

Enabling Bidirectional Interoperability between BIM and BPS through Lightweight Topological Models

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Building Performance Simulation (BPS) tools have become prevalent in the Architecture, Engineering, Construction, and Operation (AECO) sector to assess building performance for various purposes. However, some challenges persist in achieving full interoperability between BPS and Building Information Modeling (BIM). This paper proposes a different approach to BIM-BPS interoperability based on creating space-based Topological Models (TM) for data exchange using Visual Programming (VP) algorithms. The VP approach allows for complex geometrical operations, the automatic reflection of changes made to the BIM model in the BPS model, and easy synchronous modification of these models to encourage design exploration. The proposed workflow is tested on the heritage building of the Faculty of Engineering in Bologna, Italy, with the aim of establishing the basis for developing a Digital Twin (DT) of the building for optimising its energy management. This approach can also be used for the early-stage analysis of new constructions, providing a comprehensive view of building performance.

Keywords: Digital Twins, Building Topology, Building Information Modeling, Building Performance Simulation, Building Energy Modeling

INTRODUCTION

Over the past few decades, the use of Building Performance Simulation (BPS) tools has become widespread to assess various aspects of building performance related to architectural design, construction, operation, and control. These computer-generated mathematical models, which are grounded in fundamental physical principles, allow for a comprehensive simulation of thermal, lighting, acoustical, and airflow conditions, providing valuable information for making informed decisions during the early stages of a project (Wilde, 2018). With the rise of Building Information Modeling (BIM), BPS has started to be integrated into the design practice as part of more complex models that are not limited to a single discipline. This integration optimises the information flow and

provides a holistic view of architectural projects for both new constructions and renovations (buildingSMART Italy, 2021). As a result, bidirectional interoperability between BIM and BPS is now expected when designing to collect and process all relevant information about building performance within a single model (Chen et al., 2018).

Despite the frequent use of BPS tools and software in practice and research in the Architecture, Engineering, Construction, and Operation (AECO) sector, two main problems persist. Firstly, BPS simulations are often affected by the so-called "performance gap" (Chong et al., 2021). It means there is a difference between the predicted and the actual performance of a building during its operation. This gap can arise due to uncertainties, wrong assumptions made during the modeling

process, or discrepancies between the design and the as-built statuses. Secondly, there is a lack of bidirectional interoperability between BPS and BIM tools. Current practices often involve creating a second unlinked digital model starting from the BIM for conducting performance simulations. Splitting models can lead to loss of information, repetitive and time-consuming tasks, and miscoordination between designers and performance analysts, ultimately hindering the design process, especially in the early stages.

This paper addresses the latter issue by presenting a different approach for performing BIM-BPS interoperability. This approach is based on creating a lightweight space-based Topological Model (TM) as a medium for data exchange between BIM and Building Energy Modeling (BEM) using Visual Programming (VP) algorithms. The TM abstracts the representation of buildings as an aggregation of cells (spaces) that are delimited by faces (walls, floors, and roofs) and connected by apertures (windows and doors). By considering adjacencies and connections, the TM enhances the BIM by incorporating topological properties of spaces and construction elements. Moreover, it enables the retrieval of information regarding the boundary conditions of construction elements. For instance, in the TM an internal wall is treated as a vertical face that is adjacent to multiple cells, while a roof is considered a horizontal face that is adjacent to a single cell positioned below it.

The use of VP provides numerous benefits. First, it enables complex geometrical operations to match BIM volume-based geometries with BEM surface-based geometries. Second, any changes made to the BIM model are automatically reflected in the TM and BEM models, and vice versa, without manual updates. The need for file export is null, reducing the risk of losing information and avoiding time-consuming, repetitive, and coordination issues. Then, the possibility to synchronously modify these models easily encourages design exploration. Moreover, using VP can also allow access to energy-related data from other sources (e.g., occupant

schedules, energy bills, monitoring data) and use them in simulations to conduct complete and accurate analyses.

The set-up VP workflow is tested on the heritage building of the Faculty of Engineering in Bologna, Italy, to establish the basis for creating a Digital Twin (DT) of the building. This DT will be used as a decision support tool to assist building managers in optimising the facility's energy management during the operation stage. The developed workflow can also be used to conduct early-stage analysis of new buildings.

