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EC^3 & CIB W78

2025 European Conference on Computing in Construction

&

42nd CIB W78 IT in Construction Conference

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PREFACE

The joint 2025 European Conference on Computing in Construction & 42nd International CIB W78 Conference on IT in Construction was held from July 14 to July 17, 2025, in Porto, Portugal. The conference gathered more than 280 attendees who presented research results, exchanged ideas and shared experiences within the broader research area of computing in construction. This book of proceedings contains the scientific papers and extended abstracts submitted to the conference and accepted for publication after a rigorous double-blind peer review process.

The EC^3 conference is a core activity of the EC^3. The conference organisation is managed independently by a group of volunteers. The present conference is the 7th annual event of EC^3.

The EC^3 2025 proceedings provide an overview of the program, the contributions made, and the names of the organisations and individuals who contributed to the technical agenda. The scientific paper peer review process consisted of two phases. In the first phase, authors were invited to submit optional abstracts; a total of 57 paper abstracts were submitted and reviewed by their respective research area chairs (track chairs).

The second phase involved the submission of full papers that underwent a multi-round peer review process. Each full paper was reviewed by at least two reviewers from the Scientific Committee, consisting of international experts. Final decisions were made collectively by the relevant track chairs and the Program Chair. Ultimately, 193 exceptional full papers were accepted for inclusion in the proceedings and were presented at the conference.

The papers were presented during one plenary session and 34 technical sessions, covering a variety of topics, including:

- Data Sensing, Acquisition and Analysis
- Data Integration Methods and Digital Twins
- Artificial Intelligence
- Human - Data Interaction
- Product and Process Modelling
- Education, Policy and Standardisation
- Blockchain and Distributed Ledger Technology
- Virtual and Augmented Reality
- Energy Modelling and Monitoring
- Smart Manufacturing and Robotic Construction

The conference featured a poster session in which 25 posters were accepted and presented, following a double-blind peer-review process of the submitted extended abstracts. Consequently, the proceedings contain a dedicated section that also includes the peer-reviewed extended abstracts related to these posters.

Please note: All EC^3 proceedings and session recordings are available at no cost at https://ec-3.org/publications/conference/?id=EC32025. *All conference papers now have a unique DOI and are comprehensively meta-tagged to ensure easy discovery by commonly used search and indexing services.*

The conference also included four sessions dedicated to the technical committee work of the EC^3, including:

- Data Sensing and Analysis (DSA) Committee

- Modelling and Standards Technical (M&S) Committee
- Education (EDU) Committee
- Human - Data Interaction (HDI) Technical Committee

A special conference track was dedicated to early-stage researchers who presented their thesis-related work in a Pecha Kucha competition format. A total of 22 young researchers competed for the best thesis presentation. The event featured three parallel sessions, followed by a final session, all structured as a Thesis-in-3 competition.

A comprehensive workshop lasting a full day was organised for junior researchers on the topic of becoming effective authors for highly-ranked, peer-reviewed scholarly journal papers. Led by Prof. Mirosław J. Skibniewski, the workshop shared insights drawn from his 30 years of experience as the editor-in-chief of a top-ranking international research journal that focuses on construction IT and related technologies.

During a dedicated session, PhD and Junior Researcher-Mentor round tables were conducted under the #MeetTheProfessor motto, aiming to help develop the mentees' goals, career orientation and personal growth.

Technical workshops covered Semantic Web ontologies for the built environment, serious gaming for circularity, ISO 19650-6, and labelled property graphs for asset information management.

In addition to the technical content, the conference also provided opportunities for fellowship and networking in a multitude of informal events.

We extend our gratitude to the EC^3 scientific community, including both academic and industry members, for their contributions and support. We would also like to thank the Scientific Committee (specific acknowledgements are provided below) and express our appreciation to Wahib Saif, Marta Boscariol, Julia Kaltenegger, and Leonor Calado for their invaluable assistance during the conference and its preparatory stages. Additionally, we thank Sobia Bano for maintaining the conference website.

To all EC^3 2025 attendees, we sincerely appreciate your participation and involvement in this conference. We hope this experience provided opportunities to renew friendships and professional relationships, forge new ones, spark exciting new research ideas, and enjoy the scenery and inspiring backdrop of beautiful Porto! We look forward to welcoming you to future EC^3 conferences!

Dr. Ekaterina Petrova, TU Eindhoven, EC^3 Programme Chair
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The **European Council on Computing in Construction (EC^3)** is a recently established society of construction professionals, academics, researchers and national Professional Bodies, aspiring to become the leading European forum in the area of information technology in construction engineering and management.

Role of EC^3

The **European Council on Computing in Construction (EC^3)** advances professional knowledge and improves engineering practice in the built environment by fostering research, education and policy in current and emerging computing and information technologies.

EC^3 is founded on the following four pillars and corresponding Technical Committees:

- DSA: Data Sensing & Analysis
- M&S: Modelling & Standards
- HDI: Human - Data Interaction
- EDU: Education

EC^3 interacts strongly with other Architecture, Engineering, Construction and Facility Management (AEC/FM) societies in related areas, strengthen the collaborations between academia and industry in topics related to **EC^3**'s mission, spearhead research on such topics, identify and promote effective ways to advance the state of knowledge and the level of education and practice in these topics, assist in the making of policy, and support existing and new related specialty conferences and publications.

