDF.

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[3] bigladdersoftware - EnergyPlus 9.3 - Input Data Dictionary (IDD)

[4] bigladdersoftware - EnergyPlus 9.3 - EnergyPlus Weather File (EPW) Data Dictionary

[5] bigladdersoftware - EnergyPlus 9.3 - Report Data Dictionary (RDD)

After an initial IDF – enriched with the selected Output:Variable objects – simulation run, the resulted data-sets of the selected variables are printed in a comma separated text by a semi column, where each column corresponds to a unique variable time-series with the reporting frequency defined by the modeller, commonly equal to the simulation timestep.

3. BIMERR BUILDING ENERGY PERFORMANCE MODULE

Taking into account the input data requirements and the results' reporting capabilities of EnergyPlus, the first version of the BEP module prototype has been designed and developed, consisting of three main sub-components: IDF Generator; BEP simulation; and BEP Manager.

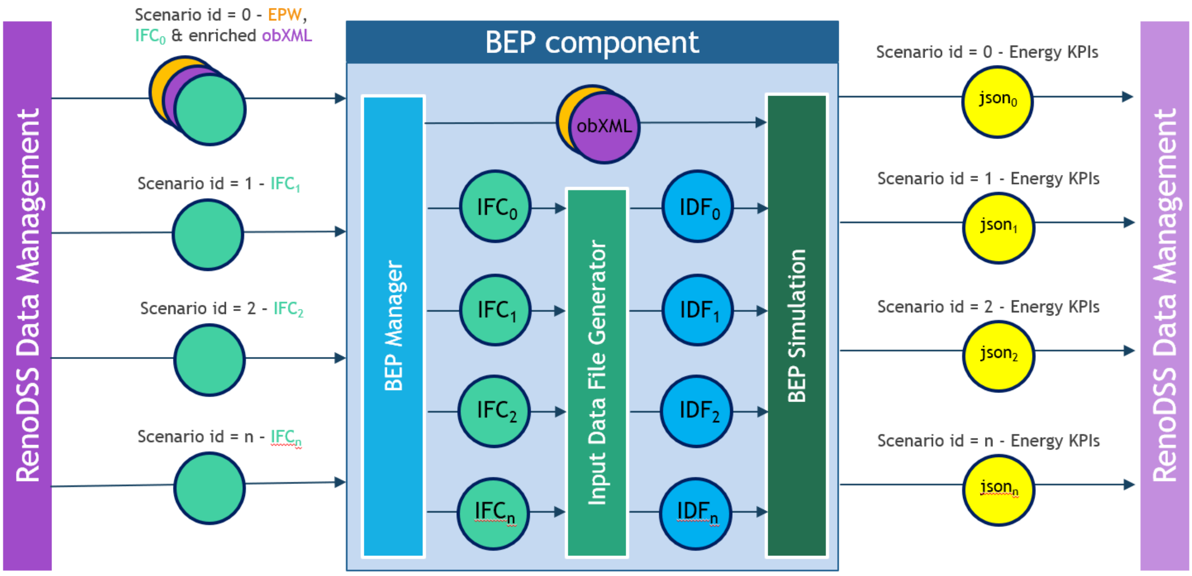

Figure 1: Architecture of the BEP module

Analysing the energy KPIs calculation process, whenever the BEP Manager receives a scenario evaluation request from the RenoDSS data Management module (in terms of energy KPIs calculation), the IDF Generator module is triggered. We assume that each scenario has a unique ID, while the scenario with ID value equal to 0 corresponds to the baseline. Based on this assumption, when the baseline evaluation is requested, a process of 6 steps is initiated.

The IDF generator sends a request for the relevant IFC, obXML and EPW files to the RenoDSS Data Management module. Retrieving the aforementioned from the RenoDSS Data Management module, the IDF generator is processing the content of the IFC file to generate the Input Data File of EnergyPlus simulation engine, while the co-simulation with the obXML, to take into account actual schedules based on data-driven occupant behaviour models, is being established. Then, the input data requirements for an

EnergyPlus simulation are met, and the IDF Generator submits a simulation request to the BEP simulation module. When the simulation is completed, outputs/report files are populated and sent back to the IDF Generator to be forwarded to the BEP Manager.