BACKGROUND

Interoperability is the capacity of computer systems or software to seamlessly access and transfer information without any corruption or reduction in quality. To achieve interoperability, BIM and BPS tools must be able to describe not just the entire building system and its various components but also their hierarchical arrangement, topological connections, mutual dependencies, and any energy-related attributes or features.

BIM to BEM interoperability

The interoperability issue between BIM and BEM has been the subject of numerous research studies. These studies concur that there are still many unresolved issues in developing BIM-based building energy modelling (Bonomolo et al., 2021).

For instance, digital environmental simulations can present a computational bottleneck concerning the complexity of geometry (Panagiotidou and Korner, 2022). On the one hand, BIM-based simulation models can result in models with high polygon counts and, therefore, in more time-consuming and less controlled simulations. On the other hand, many BPS tools need models built on regular squared mesh, such as daylight, Computational Fluid Dynamics (CFD), or safety pathfinding simulations. Moreover, BIM and BEM systems may use different geometry kernels, affecting their performance and compatibility with software tools (Costa and Sicilia, 2023).

Typically, data transmission between BIM and BEM is performed through two file formats: Industry Foundation Classes (IFC) and Green Building Extensible Markup Language (gbXML). Both have their unique advantages. IFC is considered the standard format for information exchange in BIM. On the other hand, gbXML is a format based on rectangular-shaped surfaces and their attributes rather than objects and can store nearly all the building information needed for energy simulation. IFC-gbXML integration is not straightforward because these modelling systems rely on different approaches, languages, and protocols, sometimes incompatible.

While progress has been made in improving BIM-to-BEM interoperability through IFC and gbXML, achieving bidirectional data exchange between BIM and BEM through available software is still challenging. Ideally, interoperability should allow for the energy data of a building to be stored in a single, unified model. However, most current practices involve creating a separate, unlinked digital model (i.e., the BEM) starting from the BIM. This approach to data integration is not optimal in terms of data flow.

A topology-based approach

This research investigates an alternative approach for performing BIM-BEM integration. Following the theoretical assumptions of (Jeong and Son, 2016), the proposed method is based on creating a Topological Model (TM) as a means of data exchange between BIM and BEM by using the Topologic software library (Topologic, 2019).

Topologic unifies various architecturally relevant topological concepts into a single toolkit, creating easy-to-understand models of architectural topology (Jabi et al., 2018). It is based on the premise that the different forms of spatial and material partitioning and connections within buildings can be represented through topological elements. This idea is achieved through the use of a specific information language that aligns well with the data input needs of energy simulation tools, both in terms

of geometry description and property modelling of building elements. The reason behind the use of Topologic is that it works within Visual Programming (VP) environments, such as Grasshopper, which is highly interoperable with BIM authoring tools and BEM calculation engines.

The VP-based approach entails other main benefits concerning the common IFC-gbXML approach, usually based on file export and import procedures. First, VP algorithms enable complex geometrical operations to match BIM volume-based geometries with BEM surface-based geometries. Second, any changes made to the BIM model can be automatically reflected in the TM and BEM models, and viceversa, without the need for manual updates. Then, working within a VP environment eliminates the need for file export and reduces the risk of losing information, also avoiding the time-consuming, repetitive, and miscoordination problems that usually arise during the design process when splitting models. Furthermore, the ability to modify these models easily encourages design exploration during the conceptual design stage.

In contrast, using these tools requires advanced digital skills compared to traditional solutions and, if not managed properly, does not guarantee standardised calculation procedures as commercial solutions follow international or local regulations.

CASE STUDY

The heritage building of the Faculty of Engineering of Bologna is selected as a case study. The building, built between 1932 and 1935, is a valuable example of local rationalist heritage, known for its use of industrial systems, innovative materials, and minimalist aesthetics. With a net floor area of 19,200 sqm and four levels, it has a maximum capacity of 5,000 users, including researchers, employees, and students. Despite its architectural significance, like many buildings of its age, it faces limitations in renovation due to its inherent construction characteristics and historical values. Therefore, accurate energy analysis is needed in the early stage of renovation design to identify areas and strategies

for improving the energy performance of the building.

As mentioned, although this paper presents an application on an existing building, the developed workflow can also be used to conduct early-stage analysis of new constructions following the same procedure. In fact, the VP scripts, grounded in solid theoretical and ontological concepts, are designed to be as general as possible to produce consistent and reproducible results when applied to different case studies.