Technical Committees

The role of all technical committees is to:

- Gather, maintain and disseminate information on the application of the committee's area to AEC/FM
- Organise and support joint research activities in the committee's area
- Organise and support conference sessions, workshops, and meetings in the committee's area
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The organisers would like to thank the Area Chairs and the Scientific Committee members of the European Council on Computing in Construction for their contributions to the paper review and selection process. We would also like to thank the Technical Committee members for their invaluable contributions and hard work to deliver the other activities that took place in addition to the mainstream paper presentations.

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CIB W78 Conference on IT in Construction

Porto, Portugal
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TOPOLOGICAL BIM FOR OCCUPANCY-BASED INTEGRATED ENERGY AND SAFETY ANALYSIS OF HIGHER EDUCATION BUILDINGS

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Abstract

Despite the recognised benefits of BIM and Building Performance Simulation (BPS) in managing built heritage, developing and adopting them remains a resource-intensive task. Interoperability issues make it difficult to effectively use BIM data for performance assessment in building management, limiting the possibilities of combining, integrating and using building performance data to create knowledge-based tools supporting decision-making. To address the BIM-BPS interoperability issue, this paper introduces a semi-automated approach for developing space-oriented, BPS-compatible BIMs. Applied to a university building, the presented method generates semantically rich models for integrated, occupancy-based energy and fire safety analyses, demonstrating scalability for large stocks.

Introduction

According to several studies, a thorough understanding of occupancy data is essential for effective building management (Ding et al., 2022). Occupancy conditions, indeed, significantly influence building utilisation and management practices, directly impacting both operational and strategic aspects, including maintenance, operation, and safety. Recognising and integrating occupancy data within digital building management frameworks is, therefore, critical for supporting strategic planning, enhancing daily building operations, and optimisation financial and technical resources allocated for real estate portfolios . Nonethless, this research field is still one of the less-developed areas of building science (O'Brien et al., 2020). Several technical issues still need to be resolved to integrate the occupancy dimension into digital management and assess its impact on crucial areas like energy and safety management, i.e., establishing common languages, interfaces, and protocols for a common framework, determining how to grant data matching, improving usability and interoperability of digital systems, and, above all, shifting from static to dynamic data collection approaches (Jin et al., 2021).

Among the many issues, established technologies in building design, such as BIM and BPS, still struggle to achieve full adoption within building management processes. On the one hand, BIM procedures demand significant time and resources. On the other, substantial challenges remain in achieving interoperability between BIM and BPS systems, mainly due to differences in their approaches to information and geometry modelling (Chen et al., 2018). This discrepancy, further complicated by software compatibility issues, leads to inefficient or erroneous data exchanges between BIM and BPS. As a result, it is common practice to rebuild BPS models from scratch whenever needed for analysis contrasting with the potential efficiency of using a single digital system to manage all relevant building information and conduct performance analysis.

Within this context, the DIGITMAN project is being implemented to enhance the digital management of building stock based on occupancy data. The project aims to impact the maintenance, operation, and safety management of public property portfolios, with the goal of introducing digital procedures capable of correctly allocating resources and expenses in building management while satisfying occupancy needs. As part of the project's results, this paper presents a method for developing federated digital models suitable for combined, occupancy-based energy and safety analysis. The proposed approach employs a topology-based workflow that enables the semi-automatic generation of BIMs. These BIMs serve as the foundation for deriving surrogate Building Energy Models (BEMs) and Building Safety Models (BSMs). By utilising these derived models, the workflow supports integrated analyses explicitly assessing how occupancy management choices influence these two critical aspects, which is particularly valuable for managing complex real estate portfolios, such as university campuses, where shifts in space usage directly affect building energy performance and occupant safety. The method is demonstrated through the application on a pilot site belonging to an Italian university campus.

Background

Automated BIM for existing buildings

The time and money required for manual BIM are major obstacles to its adoption in large building portfolios. Creating highly geometrically detailed models of a building's physical components is not always beneficial, as they can be excessively computationally demanding to manage, cause interoperability issues with BPS, and lead to inconsistencies in digitising large portfolios. For these reasons, recent years have seen increased investigation into computer-aided BIM generation (Banfi et al., 2022). Four major research areas have mainly emerged: (1) automated point cloud semantic segmentation, labeling, and tagging; (2) automated conversion of 3D point clouds to BIMs, i.e.' scan-to-BIM'; (3) automated conversion of 2D drawings to BIM, and (4) topology-based BIM model generation. The combination of the last two approaches appears particularly promising for two reasons. First, by not requiring digital surveys to obtain point clouds, they eliminate the need for extensive investments for conducting surveys, post-processing, and converting data, which is especially important for large portfolios consisting of dozens of buildings (such as university campuses). Second, topological modelling of buildings can facilitate the transition from product-oriented to space-oriented BIM, which is crucial for adapting BIM to BPS applications (Jabi and Chatzivasileiadi, 2021).