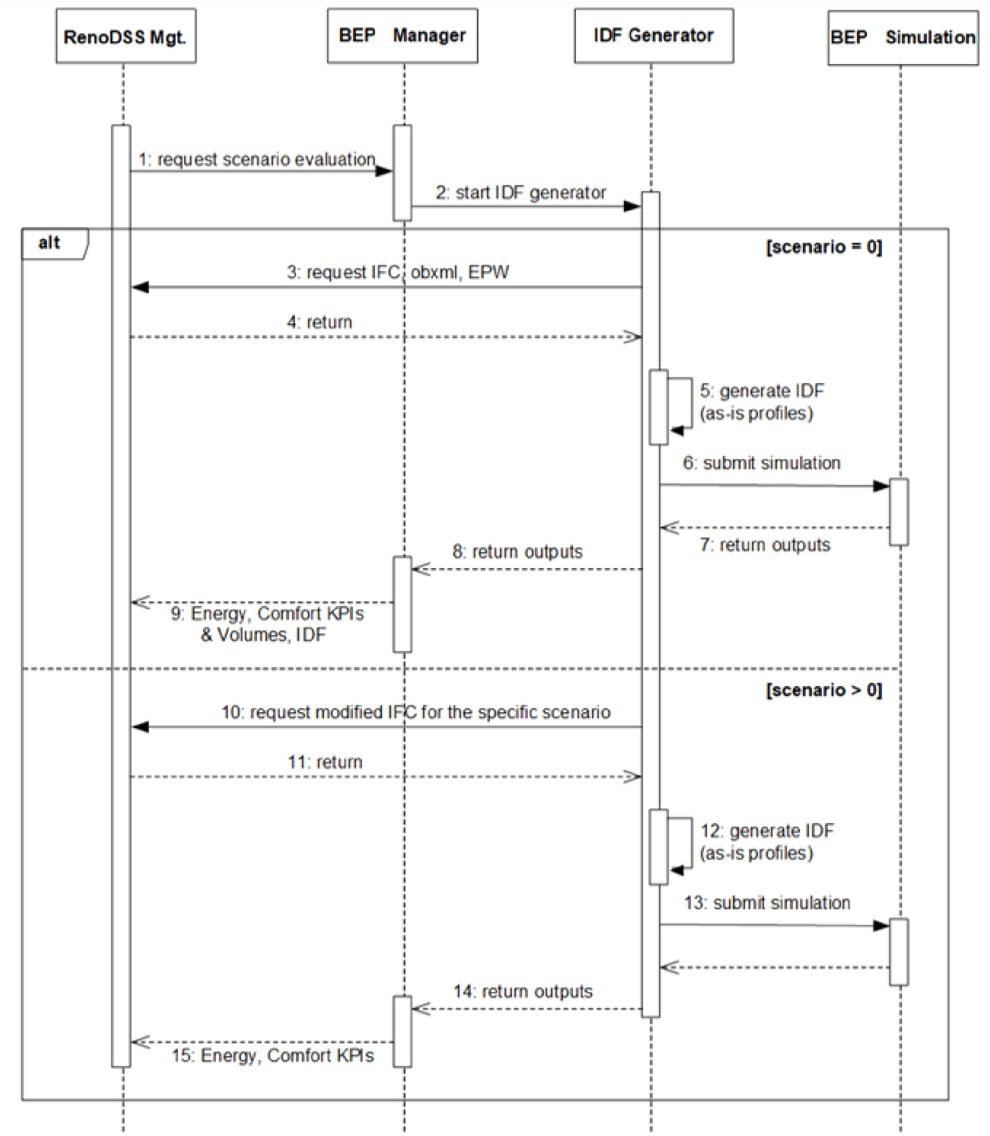

Figure 2 Sequence diagram of BEP module execution for the Energy KPI calculation - baseline (scenario = 0) and renovation scenarios (scenario > 0) [2]

Finally, the outputs/report files are processed within the BEP Manager to populate a JSON file with the KPIs that are sent to the RenoDSS Data Management module as the result of the baseline evaluation request.

An almost identical process is followed to handle requests of candidate renovation scenarios evaluation. The main difference occurs in the files requested and processed by the BEP module: since the renovation measures affect and modify objects of the IFC file only, there is no need to resend the obXML and EPW files.

In summary, the current version of the BEP module provides the following functionalities, as described in Sections 3.1, 3.2, and 3.3:

- It retrieves IFC, EPW and obXML data from RenoDSS for a specific scenario and applies a transformation process to populate the input data file of EnergyPlus.
- It automatically generates the configuration files requested for the co-simulation setup of EnergyPlus and obXML, based on the Functional Mock-up Interfaces standard (FMIs).
- Using the EnergyPlus and obXML Functional Mock-up Units (FMUs) as input, the BEP module automatically invokes the co-simulation execution.
- When the simulation run has been finished, the BEP module further processes the simulation output files and generates a JSON file as an output message (to be listened by the RenoDSS) that contains the energy KPIs values for the specific renovation scenario.

3.1 EnergyPlus Input Data File Generation

The Input Data File Generator constitutes the core component of the BEP module. Utilizing the IFC and obXML data, it generates the BEP simulation Input Data File (IDF) of EnergyPlus.

The input data of EnergyPlus can be grouped in three main categories: (1) static data that include the building geometry, construction materials, glazing information, systems used in the building, building’s spatial discretization to thermal zones, to name but a few; (2) dynamic data that consist of all time-variant data, such as user-actions, occupancy schedules at each thermal zone, use of equipment, etc; and (3) other simulation parameters that refer to features requiring domain expertise for input specification and output assessment, and cannot be captured by IFC and/or obXML.

In the following subsections, the BEP input data, required for an EnergyPlus simulation, are briefly described, while the rules that the Input Data File Generator encapsulates to automatically generate the IDF data and the co-simulation set-up, utilizing the IFC and obXML data, are presented.

3.1.1 Building Discretization to Thermal Zones

As introduced in Section 2.3, a principle modelling assumption of EnergyPlus is the spatial discretization of the building volume to thermal zones. In EnergyPlus, thermal zones are defined by instances of the Zone[6] class. Although IFC could incorporate information about the thermal zone's definition through instances of the IfcSpatialZone class, it cannot relate them with surfaces that express the boundary conditions to which the thermal zone is exposed. To overcome such a limitation, we assume that each space is treated as a thermal zone. Hence, to define the thermal zones, each building's space, defined as an IfcSpace[7] class object, is mapped to a new Zone IDD class object, whose name equals to the IfcSpace GID.

3.1.2 Building Elements – Materials Thermal Properties and Construction Data

Each building element's construction is composed by material layers' set. To define its material layers' bedding in relevant order, EnergyPlus introduces the Construction class. In IFC, each Construction is defined as an IfcMaterialLayerSet instance, composed by IfcMaterialLayers.

Delving deeper into the material and its thermal properties definition, EnergyPlus provides several classes to describe materials and their thermal characteristics, with the Material, Material:AirGap, and WindowMaterial:SimpleGlazingSystem, being the most widely used. In terms of IFC, IfcMaterial and IfcMaterialLayer[8] classes are used to capture

[6] bigladdersoftware - EnergyPlus 9.3 - I/O Reference - Zone

[7] https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/link/ifcspace

[8] https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/link/ifcmateriallayer

relevant information. Within BIMERR, the RenoDSS will provide functionalities for the IFC file's enrichment with thermal properties values of each material, utilizing the material and components database as the main data source. To that direction, the definition of property sets (IfcPropertySet), tailored to material properties capturing scope, is under investigation.

For the first release of the IDF Generator, we assume that a BIM authoring tool (Revit), enables the thermal properties of materials' exportation – necessary for the simulation – both for opaque and glazing materials. In case of transparent materials, three properties (Visual Light Transmittance, Solar Heat Gain Coefficient, Heat Transfer Coefficient) are exported and used to describe the thermal properties of transparent elements (panels, windows, glazing doors, etc.).

3.1.3 Building Elements – Geometric Representation

To describe the building geometry, the type of boundary condition applied to each building element and the construction assigned to it, EnergyPlus IDD provides several classes to define surfaces, ranging from simple rectangular surfaces to detailed descriptions, with the latest being frequently used. For detailed description, BuildingSurface:Detailed [9] (BSD) and FenestrationSurface:Detailed [10] (FSD) classes are recommended. BuildingSurface:Detailed class is used to describe opaque building surfaces, while FenestrationSurface:Detailed class is used to describe transparent building surfaces. Their geometry representation can be described by planar surfaces only (a set of vertices in a specific order).