METHOD AND TOOLS

The methodology for performing interoperable building performance simulations from BIM models is described in this section. As mentioned, it relies on the creation of a topological model as a means for data exchange, which is performed thanks to VP scripts that use Application Programming Interfaces (APIs) to enable direct communication with both BIM and BEM software.

In particular, Grasshopper is used as the VP software. Thanks to the Rhino.Inside.Revit plug-in (McNeel & Associates, 2023), it enables interaction with the APIs of Autodesk Revit, through which the BIM is realised. The TM is created using Topologic, while Ladybug Tools (Ladybug Tools, 2022) are used

to model the BEM and run simulations within the Energy Plus engine.

While the method may seem to result in distinct models (i.e., the BIM, the TM, and the BEM), the aim is to have parallel and interconnected models, each serving a specific function and storing the data needed to perform that function in the most adequate format, avoiding any export operation and data loss. The BIM furnishes the semantic framework; the TM abstracts the geometry from the BIM and prepares it for the BEM, selects the Model View Definition (MVD) required for simulation purposes, and transfers energy-related data; the BEM stores all these data and use them to perform the energy analysis.

The workflow is synthetically described in Figure 1 and is detailed in the following paragraphs.

From BIM to TM

The first step of the workflow consists of modelling the BIM and, starting from it, the TM.

Building Information Modeling. The BIM, realised in Autodesk Revit, represents the elements of the building, their geometries, their semantic relations, and their static properties. It integrates the geometric data of building elements with

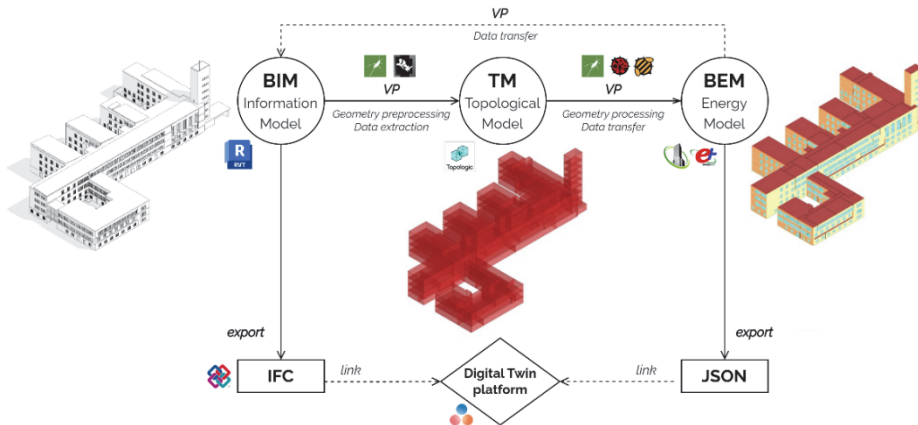


Figure 1
Workflow and
toolchain.

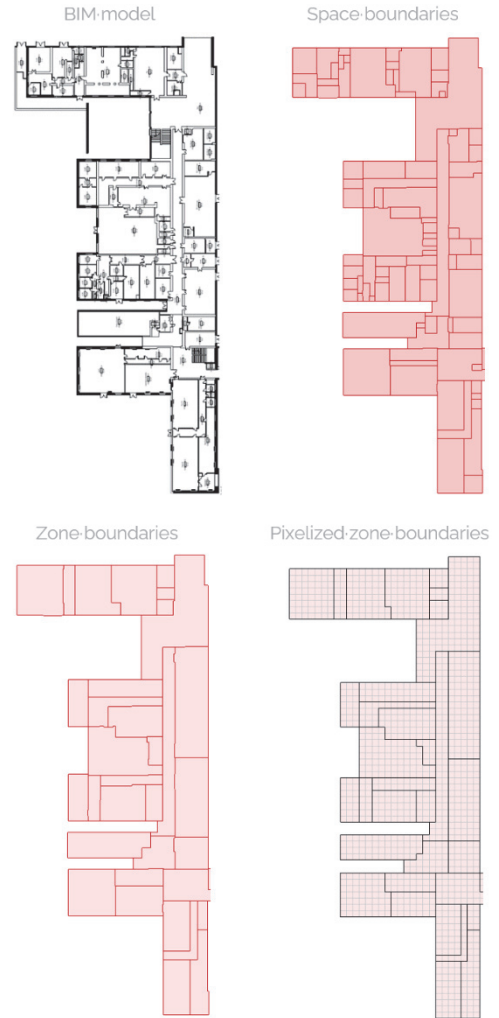
Figure 2
From BIM to TM.
Abstraction of
Revit's spaces in
Topologic cells.

information related to the functions hosted in spaces, the thermal characteristics of the opaque and glazed envelope, and the energy loads of zones. Its semantic structure contains spatial elements (i.e., ifcBuilding, ifcBuildingSorey, ifcSpace, and ifcZone) and construction elements (i.e., ifcWall, ifcRoof, ifcSlab, ifcWindow, and ifcDoor). Particular attention is paid to modelling opening and envelope components from the perspective of their use in the BEM environment.