BIM-based energy modelling

With the increasing popularity of BIM, BPS has started to be used in management procedures as part of more complex cross-disciplinary models. Still missing, nevertheless, is bidirectional communication between BPS and BIM. Current practices often require beginning with the BIM and creating a second, unlinked digital model to conduct performance simulations. This leads to information loss, time consumption, repetitive steps, and misconceptions.

Numerous research studies on the interoperability issues between BIM and BEM indicate that many issues remain unresolved. A central gap is that BIM-based energy simulations may result in processing bottlenecks because of the intricacy of BIM geometry, leading to longer and unpredictable simulation runs. Another gap is related to the exchange of information between the typically available data formats for BIM and BEM, such as IFC, gbXML and EnergyPlus Input Data Format (IDF). Indeed, not all the properties codified by IFC are transferable to gbXML and IDF, and viceversa.

There have been several attempts to close the interoperability gaps like improving manual "export-import" procedures using commercial instruments (Porsani et al., 2021), developing custom tools to enable BEM geometry reconstruction from BIM (Yang et al., 2022), and integrating custom automation within software already used by professionals (Kamel and Kazemian, 2023). Nevertheless, while they address interoperability challenges, they primarily focus on optimising the conversion process from BIM to BEM, rather than on joining the generation of both models, which is a key objective of this study.

BIM-based safety modelling

BIM is also relevant to managing safety in buildings, for instance, for analysing risk conditions implying the activation of evacuation process.

When connected to Building Automation Systems (BAS) and Computerised Maintenance and Management Systems (CMMS), BIM can support data-driven risk assessment, supplying data to facility managers about the current use and status of the spaces (Yakhou et al., 2023). Moreover, the feature characterisation for sensitive building components (e.g. doors), systems (e.g. alarm, fire suppression), and spaces (e.g. corridors, staircases, safe areas), as well as for the occupants (in terms of number, position and typology over time), can ensure risk assessment through both BPS (D'Orazio et al., 2024) and quasi-real-time approaches (Yenumula et al., 2015).

Predominant applications in the safety management field are related to fire safety, given its relevance according to the regulatory framework. Nevertheless, although previous works demonstrated the capabilities of BIM-based methods, current approaches seem to be still limited in supporting decision-makers in simply evaluating the impact of operation choices (to improve the scenario from a "how-to" standpoint) and possible alternatives in building transformation (in a "what-if" perspective), considering the correlation between building spaces and occupants only in single domains like fire safety or energy efficiency (Malagnino et al., 2022). In this sense, the connection with common BIM-based modelling issues is fundamental to ensure an occupancy-oriented and multi-purpose approach with other facility management pillars, such as energy efficiency, occupancy optimisation, and maintenance management, which can take advantage of multicriteria analysis.

Methodology

Overview

The proposed methodology is organised into several phases: (1) Topological BIM, (2) BIM-to-BEM, (3) BIM-to-BSM, and (4) multicriteria analysis (Figure 1). The first involves semi-automatically creating the BIM enriched with all the information necessary for energy and safety analyses, also called Topological BIM (TBIM). These refer to space-oriented, topological information-rich models, suitable for direct transformation and use in simulation environments (Massafra et al., 2024). The second step comprised the automated BIM-to-BEM conversion. Similarly, the BIM is transformed into a BSM in the third step. In the final phase, simulations are run, and the results are interpreted in an integrated manner using project-defined KPIs to identify the optimal management strategies regarding space use, energy needs, and occupant safety. The first three phases are presented in this paper, while the last, under development, will be the subject of future publications.

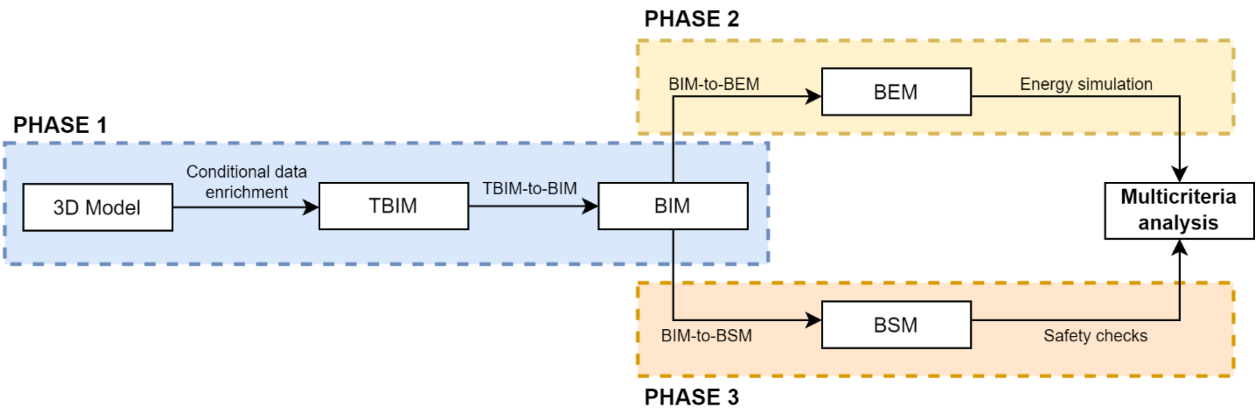

Figure 1: Methodological overview.