In terms of the IFC schema, relevant information is captured by instances of the IfcRelSpaceBoundary2ndLevel (SB2L) class (see Figure 3), whose connection geometry is restricted to planar surfaces only, thus aligned with the geometry representation requirements of EnergyPlus. Each SB2L is translated to a BSD or a FSD object as follows:

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[9] bigladdersoftware - EnergyPlus 9.3 - I/O Reference - BuildingSurface:Detailed

[10] bigladdersoftware - EnergyPlus 9.3 - I/O Reference - FunestrationSurface:Detailed

BSD: If the SB2L does not have a Parent Boundary, it is translated to a BSD object, whose Name and Zone Name properties values are equal to the space boundary GID and the space boundary Relating Space GID, respectively. For the Surface Type definition, the Related Building Element, the Corresponding Space Boundary, and the normal vector data of the SB2L are processed. Moreover, if SB2L is external, then for the generated BSD the following hold: Outside Boundary Condition, Sun Exposure, and Wind Exposure properties values are set to Outdoors, Sun Exposed and Wind Exposed, respectively; else, the Outside Boundary Condition value is set to Surface, and the Outside Boundary Condition Object is the corresponding space boundary GID. Completing the transformation to a BSD class object, Number of Vertices and coordinates of each vertex are fulfilled according the space boundary geometric representation.

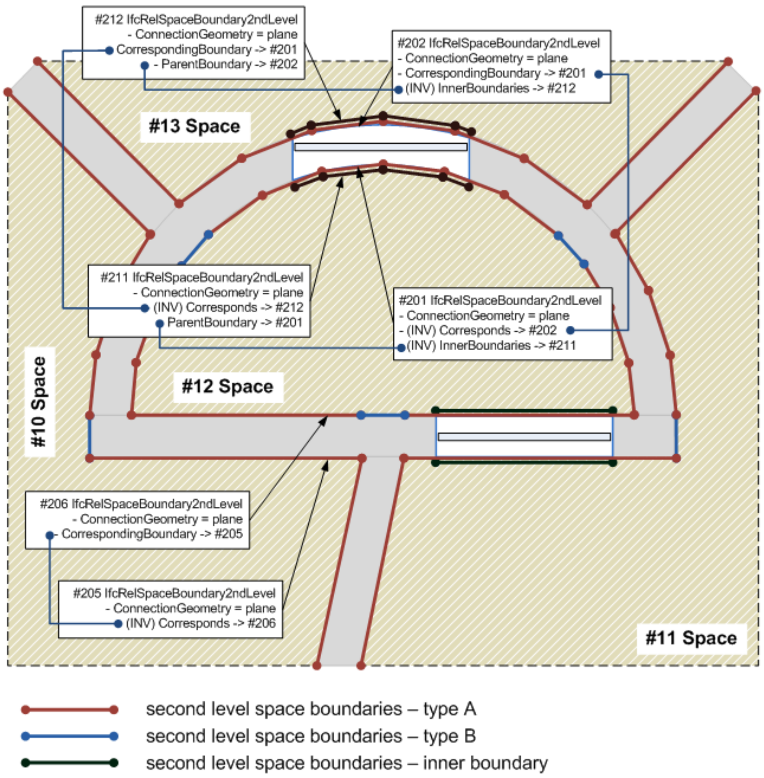

Figure 3 An illustration of the 2nd-level space boundaries relationships[11]

[11] https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/link/ifcrelspaceboundary2ndlevel

FSD: If the SB2L has a Parent Boundary, it is translated to a FSD object, whose Building Surface Name is the parent boundary surface GID. If its Corresponding space boundary has a relating space, the Outside Boundary Condition Object is the corresponding boundary GID. If the SB2L's construction consists of opaque Materials, the Surface Type of the FSD object is Door; else the Surface Type is Window. Completing the transformation to a FSD class object, Number of Vertices and coordinates of each vertex are fulfilled according the space boundary geometric representation.

It is worth mentioning that although the 2nd-level space boundary data correctness is prerequisite, the IFC files often contain data that are missing or incomplete due to design errors or exporting software imperfections. Hence, a consistent way of capturing the 2nd-level space boundary topology is of paramount importance. In view of this, an algorithm that generates that topology is being developed within T5.3 [1]. In the same context, a 2nd-level space boundary generation tool, CBIP, has recently been developed [21], to calculate the 2nd-level space boundary surfaces based on the geometrical information of the architectural elements (walls, spaces, slabs, openings, etc.) contained in its input IFC file and enrich it by populating appropriate IFC data classes in its output. Since the T5.3 algorithm development is still in progress, IFC files, enriched with the 2nd-level space boundaries data by the CBIP tool, have been used for experimentation and preliminary validation purposes of the IDF Generator.

3.1.4 Energy Systems – HVAC primary and secondary equipment

Regarding the modelling of energy systems and equipment within EnergyPlus, three different modelling approaches of increasing granularity could be applied. The simplest approach utilizes the ideal systems concept; here, detailed modelling of the HVAC system components is not requested, but only information about the zone controls, zone equipment configurations, and the ideal loads system components. A more detailed modelling approach is based on the HVAC templates concept[12] of EnergyPlus, where objects of certain classes are defined with minimal effort, that are automatically expanded into EnergyPlus HVAC inputs of high granularity. The most advanced (and detailed)

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[12] bigladdersoftware - EnergyPlus 9.3 - I/O Reference - Group - HVAC Templates

modelling option allows detailed definition of each component's characteristics, water and air loops, etc. The templates-based option is sufficient to cover the BIMERR test-cases, and relevant transformation rules of the IDF Generator have been implemented; however, advanced (and detailed) modelling of components might have to be supported on an as-needed basis.

Although the IfcHvacDomain[13] defines basic object concepts for the HVAC primary and secondary equipment description, it suffers from limitations in the definition of HVAC systems from a BEP simulation perspective [22]. Commonly, HVAC modelling in BEP simulation engines requires further information than what is included in an IFC file. To address this drawback, within BIMERR, user defined IfcPropertySets that will be used to capture data required for the EnergyPlus HVAC templates-based description are under development.