To deliver the proposed case study's BIM model, the building's geometry was captured through a Terrestrial Laser Scanning (TLS) survey of the external facades, supplemented by technical drawings provided by the owner. Data were collected in situ, from archival documents and by administrators to fill in the energy-related information of the BIM. Moreover, data provided by the university's Asset Management Service (AMS) were used to create reliable occupancy schedules that, stored in CSV files, were linked to the spatial elements of the BIM thanks to unique identifiers.

Topology Modeling. Following the workflow, the BIM space elements are selected from Autodesk Revit with the help of Rhino.Inside.Revit plug-in and their geometry is preprocessed using Grasshopper. Spaces are first grouped into different lists according to the thermal zone to which they belong. The zoning strategy consists in grouping adjacent spaces with similar functions, occupancy patterns, exposure conditions, and HVAC systems.

After grouping, the boundary representations of the adjacent spaces in the same zone are welded to form the geometry of the zones. A step-by-step approximation algorithm is executed to transform the high-resolution geometries of the BIM into simpler and more lightweight geometries, readable from the TM and the BEM. In particular, a controllable pixelisation process is applied to the 2D boundaries of the zones to approximate the original BIM's geometry in a square mesh form (Figure 2). The pixelisation process also ensures that the edges and faces of adjacent zones align properly.



The pixelised zones are abstracted as Topologic Cells using the "Topology.ByGeometry" constructor node. This passage transfers the properties of the BIM zone elements, listed in Table 1, to the topological cells through the "Topology.SetDictionary" function.

Subsequently, the opaque envelope elements, modelled in the BIM as layered objects, are associated with Topologic Faces, which are the planar faces that bind the TM cells. Since the cells serve as the TM's unit spatial element, the faces' properties can be interpreted as cell attributes. Therefore, by associating the TM faces with the BIM objects, the thermal properties of the construction can be transferred from the BIM elements (e.g., walls, roofs, and slabs) to the TM faces and, therefore, to the TM cells.

From the technical point of view, first, Revit's walls, floors, and roofs are referenced in Grasshopper. Then, the association between the TM faces and the BIM volume-based objects is accomplished through a raycasting operation between the TM's surface geometries and the BIM's volume geometries. This step also implies transferring energy-related information of envelope elements (in Table 2) to the TM thanks to dictionaries.

Cell.PropertySet	Cell.Properties
Cell.Common	Zone ID [str], Zone Name [str]
Cell.Relationships	<i>ChildOf</i> : Building [rel], Building Storey [rel], Building Block [rel] <i>ParentOf</i> : Faces [rel], Apertures [rel]
Cell.Quantities	Gross Volume [m3], Net Volume [m3], Gross Area [m2], Net Area [m2], Gross Height [m], Net Height [m]
Cell.LightingAndEquipment	ArtificialLighting [bool], IlluminanceSetpoint [lux], LightingPowerDensity [W/m2], EquipmentPowerDensity [W/m2], LightingSchedule [sch], EquipmentSchedule [sch]
Cell.OccupancyRequirements	IsOccupied [bool], AreaPerOccupant [mq/pp], OccupancyNumber [pp], OccupancType [str], OccupancySchedule [sch]
Cell.ThermalRequirements	IsHeated [bool], IsCooled [bool], IsVentilated [bool], TemperatureSummerMax [°C], TemperatureSummerMin [°C], TemperatureWinterMax [°C], TemperatureWinterMin [°C], HumidityMax [%], HumidityMin [%], NaturalVentilationRate [m3/s-m2], MechVentilationRate [m3/s-m2], CoolingSchedule [sch], HeatingSchedule [sch], VentilationSchedule [sch]

Table 1
Cell properties transferred from the BIM to the TM.