Phase 1: Topological BIM

The TBIM process, synthesised in Figure 2, has been conducted using a methodology developed in previous research (Massafra et al., 2024).

3D modelling

The initial step for delivering the TBIM is to model the building's geometry. This is done by creating a closed 3D BRep object for each building space by retracing the administrators' CAD drawings in a 3D modelling environment. This volume, representing the gross shape of the space boundary, is then transformed into a Topologic "cell", serving as the foundational spatial unit in the digital model.

Topology modelling

The topological relationships between the model's core elements are established in the second step. Thanks to Topologicpy, the cells are combined into a higher-level spatial entity known as the "cell complex", a digital model consisting of topologically interconnected spaces and binding surfaces (i.e., the "Collector Model") to transform the geometric cells into topological cells. Although the cells do not contain any data at this point, they are prepared to be populated with information. For this reason, they are called "Informational Collectors," serving as the primary data aggregators in the modelling process.

Information enrichment

In the third step, conditional modelling assigns information to the elements within the Collector Model.
First, functional data is added to the Collectors by attributing "Informational Load Dictionaries" (ILDs) to them. ILDs are JSON dictionaries, each representing a specific space occupancy type (e.g., office, classroom, corridor, etc.) and containing relevant operational and safety data (e.g., thermal setpoints, electricity loads, area per occupant, etc.). To enrich a Collector, a space occupancy type is assigned to it, choosing between the occupancy types modelled in the ILDs, and the corresponding ILD is transferred to the corresponding cell, enriching it with the ILD's embedded data. Next, after adding data to the cells, ILD information is transferred to the adjacent faces, binding the cell by executing topological queries. For instance, a partition wall is informed of the occupancy types of the spaces it delimits (e.g., "corridor-office") and respective data (e.g, "unheated-heated"). The faces then undergo additional data enrichment using the "Informational Rulesets" (IRSs), mainly containing construction data about envelope components (e.g., thickness, material, and thermal properties of walls, floors, roofs and openings). These key-value dictionaries contain "conditions" and "styles" applicable to faces. The conditions specify the property values a face should have for applying the IRS to it, while the styles define the new data to be assigned to the face if it meets the conditions. The assignment of IRS data is also carried out through topological queries. Each IRS is applied iteratively to each face within the Collector Model. The condition values are accessed and compared to the face's properties for each face. If a match occurs, the dictionary containing the style data is added to the face; if not, the iteration proceeds to the next face. The outcome is the so-called "Style Model", a Topologic cell complex containing the ILDs' data (operational data) and IRSs' data (construction data).

BIM modelling

To finalise the BIM, the apertures are created. They include doors, holes, and windows. Doors represent apertures allowing for horizontal passage between adjacent cells on the same storey, while holes for vertical passage (e.g., between staircases). Windows, instead, link the cells to the external environment. Such apertures are modelled as face elements in Topologicpy, based on the IRS data associated with the faces hosting them.
Subsequently, the Style Model is converted into a Topologic graph to perform graph analysis and detect and correct any errors in the topology modelling process. The outcome is the TBIM, a Topologic cell complex semi-automatically populated with data relevant to BPS analysis. The components in this model (i.e., cells, faces, and apertures) form a network of interconnected objects suitable for direct transformation into BEM and BSM.
As the last substep of the BIM phase, using pyRevit and aligning Topologic's class hierarchy with Revit's and IFC's element classes, the Topologic TBIM is

transformed as an Autodesk Revit model. Following this, minor manual adjustments are made to specific instance objects in Revit and direct IFC export is performed. For example, TBIM's apertures, by default placed at the centre of faces, are repositioned as needed, and any errors in construction data assignments to faces and apertures are corrected. Moreover, the properties that cannot be represented in the ILDs on a functional basis and need to be assigned space by space are added to spaces (such as for some specific safety attributes). All these modifications are synchronised with the Topologic model. The outcome is a streamlined BIM model, available in Revit, IFC, and Topologic JSON formats, containing all the essential information for energy and safety analyses.