3.1.5 Other Simulation Parameters

An efficient selection of: (a) surface convection, (b) conduction and heat balance algorithm, (c) equipment and system sizing, (d) daylighting, (e) dynamic fenestration controls airflow analysis model, along with (f) simulation start and end time (defined by: month, day, hour and minute), (g) simulation inter-sample time interval (in minutes), (h) preferred outputs, to name but a few, requires domain expertise that none of the current BIMERR data models can capture. These features fall under the other simulation parameters category and influence the simulation performance in various ways.

The inclusion of intermediate data models (e.g. SimModel [23]) as part of the BIMERR data models could be investigated towards bridging the "Other Simulation Parameters" data gap between BIM and BEPs. However, the added value of such inclusion would be minimal: (1) none other component of the BIMERR toolchain requires such data; (2) none of the BIMERR data providers (BIM Digital model creation tools) to the BIMERR

[13] https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/link/ifchvacdomain

Interoperability Framework (BIF) is capable to generate the "Other Simulation Parameters" information.

To meet the "Other Simulation Parameters"[14] data requirements, the EnergyPlus IDF is enriched with one instance of each of the following classes: SimulationControl; Building; RunPeriod; Timestep; SurfaceConvectionAlgorithm:Inside; SurfaceConvectionAlgorithm: Ouside; HeatBalanceAlgorithm, whose properties have been carefully set to prefixed values, according to several simulations that run and are analysed to find the combination that keeps the simulation accuracy and runtime in balance.

3.1.6 Time-variant Data – Occupant Behaviour Models

To achieve a modular-like co-simulation between obXML and EnergyPlus, the FMUs-based approach has been selected. To prepare EnergyPlus for such a data exchange, instances of the following IDD classes are automatically generated, based on the obXML content:

- ExternalInterface:FunctionalMockupUnitExport:From:Variable[15]; and
- ExternalInterface:FunctionalMockupUnitExport:To:Schedule[16].

Instances of the former class are used to expose the EnergyPlus outputs to obXML (e.g zone temperature, relative humidity), while instances of the latter are used to set the time-variant data of different controllable elements in EnergyPlus (e.g. thermostat setpoints, occupant presence) to the values retrieved from the obXML simulation.

3.2 EnergyPlus IDF and ObXML Co-Simulation

Having completed the automated EnergyPlus IDF generation, both EnergyPlus IDF and obXML are automatically exported to FMUs, utilizing dedicated software packages.

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[14] bigladdersoftware - EnergyPlus 9.3 - I/O Reference - Group - Simulation Parameters

[15] bigladdersoftware - EnergyPlus 9.3 - I/O Reference - FMU export from Variable

[16] bigladdersoftware - EnergyPlus 9.3 - I/O Reference - FMU export to Schedule

EnergyPlusToFMU[17], a software package written in Python, is triggered to generate the FMU using EnergyPlus IDF and EPW files as inputs, and obFMU[18] receives the obXML as input and generated the relevant FMU. Both FMUs are then imported to pyFMI to perform the co-simulation.

3.3 Simulation Output – Post Processing

Output of the aforementioned co-simulation is a CSV file, which contains reported values of output variables that have been defined by instances of IDD's Output:Variable class. At this point it is worth mentioning that, by default, the variable names are prefixed, according to the name-coding that the EnergyPlus back-end understands to perform the calculations. However, EnergyPlus provides to the user the flexibility to report the same variables with custom variable names, utilizing the EnergyManagementSystem:Sensor[19] class. The BEP manager is responsible for translating the output-CSV to a meaningful JSON format file that the RenoDSS data management module expects. In order to facilitate this post processing method of the BEP module, instances of the EnergyManagement System:Sensor are generated, whose names are set to the KPI IDs that are listed in Section 2.1.

3.4 Integration Plan in RenoDSS

Table 3 summarizes the integration plan of the BEP module in the RenoDSS. During the first period (M20), whose scope was to early detect major potential drawbacks that may affect the BEP performance in the pre-validation and validation phases, an initial version of interfaces has been released to start experimenting with the RenoDSS and the BEP module data exchange. In M22, based on lessons learnt due M20, additional functionalities that deal with supplementary data transfer requirements for candidate renovation scenarios evaluation will be developed towards delivering the Energy KPIs

[17] FMU Export of EnergyPlus - EnergyPlusToFMU

[18] OB Modeling Tool - obFMU

[19] bigladdersoftware - EnergyPlus 9.3 - I/O Reference - EMS:Sensor

calculation back-end of BEP module, ready to be used for the pre-validation activities on M26. Verification and validation experiments of RenoDSS performed in the pre-validation pilot sites will pave the way to further extensions and refinements of the BEP module to finally deliver the second version of the all RenoDSS components, including the BEP module, well-integrated for deployment and use at the real renovation pilot sites on M30.

Table 3 Integration Plan of the BEP module in the RenoDSS

Integration Activity	M20	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30
Initial integration and testing of the BEP module & the RenoDSS back-end											
1st version of a fine-grained BEP module integration with the RenoDSS engine and UI											
Further improvements on the BEP module based on actual data samples from the BIMERR digital building model creation tools for integration in RenoDSS											
Full integration of the BEP module with the RenoDSS for deployment and use at the real renovation pilot sites											

3.5 Technology Stack and Implementation Tools

According to the BIMERR architecture, the BEP module acts as the RenoDSS backend for the Energy KPIs calculation. Within T7.5, where the RenoDSS UI development and its components integration are taking place, state-of-the-art technologies (e.g. Angular, Typescript, NGRX Entity/Store, Leaflet, and PostgreSQL) are utilized for the presentation (frontend) and the data storage layers, as they will be documented in the D7.9 – *Integrated Renovation Decision Support System 1* [1].

Concerning the business logic layer, the first release of the BEP module has been developed in Python 3.7.6, utilizing backend technologies that are listed in Table 4.