Face.PropertySet	Face.Properties
Face.Common	Face ID [str], Face Name [str], Face Type [str]
Face.Relationships	<i>ChildOf</i> : Building [rel], Building Storey [rel], Building Block [rel], Cell [rel] <i>ParentOf</i> : Apertures [rel]
Face.Quantities	Length [m], Width [m], Height [m], GrossSideArea [m2], NetSideArea [m2], GrossVolume [m3], NetVolume [m2], GrossWeight [kg], NetWeight [kg]
Face.Materials	MaterialLayer1: [Name [rel], Thickness [m], Conductivity [W/mK], Density [kg/m3], SpecificHeat [K/kgK]]; MaterialLayer2: [Name [rel], Thickness [m], Conductivity [W/mK], Density [kg/m3], SpecificHeat [K/kgK]]; MaterialLayerN: [Name [rel], Thickness [m], Conductivity [W/mK], Density [kg/m3], SpecificHeat [K/kgK]]
Face.ThermalProperties	U-Value [W/m2K], R-Value [m2K/W], VolumetricHeatCapacity [J/Km3]
Face.Common	Face ID [str], Face Name [str], Face Type [str]

Table 2
Face properties transferred from the BIM to the TM.

Aperture.PropertySet	Aperture.Properties
Aperture.Common	Face ID [str], Face Name [str], Face Type [str]
Aperture.Relationships	<i>ChildOf</i> : Building [rel], Building Storey [rel], Building Block [rel], Cell [rel]
Aperture.Quantities	Width [m], Height [m], Area [m2], Perimeter [m]
Aperture.ThermalProperties	U-Value [W/m2K], SolarHeatGainCoefficient [float], VisibleTrasmittance [float]

Table 3
Aperture properties transferred from the BIM to the TM.

In the next step, the glazed envelope elements are modelled in the TM as Topologic Apertures, which are the apertures of the faces that delimit cells. Window, curtain wall, and door elements are picked in Grasshopper from the BIM following the same procedure explained for the spaces and the opaque envelope; then their 3D geometries are transformed into 2D surfaces by extracting their 2D profile and projecting it on the TM faces they belong. In this case, the association between the BIM and the TM elements is direct, with one TM aperture corresponding to one BIM element. Following Topologic's hierarchy, apertures and their properties (in Table 3) can be interpreted as face attributes and, therefore, as cell attributes. In the last step of topology modelling, the TM's cells, enriched with BIM's valuable information, are aggregated in a

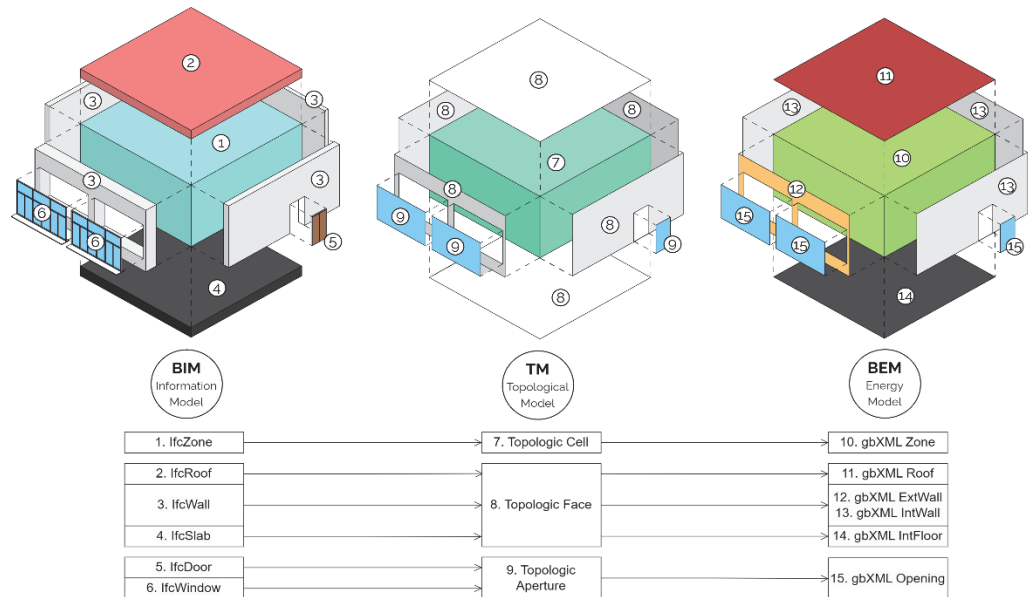
unique Topologic CellComplex, representing the whole building as the aggregation of its zone.