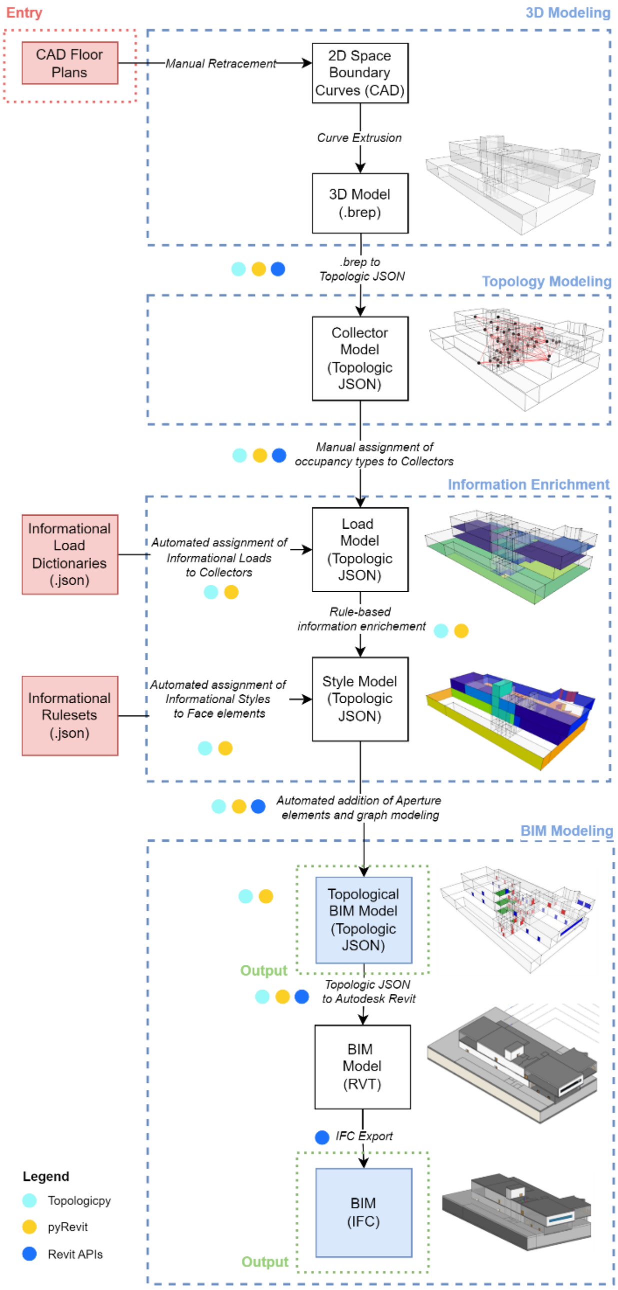

Figure 2: Topological BIM process.

Phase 2: BIM-to-BEM

The BIM-to-BEM conversion uses a Python algorithm that aligns Topologic's and IFC's element classes and properties with those of Ladybug Tools (via the Honeybee Energy APIs) and EnergyPlus (EP) (via the Eppy library). The process consists of the following steps (Figure 3).

Spatial BEM

In the first step, the zoning and geometry processing of the TBIM is performed. In particular, the Topologic TBIM, which has wireframe geometrical representation, is used to model the BEM's geometry.

First, the TBIM cells are aggregated into Topologic cluster objects representing the BEM's thermal zones. The zoning process makes use of the topological methods to cluster neighbor cells and ML techniques (i.e., K-Means clustering) to further group them according to their occupancy and operational data, which are retrieved from the IFC model (for this application, the attributes considered for space clustering are: "is occupied", "is heated", "is cooled", and "area per occupant"). Second, aggregation operations like sum, average, weighted average, minimum, and maximum are executed to transfer the cells' data pertinent to energy analysis to the thermal zones. Following that, by integrating Topologicpy with the Honeybee (HB) APIs, the Topologic faces are converted into HB faces, and the Topologic apertures into HB apertures. Zone by zone, HB faces and apertures are given as input to the HB "Room" method, creating the energy zones forming the "Spatial BEM" in the HBJSON format. When creating the HB model, the boundary conditions between the HB faces that make up the model (i.e., "outdoor", "adiabatic", "ground") are automatically computed. Moreover, the faces of the building adjacent to other buildings are manually set to "adiabatic". The result is the "Spatial BEM" in the HBJSON format.

Topological BEM

The second step involves creating the "Topological BEM" by adding construction data to the Spatial BEM. Opaque envelope data is extracted directly from the "IfcMaterialLayerSets" associated with the "IfcWalls" and "IfcSlabs" in the IFC model, getting the thickness, conductivity, density, and specific heat of the "IfcMaterials" composing the layer sets. IfcMaterials are thus converted into HB "EnergyMaterial" objects, which are then used within HB "OpaqueConstruction" objects. Subsequently, the thermal data of the apertures is transferred to the components of the HB model, with glazed component data (thermal transmittance, solar heat gain coefficient, and visible transmittance) extracted from the "IfcWindowTypes" and "IfcDoorType" of the IFC, respectively converted into HB "WindowConstruction" and HB "Door" objects. The infiltration rate of the envelope is also set during this step.

Full Topological BEM

The third step involves creating the "Full Topological BEM" in the IDF format by setting space operational data,

occupancy and HVAC schedules and context standings to the Topological BEM.
After converting the HB model into IDF, static operational data are transferred from the IFC to the IDF. Occupancy data assigned zone by zone to IDF "People" elements includes people per floor area in operational conditions. Lighting data, assigned instead to IDF "Lights" objects, consists of the electric power density of lighting devices. Similarly, equipment data, assigned to "ElectricEquipment" IDF objects, include the electric power density used by electrical appliances. Thermal and humidity control data are assigned to IDF "HVACTemplate: ZoneIdealLoadsAirSystem" objects. These mainly include temperature and humidity setpoints. Finally, ventilation data are assigned to "DesignSpecification:OutdoorAir" objects, which specify the method for calculating outdoor air changes, the outdoor airflow per person and zone floor area.
For modellig the schedules, input schedule data is sourced from JSON files containing schedules formatted as the HB APIs require for modelling the "ScheduleRulesets". These data are then transformed into IDF "Schedule:Compact" objects, such as occupancy schedules (occupancy density in each zone for every hour of the year) and lighting and equipment schedules (percentage of power usage for lighting and equipment per hour) and boolean types, such as the availability schedules for heating, cooling, and ventilation systems.
Finally, to simulate shade effects on the model, context elements that cast shadows on the building (vegetation, surrounding buildings, shading systems) are modelled within a 3D modelling environment, exported as BRep entities, converted into Topologic faces, and then linked to the BEM as "Shade" elements.