Table 4: Technologies and libraries used in BIMERR BEP module

Name of the technology/library	Version	License
EnergyPlus	9.3	BSD 3-Clause

Name of the technology/library	Version	License
ObXML	1.3.3	BSD 3-Clause
ObFMU	1.3.3	BSD 3-Clause
EnergyPlusToFMU	3.0.0	BSD 3-Clause
pyFMI	2.5	LGPL-3.0 License
IfcOpenShell	0.5.0	LGPL-3.0 License
Flask	1.1.1	BSD 3-Clause
Flask Restful	0.3.8	BSD 3-Clause

EnergyPlus is the simulation engine that performs the Energy KPIs calculation (for further information refer to Section 2.3). IfcOpenShell is an open source (LGPL) library, available in Python, for working with the Industry Foundation Classes (IFC) file format. ObFMU is a tool that, based on the obXML, creates the occupant behaviour Functional Mock-up Unit (FMU) for co-simulation using the Functional Mock-up Interface (FMI). Eppy is a python library for EnergyPlus IDF files and EnergyPlus output files handling, providing functions for navigation, search, and modification of the IDF instances. EnergyPlusToFMU is a software package written in Python used for exporting the building simulation program EnergyPlus as a Functional Mock-up Unit (FMU) for co-simulation. PyFMI is a python FMI library for loading and interacting with Functional Mock-Up Units (FMUs), which are compiled dynamic models compliant with the Functional Mock-Up Interface (FMI). Flask micro web framework and its Restful extension are used to expose the BEP module as a service.

3.6 API Documentation

The data exchange between the RenoDSS data management and the BEP module is achieved as follows:

- IFC, obXML and EPW files, scenario ID, user ID and project ID are sent from RenoDSS data management module to the BEP module via HTTP Post requests to the BEP REST endpoint.
- The BEP module backend data pre-processing, transformation, co-simulation and post-processing methods are performed to generate an Energy KPIs JSON file, which consists the response of the request.

The BEP module API is documented in Swagger as Figure 4 depicts.

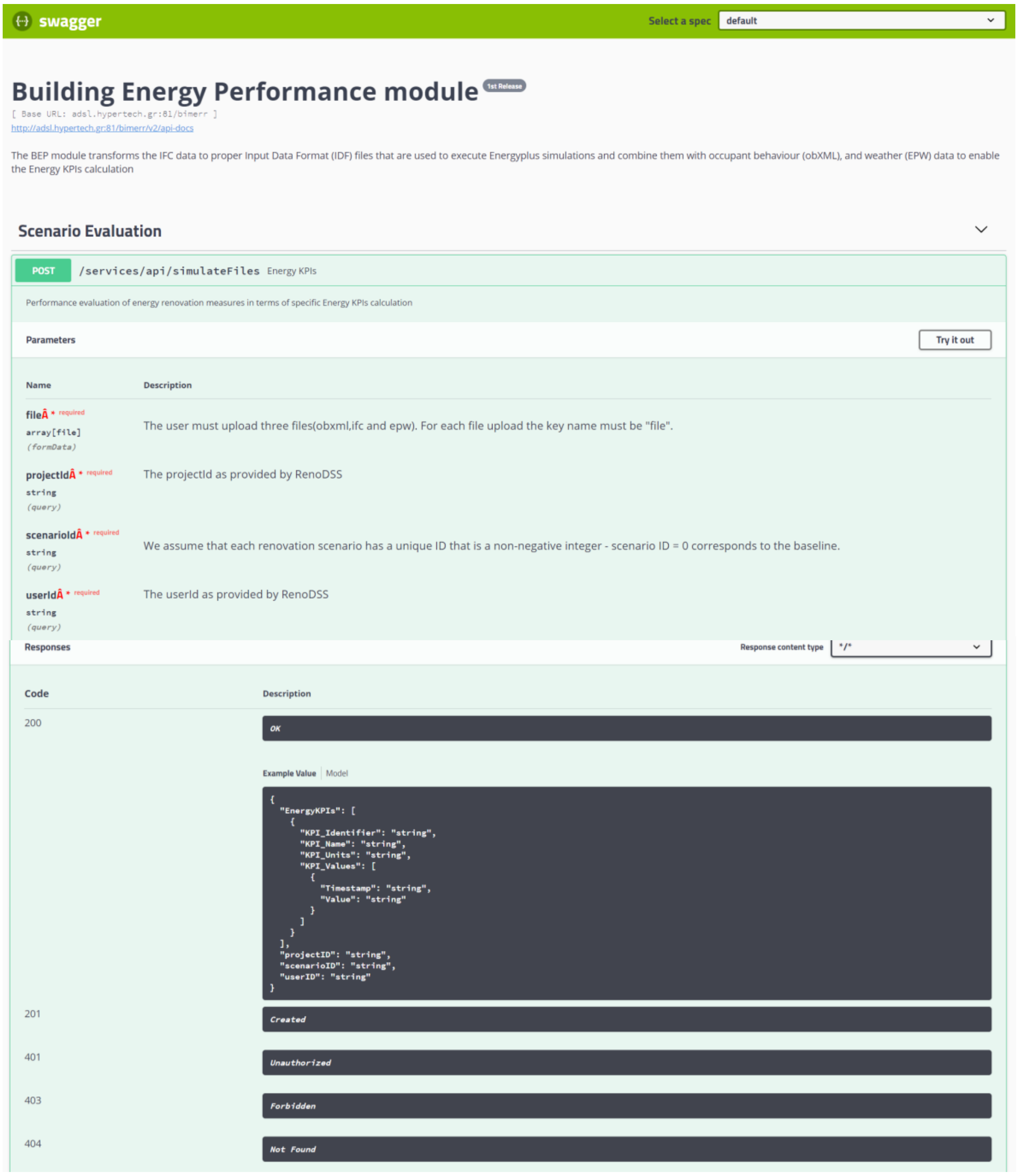

Figure 4 The BEP module API documented in Swagger[20]

[20] http://adsl.hypertech.gr:81/bimerr/swagger-ui.html

3.7 Assumptions and Restrictions

Since the development of BIMERR digital model creation tools for the IFC and obXML data models population is in progress, and the pre-validation and integration activities have been planned for the next period, the first release of the BIMERR BEP module adheres to certain assumptions/restrictions that are listed below:

- Material thermal properties – we assume that the IfcPropertySet that is going to be developed so that relevant information can be captured by the IFC will be aligned with the properties sets requested for the Material, Material:AirGap and WindowMaterialSimpleGlazingSytem objects definition, thus allowing an IFC to IDF one-to-one mapping to be performed;
- HVAC preliminary and secondary components – similarly, to the approach that is going to be followed for the material thermal properties handling, we assume that the under investigation IfcPropertySets which will be used to capture the HVAC energy related data for types of systems that correspond to the actual HVAC system of the pre-validation and validation sites, will meet the respective HVAC templates input data requirements.
- Although EnergyPlus supports simulation of renewable energy generators (e.g photovoltaic systems), IFC cannot capture the relevant information; alternative data models or the IFC extension shall be investigated so that IDF Generator transformation rules will be properly extended.
- Currently, the RenoDSS and the BEP module communication is synchronous; however, since numerous candidate renovation scenarios evaluation requests are going to be sent in parallel, the use of asynchronous communication tools and highly scalable cluster computing techniques to distribute computations and to gather results are going to be investigated and implemented.
- As the BEP module does not interact directly with the BIMERR Interoperability Framework (BIF), we assume that its data requirements are met by information that is stored to the BIF by other BIMERR applications and queried through RenoDSS, while the Energy KPIs are send back to the BIF, utilizing the RenoDSS data management module.