From TM to BEM

At this point, the BEM model is realised starting from the TM model. The geometries and properties of the TM are used as the basis for creating the BEM elements in Grasshopper through Honeybee from Ladybug Tools. The TM cells are transformed in gbXML Zone elements, while the cell faces and apertures in gbXML construction elements.

Federating models. As a result of this new model transformation, each modelled element is contemporarily represented through three different but federated ontologies: the IFC, the Topologic, and the gbXML ones (Figure 3).

Figure 3
Federating IFC,
Topologic, and
gbXML models



One of the key purposes of the ontology federation is to establish a shared understanding of the data and its semantics across various models. This shared understanding is achieved through the development of a standardized and consistent

representation of concepts, relationships, and properties. Through mapping and aligning the data structure of the models, the exchange of data between them is enhanced ensuring that data from one model can be understood and utilized by other

models, regardless of their differences in structure or format. For instance, building zones are designated as "lfcZone" in Revit, "Cell" in Topologic, or "gbXML Zone" in Honeybee. Or, opaque vertical envelope elements are described as "lfcWall" in Revit, "Face" in Topologic, and "gbXML Exterior Wall" in Honeybee. The benefit is that each element representation remains in its native environment performing efficiently the tasks for which the modelling environment was born.

Building Energy Modeling. Once the ontologies are federated, the BEM model creation is brought off to assign to the BEM all (but not only) the BIM's information in Table 1, Table 2, and Table 3. This automated data transfer approach allows for that, if updates are needed to the BEM, new data can be easily inserted in the BIM and automatically reported in the BEM.

Moreover, external dynamic data, which cannot be stored in the BIM, are also added to complete the BEM. They mainly pertain to climatic data and schedules. Regarding the first, the EnergyPlus Weather File (EPW) format is used to model climatic data. This format is composed of a header, which contains basic location information (e.g., longitude, latitude, time zone, elevation, average ground temperatures, and holidays) typically followed by 8760 lines of data, one for each hour in the year, that contains values related to weather parameters such as dry bulb temperature, relative humidity, horizontal and normal radiation, horizontal and normal illuminance, wind speed, sky cover, and others. For setting up the workflow, the EPW file available for the weather station of Bologna Borgo Panigale, Italy, is downloaded from the Energy Plus repository. In addition, context elements are created in Grasshopper to allow a more realistic simulation of shadings (Figure 4). On the other hand, HVAC schedules and occupancy schedules are modelled and input. The formers are given by the building managers; the latters are extracted from the academic timetable, the only available data source for estimating the number of students inside the

case study building. Since each lesson is associated with a specific time, classroom, and course in the AMS, knowing the number of students attending each course makes it possible to make a hypothesis about the planned number of people inside classrooms for every academic year, which impacts the energy behaviour of the building. HVAC and occupancy schedules are created in a CSV file and linked to the BIM, TM, and BEM models, thanks to unique IDs.

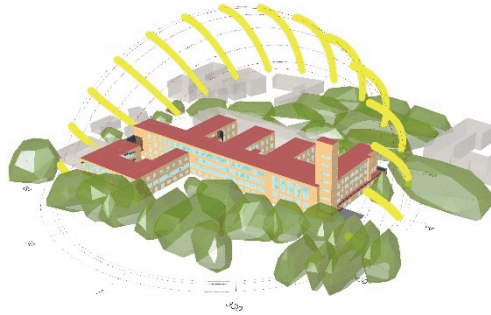


Figure 4
Building Energy
Model of the
Faculty of
Engineering of
Bologna.

Building Energy Simulation. The BEM simulation consists of a physics-based simulation to calculate the energy behaviour of the building. By taking local weather data as input and describing building zones (including geometry, materials, and occupancy), the BEM allows for calculating thermal needs, system response to those loads, resulting energy use, and related metrics.

Before running the energy simulation in Energy Plus, simulation options are set by passing from Ladybug Tools components. In this case study, a simulation was conducted for each hour from January 1st, 2022 to December 31st, 2022 with the purpose of calculating the energy loads (cooling load, heating load, electric light and equipment loads), as well as the gains and losses (people gains, solar gains, infiltration energy, ventilation energy) within each of the 92 zones of the building. At the overall building scale, these inputs resulted in a total of 313.290 smc of natural gas being used for heating, 538.842 kWh of electricity for equipment, and 631.348 kWh of electricity for lighting.