Calibrated BEM

In the last step, the simulation parameters are configured through Eppy, the output variables (which refer to the KPIs to be analysed through the simulation) are set, and climatic data are inputted into the BEM using the EPW format. Simulations are iteratively run, and the BEM is calibrated and validated. The calibration of thermal demand is conducted through a tuning process, which involves comparing measured indoor temperature data (collected via sensors) with simulated indoor temperature data generated by EP. This process includes adjusting temperature setpoints until the difference between the average measured and simulated temperatures is less than 1°C each month. This approach relies on the principle that energy demand is directly proportional to the temperature difference between the interior and exterior environments. Therefore, when simulated indoor temperatures closely align with actual measured temperatures, the simulation model is deemed suitable for accurately estimating thermal demand. In contrast, electricity consumption related to lighting, equipment, and ventilation is calibrated using actual electricity consumption data collected from the building. The output model is used to run EP simulations and calculate energy-related KPIs.

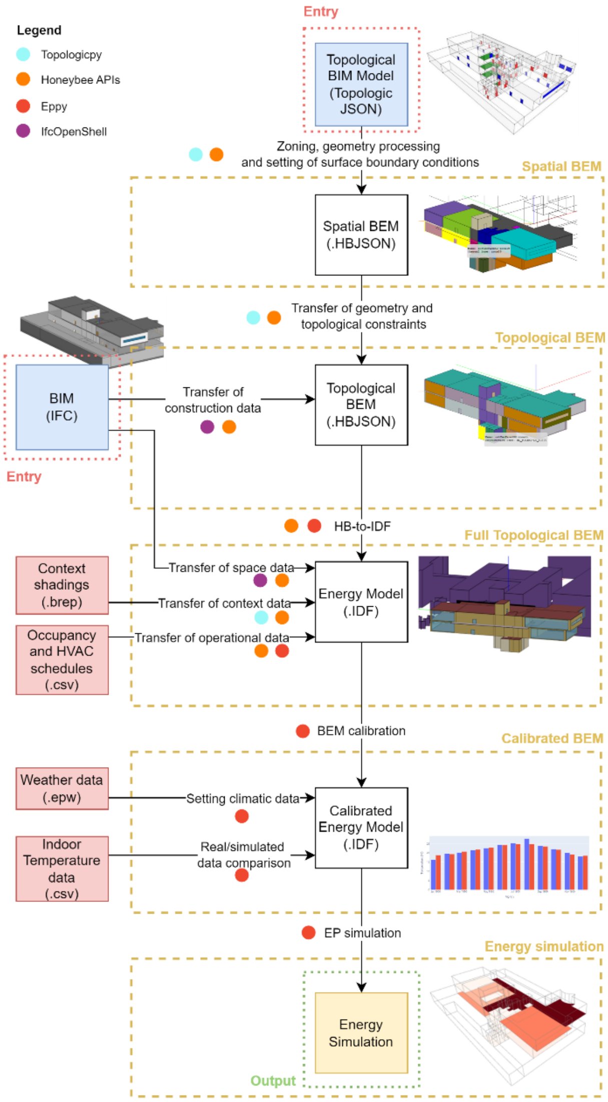

Figure 3: BIM-to-BEM process.

Phase 3: BIM-to-BSM

The BIM-to-BSM conversion, in Figure 4, is achieved using another Python algorithm, which aligns Topologic's and IFC's classes with the Italian fire prevention code (Ministry of Interior (Italy), 2020).
By using Topologicpy, three distinct graphs are created to perform the checks required by the fire safety code on the IFC: the "Passage", the "Isovist", and the "Skeleton" graphs. These graphs are data structures composed of nodes and edges that respectively represent objects (including. Spaces, corridors and openings) and the relationships between them while also allowing for embedding semantic information (class membership in the ontology) and attributes (e.g., the number of people in a space or the width of a door).

Passage graph

The "Passage Graph" maps the relationships of passage between the various spaces in the building. It is an "ageometric" graph where nodes represent spaces or doors and edges connect spaces to adjacent doors.

To construct the passage graph, the geometry of each door is processed as a BRep using IfcOpenShell, and a bounding box is then computed for each door using Topologicpy. Then, through Topologicpy, each IfcSpace object is also processed into a BRep representation and transformed into a Topologic Cell. To establish connections, vectors are emitted from the bounding box of each door, directed outward along the door's normal and extending in both directions. Whenever these vectors intersect a space, a connection is determined between the respective door and space. This relationship is then mapped into a Topologic graph by creating edges linking the centre of the door to the centre of intersected spaces.