3.8 Installation Instructions

The BIMERR BEP module is, accessible via a rest API, thus installation or downloading of any component is not required.

3.9 Usage Walkthrough

As an initial demonstration of the BEP module performance, a hypothetical building whose IFC file is enriched with the 2nd-level space boundaries [21], internal gains, and material thermal properties, has been selected. It is a two-storey building, hypothetically located in Athens - Greece, consisting of six spaces and a variety of components including transparent and opaque doors, windows, and curtain walls which also contain opaque and transparent sub-components (doors, windows and plates).

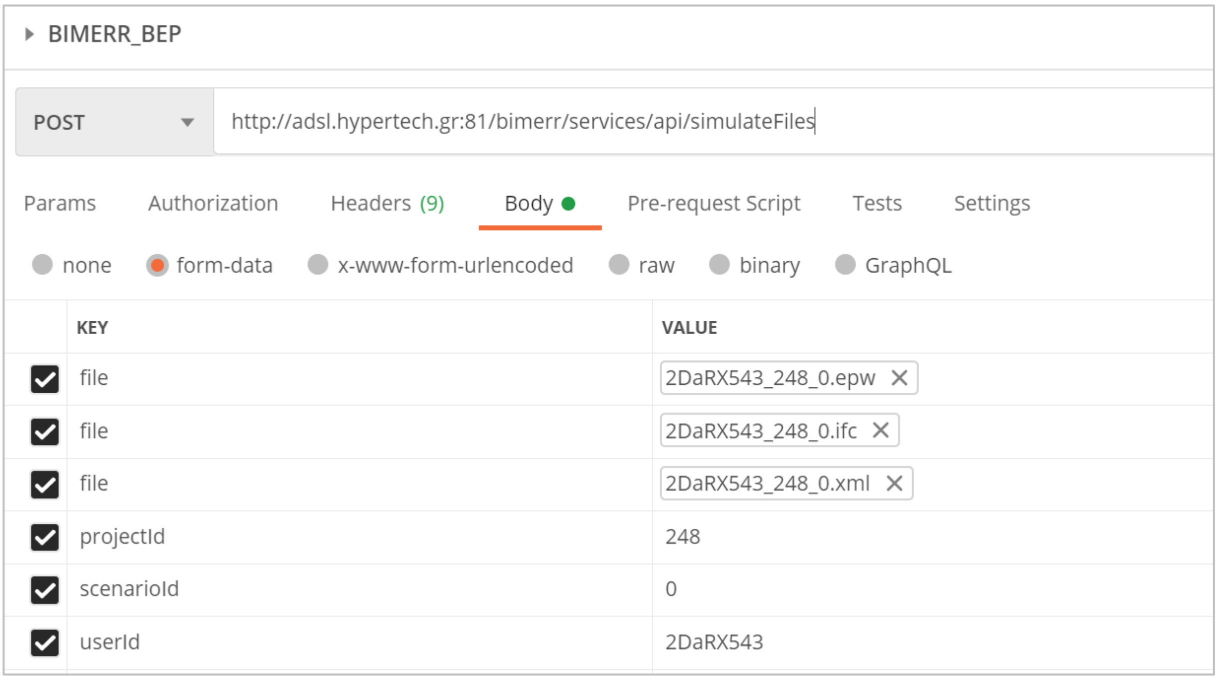

Figure 5 Postman request to the BEP module endpoint for the baseline Energy KPI calculation

The EPW file has been downloaded from the EnergyPlus weather data website[21], while an obXML has been created so that probabilistic models are used to mimic the user actions on the HVAC system's thermostat setpoints.

A Postman request to the BEP module is depicted in Figure 5. Initially, the URL[22] is entered, the EPW, IFC and XML files are uploaded, and the project, scenario and user IDs are defined.

Sending the request, the IFC, EPW and obXML files are received and the IDF Generator's transformation process is performed on the three-dimensional IFC data of the building. Although the BEP module does not provide any UI so that its results can be rendered, to evaluate the performance of the IFC to IDF transformation process, the generated IDF has been downloaded and imported to SketchUp, utilizing the OpenStudio plugin.

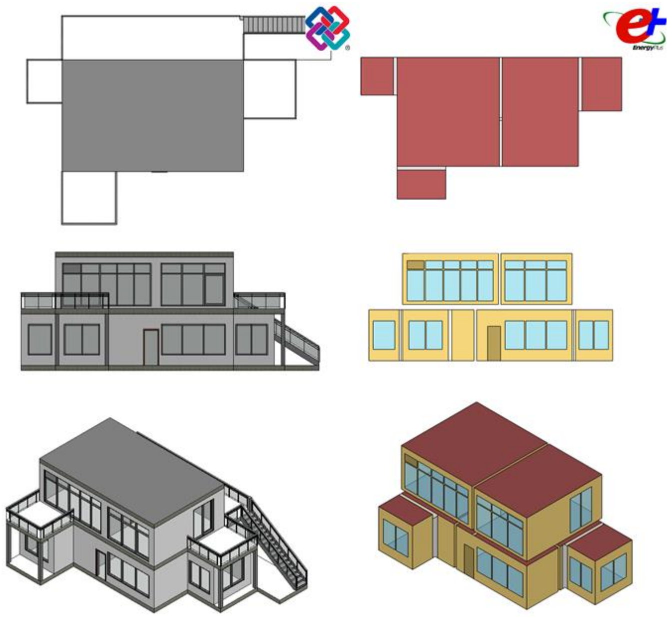

Figure 6 IDF Generator results – Rendering the generated IDF geometry in SketchUp

[21] https://energyplus.net/weather-location/europe_wmo_region_6/GRC//GRC_Athens.167160_IWEC

[22] http://adsl.hypertech.gr:81/bimerr/services/api/simulateFiles

As Figure 6 illustrates, the EnergyPlus Simulation Input Data File Generation tool correctly identifies: (1) Building and Fenestration surfaces; (2) their boundary condition type (different colours); (3) the corresponding surfaces, when boundary condition type is surface"; (4) the surface type; (5) the surface construction; and (5) the 3D geometry representation of each surface.