From BEM to BIM

Energy-related data from simulation results are finally integrated into the BIM, and the information loop is closed.

Enriching BIM with energy simulation results.

After running the simulation, the synthesis of the simulated data is sent to the BIM thanks to the Revit APIs. For instance, the estimated energy amount needed annually for heating, cooling, and lighting is attached to each `IfcZone` of the BIM.

Integrating BEM and BIM in a web application. In

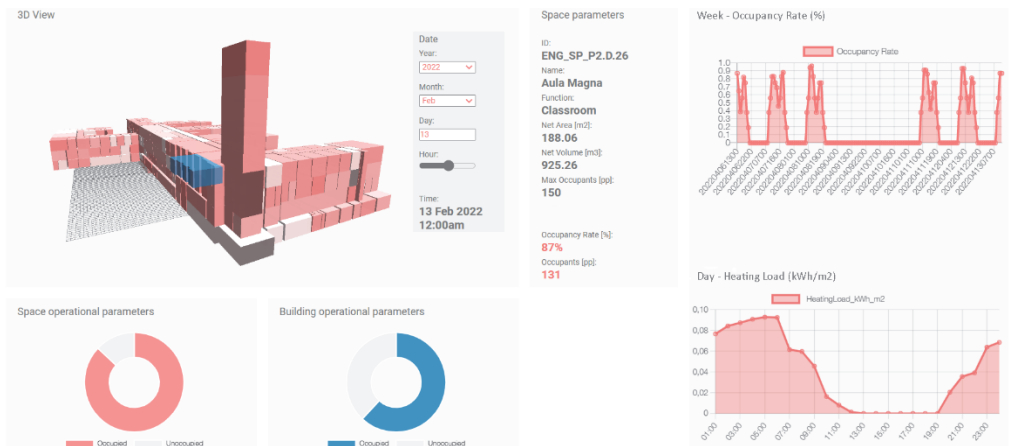
addition, simulation results and BIM data are exported in JavaScript Object Notation (JSON) as objects containing static and dynamic properties of zones. These JSON objects allow for easily accessing

the simulation results in a web application through a simple web browser and visualising them in charts and on the IFC model of the building, hour by hour and zone by zone (Figure 5).

This DT application prototype, developed in JavaScript thanks to the IFC.js library (IFC.js, 2023), enhances the readability of linked BIM and BPS data. It allows fast consultation of data from complex models and workflow for non-digital experts. In this case, building managers without BIM skills could use it to acquire awareness about the energy behaviour of the building.

Future developments will integrate BIM and BPS data with real sensor data, allowing the evaluation of real-time relationships between occupancy and energy in a Digital Twin (DT) environment.

Figure 5
Visualisation of energy results on IFC in the developed web application



CONCLUSION

This paper discusses the interoperability challenges between Building Information Modelling (BIM) and Building Energy Modelling (BEM) systems, which are typically difficult to overcome due to differences in modelling approaches, data formats, and software compatibility, by proposing a different approach for BIM-BEM integration. This approach involves creating a Topological Model (TM) as a means of data

exchange between BIM and BEM. Through VP algorithms, the TM model enables complex geometrical operations, automatic updates, reduced file exports, and easy modification of both models. However, this method requires advanced digital skills and proper data flow management to ensure standardised procedures.

The case study of the heritage building of the Faculty of Engineering of Bologna is chosen to test the method and conduct an accurate energy

analysis. First, a BIM is created in Autodesk Revit to integrate building element geometry with information on thermal characteristics and energy loads of zones. The geometries of BIM's space elements are preprocessed through VP scripts, simplified, and transferred to the TM and BEM using Revit's and Energy Plus' APIs in Grasshopper. Starting from the TM, a BEM model is created using Honeybee from Ladybug Tools.

In the workflow, each element modelled for the energy analysis is represented through three different ontologies - the IFC one for the BIM, the Topologic one for the TM, and the gbXML one for the BEM – but remains in its native environment allowing efficient performance of its intended tasks.

After running the simulation, the results are exported into JSON files, which are linked to the IFC file of the building and visualised in a Digital Twin (DT) application prototype, enhancing information readability and data accessibility for non-digital experts.

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