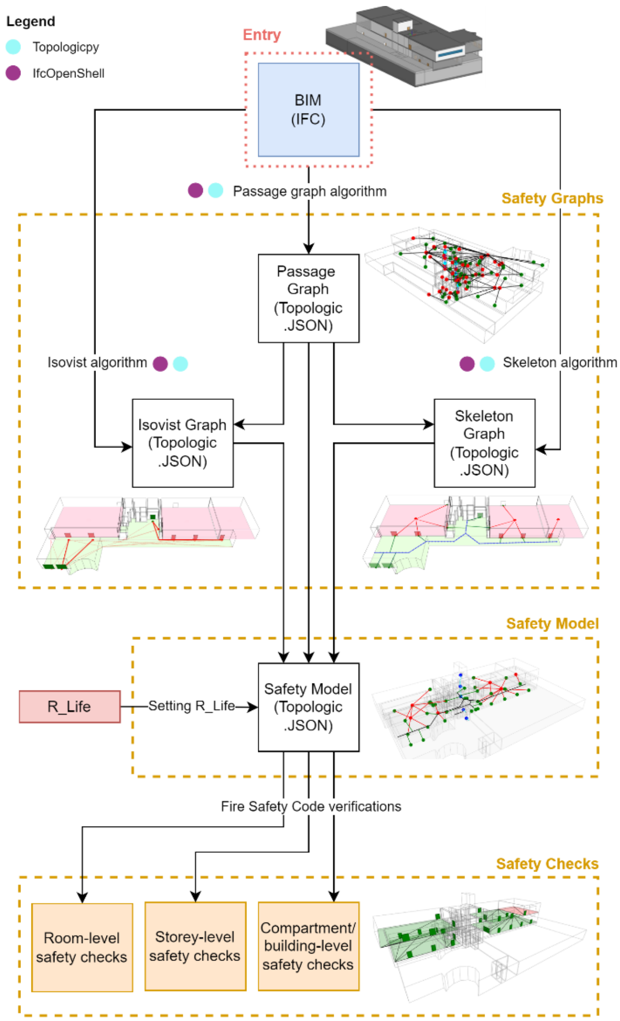

Figure 4: BIM-to-BSM process.

Isovist graph

The "Isovist Graph" helps determine the shortest path connecting occupied spaces to the nearest emergency exits on the storey. It is called "Isovist" because its underlying algorithm is the isovist algorithm, which corresponds to the "straight-line" method required by the Italian Fire Safety Code for calculating evacuation route lengths. To generate the isovist graph, for each "IfcBuildingStorey" in the IFC, the isovist algorithm is iterated from every internal door to every emergency door. The process continues until a direct line connecting the occupied door to the emergency door is found or until a polyline passes through the occupied door (the emergency door) and all intermediate concavity points are identified. Once constructed, the resulting lines are grouped in a Topologic graph that the shortest path algorithm can process to find the shortest route between the occupied and emergency doors.

Skeleton graph

The "Skeleton Graph" is used to map the flow of people through the building's evacuation routes and to perform necessary checks, such as verifying corridor widths based on the number of people using them. This graph is named according to its underlying algorithm: the skeleton algorithm. It is generated by processing each circulation space in the IFC model. The process involves converting the circulation space into a Topologic cell, extracting the lower face of the cell, and applying the skeleton algorithm to it to generate the skeleton wire the skeleton wire undergoes further processing: 1) non-ridge wires (not on the skeleton's ridge line) are removed, 2) the ends of the skeleton are extended to reach the boundaries of the IfcSpace, 3) internal and emergency doors are connected to the nearest vertex of the skeleton wire. At the end of this process, all resulting edges are grouped into a Topologic graph for each circulation space. These space-level graphs are then merged storey by storey, and finally, connections between floors are added through staircases.

Safety checks

The three graphs are then used to perform the below-mentioned checks according to Italian Fire Safety Code about "Deemed-to-satisfy" solutions. In particular, verifications depend on the risk profile concerning human life safety R_{life} assigned to each compartment/building, since it implies different levels of assignment criteria for evacuation routes performance and thus specific "deemed-to-satisfy" solutions. RlIn particular, R_{life} depends on the combination between the compartment/building intended use (i.e. the most relevant or frequent one) and the hazard conditions (i.e. the heat release rate - HRR). It can be assigned according to a tabular approach provided by the Code itself,. Since it provides significant examples of Rlife which can be directly used by the designer, being easy as much to be also applied by low-expert technicians. Additional verifications about the variation of occupancy rate and presence and rate of vulnerable users (e.g. with motion/sensory disabilities), as well as the fire load rate, could also overlap to vary R_{life}, and thus evaluate the effectiveness of solutions under building alternative use conditions without layout variation. Finally, it is worth noting that the Fire Safety Code relies on considering a unique fire ignition point, thus excluding arsons with multiple ignition points. Calculations are run at the space, storey, and compartment/building levels.

Basic space-level verifications refer to checking the minimum number of independent exits (including redundancy, that is, verifying that one door is unavailable per time) and their width (as the occupancy multiplied by unit per width), intended to prevent localised overcrowding effects of doors as bottlenecks. Additional space-level verifications refer to the door handling typology, opening direction (UNI EN 1125/UNI EN 179), and the minimum height of escape routes.

Storey-level verifications are based on the ones of the space level, thus requiring checking the number of horizontal escape routes (i.e. rooms, corridors and doors placed along them, until the staircases) along with minimum width (including redundancy verifications) and height. Since occupants can enter the escape routes from different initial rooms, the occupancy is evaluated as occupants' sum by route section. Dead-end route sections are considered if present.