Moreover, Figure 7 shows that the IDF Generator manages to map information of materials, thermal properties, and construction of the building elements properly.

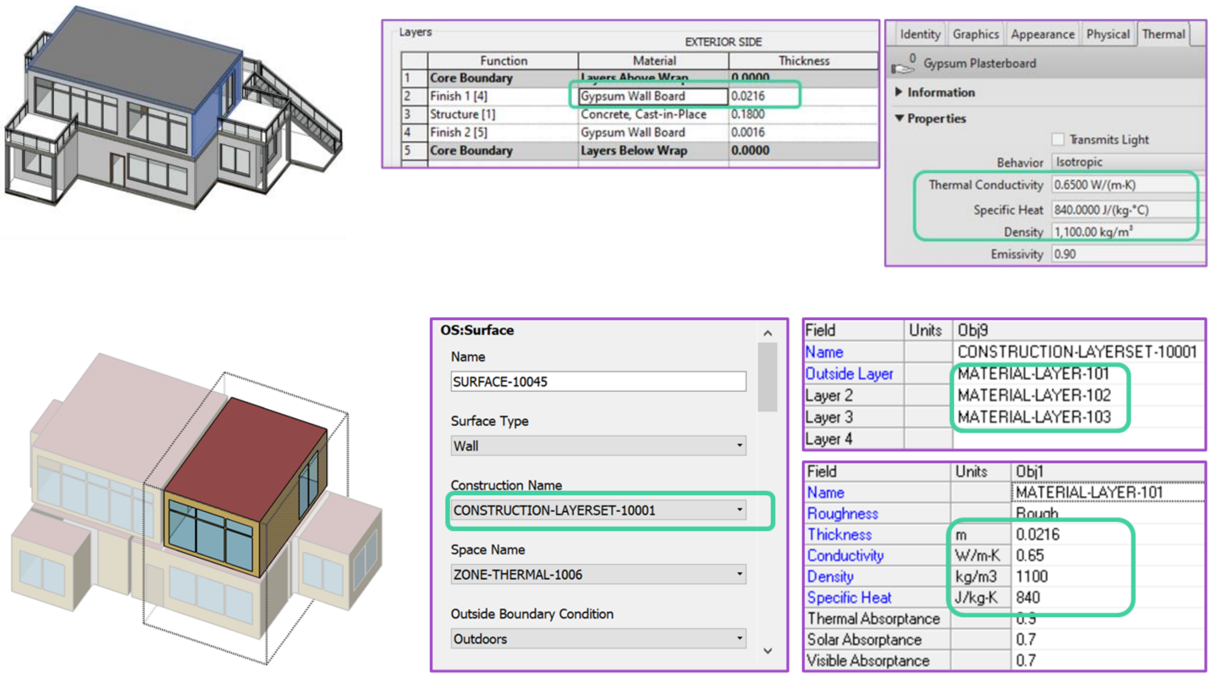

Figure 7 IDF Generator results – Construction (material layers sets) and material thermal properties

With the IDF correctly generated, ObXML and EnergyPlus are co-simulated to eventually calculate the Energy KPIs. A subset of the co-simulated parameters setup is depicted in Figure 8.

The EnergyPlus Output file includes all the data requested and post-processed to populate the Energy KPIs JSON data model, which consists the response to the previously described request (see Figure 5). A subset of that response is presented in Figure 9. Note here that the year values are missing from the timestamps of the Energy KPIs JSON, since the reported KPIs values are for a typical, and not specific, annual meteorological year. In more detail, there are two main different categories of climate data sources: (1) Annual

Meteorological Year (AMY) that includes measured data from a local weather station and for a specific year; (2) Typical Meteorological Year (and more precisely TMY3) that contains representative climate data for a given location - here data for the last 15 years measured from weather stations located in airports are collected and statistically process to conclude to typical/representative weather data for each hour of the year.

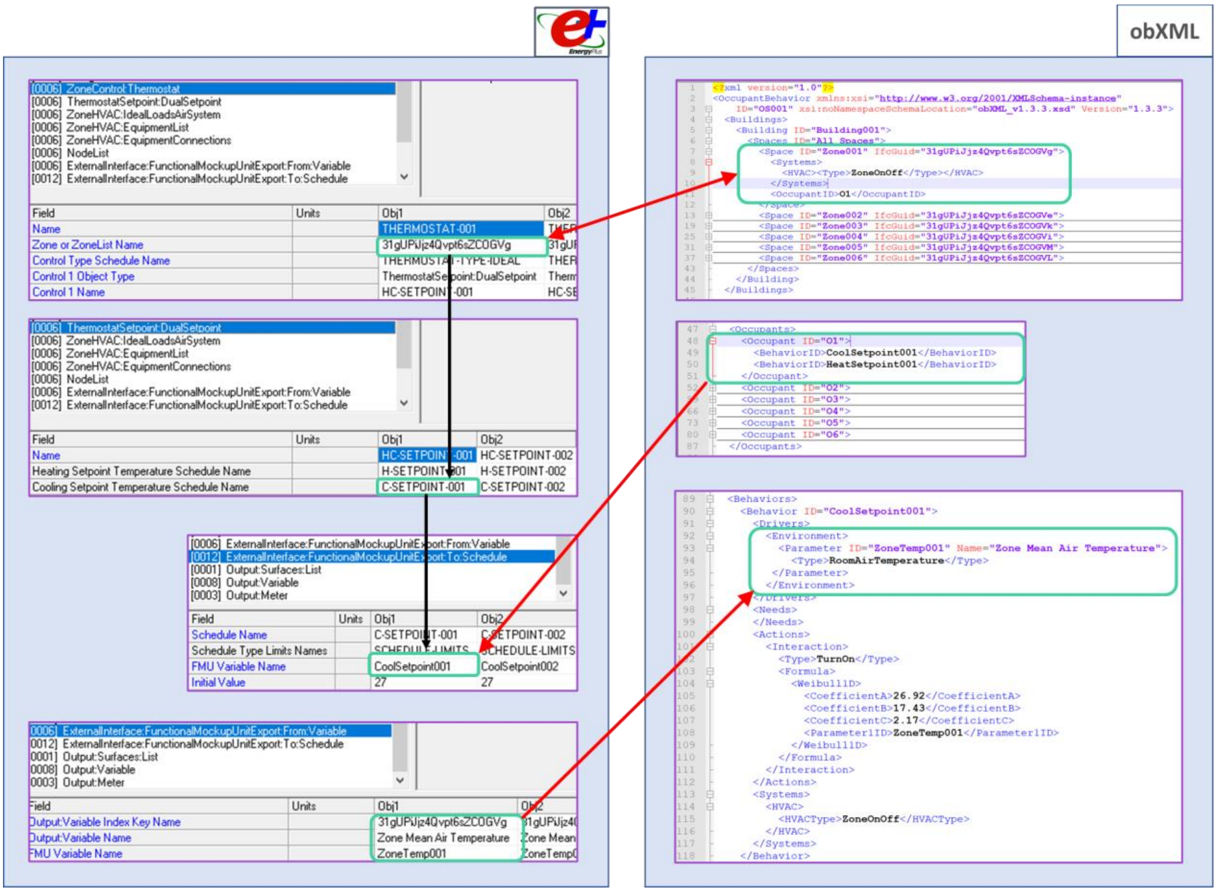

Figure 8 EnergyPlus and ObXML co-simulation: parameters setup – EnergyPlus sends the zone air temperature to and receives the thermostat cooling setpoint from the obXML at each timestep

Although TMY3 files cannot capture local microclimate effects, research studies in the BEPs domain have concluded that AMYs are not appropriate for annual BEP simulation and a decision-making process (evaluation on candidate renovation measures), since a single year AMY is not representative of a longer period. For the specific experiment, a TMY-source EPW file has been used, hence the year values are missing.

```
{
    "userID": "2DaRX543",
    "projectID": "248",
    "scenarioID": "0",
    "EnergyKPIs": [
        {
            "KPI_Identifier": "EN1",
            "KPI_Name": "Total primary energy consumption",
            "KPI_Units": "kWh.m^2.year",
            "KPI_Values": [
                {
                    "Value": "65.2",
                    "Timestamp": "12/31 24:00:00"
                }
            ]
        },
        {
            "KPI_Identifier": "EN2",
            "KPI_Name": "PENRT Primary energy non-renewable total",
            "KPI_Units": "kWh.m^2.year",
            "KPI_Values": [
                {
                    "Value": "65.2",
                    "Timestamp": "12/31 24:00:00"
                }
            ]
        },
        {
            "KPI_Identifier": "EN3",
            "KPI_Name": "Electric energy consumption",
            "KPI_Units": "kWh.m^2.year",
            "KPI_Values": [
                {
                    "Value": "65.2",
                    "Timestamp": "12/31 24:00:00"
                }
            ]
        },
        {
            "KPI_Identifier": "EN4",
            "KPI_Name": "Natural gas energy consumption",
            "KPI_Units": "kWh.m^2.year",
            "KPI_Values": [
                {
                    "Value": "0.0",
                    "Timestamp": "12/31 24:00:00"
                }
            ]
        },
```

```
{
    "KPI_Identifier": "EN8",
    "KPI_Name": "Heating load profile",
    "KPI_Units": "W",
    "KPI_Values": [
        {
            "Value": "3200.0",
            "Timestamp": "01/31 24:00:00"
        },
        {
            "Value": "4650.0",
            "Timestamp": "02/28 24:00:00"
        },
        {
            "Value": "3320.0",
            "Timestamp": "03/31 24:00:00"
        },
        {
            "Value": "2100.0",
            "Timestamp": "04/30 24:00:00"
        },
        {
            "Value": "670.0",
            "Timestamp": "05/31 24:00:00"
        },
        {
            "Value": "0.0",
            "Timestamp": "06/30 24:00:00"
        },
        {
            "Value": "0.0",
            "Timestamp": "07/31 24:00:00"
        },
        {
            "Value": "0.0",
            "Timestamp": "08/31 24:00:00"
        },
        {
            "Value": "0.0",
            "Timestamp": "09/30 24:00:00"
        },
        {
            "Value": "450.0",
            "Timestamp": "10/31 24:00:00"
        },
```


Figure 9 Subset of the Energy KPIs JSON – the BEP module response

3.10 LICENSING

The BIMERR BEP module is a closed source component.

4. Conclusions and Plan for Second Iteration

The focus of this deliverable has been the documentation of Building Energy Performance module; a module that retrieves information for the RenoDSS data management module, transforms that information to proper simulation input data files, launches appropriate simulation engines and aggregates simulation outputs to compute predefined Energy KPIs and communicate them back to RenoDSS.

In alignment with T7.3 work-planning, a survey on existing BEP simulation methods and the selection of the BEP simulation engine that best fits the project objectives have been completed, while the first version of functionalities, data flows specifications, interfaces and messages have been delivered as planned, currently being evaluated in the context of T7.5.

Since this work reflects the activities that have been accomplished for the initial release of the module, assumptions and restrictions have been considered and reported in the homonymous section (see Section 3.7).

With the BIMERR digital model creation maturity-level being estimated "high" in near future, actions will be taken to overcome those assumptions and restrictions. Additional rules and functionalities that deal with the HVAC and renewables data transformation and supplementary data transfer requirements for candidate renovation scenarios evaluation have been planned. Furthermore, towards decreasing the BEP module's response time and taking into account that several renovation scenarios evaluation requests will occur, asynchronous communication tools and highly scalable cluster computing techniques are going to be implemented. On top of that, since the current co-simulation setup significantly increases the computation time, the implementation and the performance evaluation of alternative approaches for the obXML and IDF data-exchange have been planned.

Based on verification and validation experiments performed in relevant environments (pre-validation pilot sites) the BEP module will be further extended and refined to eventually deliver its second version on M30.

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