Compartment and building-level calculations concern vertical routes. In case staircases are present, verification on the minimum width is performed using the same rationale for horizontal escape routes and doors, including redundancy check. The unit width per person is here considered based on the evacuation method ("simultaneous evacuation" or "phased evacuation"), which varies the simultaneous maximum occupants number in the staircases. Finally, overall verifications on the whole maximum route length, comprising all the horizontal, vertical and dead-end sections, are performed by comparing values with occupancy-based and R_{life}-based thresholds. Since a building could be composed of one or more compartments, such verifications are also referred to at the compartment level.

Demonstration

Case study

The overall approach has been validated on the Lecco Campus, a university campus belonging to Politecnico di Milano. It is located in Lecco (45° 51' N, 9° 23' E), characterised by a temperate Mediterranean climate (Köppen-Geiger classification Csa), with warm, dry summers, cold, moderate winters, and seasonal variations pronounced. The campus comprises five buildings dedicated to teaching and research, with a total area of 47,000 m², 29 classrooms and 2,850 students hosted.

In this paper, one of them, Building 10, is analysed. It is a standalone structure with two elevation levels and an underground level, connected to another building, Building 9, through a suspended enclosed bridge. Both above-ground levels have a gross height of 5 meters and a net height of 3.8 meters. The building accommodates primarily academic functions (classrooms and study rooms) and related services (restaurant and toilets). All major spaces are served by independent HVAC systems, one for each space, capable of handling varying occupancy conditions. Two fire escape staircases are located on the structure's north side, providing escape routes for occupants of the first floor and personnel accessing the roof. The structure is made of prefabricated concrete elements, with most of the south, east, and west façades that are glazed.

Occupancy levels considered in the analysis are those measured by the university's administrative office at the beginning of each semester. An average occupancy of 15% of the maximum classroom capacity is estimated for periods without scheduled lectures. This estimation was based on field measurements and classroom reservation data, which indicate that exam-related occupancy rarely exceeds 30% of maximum capacity and only for short durations. Occupancy sensors installed in some relevant classrooms of the case study will allow for more precise occupancy schedule modelling in the future.

Indoor temperature data used for the energy model calibration were obtained from sensor logs installed in two significant classrooms within the building over the last year, while weather data were collected from a weather station close to the analysed building over the last three years.

Results and future developments

The presented workflow was applied to the case study to analyse its current energy and safety conditions.

The analysis conducted through the proposed method allowed us to calculate the following energy- and safety-related KPIs: utilisation rate (percentage of occupied time relative to total available time), occupancy rate (average occupants versus maximum capacity), energy need (ideal energy in tons of oil equivalent for heating, cooling, lighting, ventilation, and appliances), energy costs (expenses for fuels associated to energy needs), CO2 emissions (CO2 output associated to energy needs), ratio between the effective and deemed (by Code standards depending on occupancy and R_{life}) values for the width of door/horizontal and vertical escape routes, and for their length (possibility to solve evacuation requirements according to the means of egress), vulnerable users' rate (to compare different scenarios of intended use).

Future developments will regard integrating the BIM, BEM and BSM into a unique decision support system and running multicriteria analyses to evaluate the impacts of occupancy variation on space use, energy need, and occupant safety. Normalised values will be used to unify KPIs into the multicriteria metrics, thus obtaining values in the range (0;1], where 1 represents critical conditions. Values >1 would be cut to 1 to represent unacceptable scenarios in the given overall range.

Conclusion

The instrumental framework described in the paper presents advantages and limitations over traditional BIM and BPS methods, which should be discussed.

Starting from the benefits, we believe that four key factors contribute to the methodology's efficacy: 1) the use of abstract topological models, which are straightforward, easy to handle, and compatible with both the BIM and BPS schemas, for achieving interoperability; 2) the standardisation and semi-automation of the model generation and information enrichment procedures, which confers computational control over the modelling process, reduces human error (a common occurrence in conventional BIM workflows), and maintains the information's semantic integrity; 3) the use of graph networks to link spatial information with performance data, enabling complex information arrangement, especially if compared to more usual data structures such as relational databases, 4) the use of a project's common ontology allowed semantic data exchange between the BIM and its surrogate models (BEM and BSM), directly derived from the TBIM rather than being created from scratch. With regard to BSM, it is worth notice that the same rationale could be extended to other national and international contexts encompassing the space occupancy and typology (e.g. see (ICC Digital Codes, 2021)).

On the other hand, several shortcomings still need to be addressed: 1) only prism geometries are currently supported by the toolkit, 2) the size of the building has a significant impact on computational performance, 3) although the toolkit uses open-source libraries, the main TBIM functions were developed within pyRevit in Autodesk Revit, which is a closed BIM environment, 4) since HVAC systems were not included in the BEM, the method was limited to estimating energy requirements rather than actual energy use. These constraints will be addressed in future expansions, with an in-depth focus on refining energy model calibration and enhancing HVAC system modelling.

Despite areas for technical improvement, overall, the approach aligns with the project's research objectives. Indeed, the method demonstrated its utility in enabling topology-based BIM modelling and facilitating the shift from product-centered to space-centered information modelling for building management.

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