IFC-based semiautomated building energy model creation and simplification for Building Energy Simulations

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Abstract

The complexity of building energy models (BEMs) for large buildings leads to increased computation times due to complex geometries and numerous heat transfer elements. Therefore, uncertainty analysis and energy retrofit optimization tasks are challenging for these large buildings.

To address this, a workflow has been developed that generates simpler BEMs, enabling faster simulations at the cost of reduced accuracy. This workflow uses IFC data from laser scanning as input, creates the detailed BEM geometry, and simplifies it through predefined space-to-zone merging paths, either purely random or guided by building physics expertise, to provide a set of geometries with varying degrees of simplification. These data are used to generate and simulate BEMs with different levels of geometric complexity.

The results are presented as a Pareto front, illustrating the trade-off between computation time and accuracy. This Pareto front validates the relevance of zone grouping criteria based on building physics expertise.

Key innovations

- Establishes the trade-off between computation time and accuracy in BEMs with varying levels of detail through automated generation from an existing BIM.
- Combines a novel semi-automated BIM2BEM process with a second-level space boundary (2LSB) simplification method.
- Validates the relevance of building physics expertise for the simplification of BEM geometry.
- Enables parallel district-scale simulations by utilizing intermediate-detail BEM, avoiding the simplification of buildings into single zones or the complexity of fully detailed models.

Practical implications

The proposed methodology establishes a trade-off between computation time and simulation accuracy for Building Energy Modeling (BEM), represented as a Pareto front. Building Energy Models represented on the Pareto front vary in geometric detail, corresponding to different space-to-zone merging scenarios, allowing to select the best configuration for a specific level of simulation accuracy.

Introduction

The automatic generation of Building Energy Models (BEMs) from Building Information Models (BIMs) has gained significant research interest (O'Donnell, 2013; Ramaji et al., 2020), termed BIM2BEM. Different BIM2BEM translation approaches have been explored based on the target simulation engine. Jeong et al. (2014) employed Modelica as the primary computational tool, enabling seamless model translation for dynamic simulations, while EnergyPlus is also widely adopted for building energy performance analysis within the BIM2BEM workflow (Wu et al., 2023). Although some progress has been made towards automating or semi-automating this process, achieving reliable and efficient model generation remains challenging, primarily hindered by two key issues: low-quality BIM input data (Wang et al., 2024) and the increasing geometric complexity of building structures, particularly in large-scale buildings (Yang et al., 2022). In the latter case, the resulting BEMs are often large and require extended computation times. This delay becomes even more critical in scenarios where multiple retrofitting options must be evaluated through numerous simulations, further hindering the overall retrofit decision making.

Methodology

The proposed methodology consists of two stages: a first stage related to BIM treatment and a second stage related to BEM generation and simulation. The first stage involves a BIM-based process where geometric operations are performed to generate the detailed geometry of a large building from the IFC BIM input data, and simplified geometries are created, in the form of gbXML files (energy-oriented BIM standard), through multiple space-to-zone merging paths. In the second stage, for each simplified geometry generated in the first stage, a simulation-ready Modelica BEM is generated and simulated. These stages are discussed in detail in the following subsections.

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A. BIM-stage

The first processing stage of the introduced methodology consists of four processing steps as indicated in the block diagram of Figure 1. Following the order of the blocks in Figure 1, these steps are:

A1 BIM geometry extraction using the Geometry Exporter (Katsigarakis et al., 2021).
A2 Generation of the BEM geometry using the CBIP process (Lilis et al., 2017).
A3 Generation of spaces-to-zones merging paths using a novel Space Graph Reduction (SGR) tool.
A4 Generation of simplified BEM geometries in the form of gbXML using the simplification tool (Lilis et al., 2019) using as input the initial BEM geometry and the spaces-to-zones merging path rules obtained from steps 2 and 3.

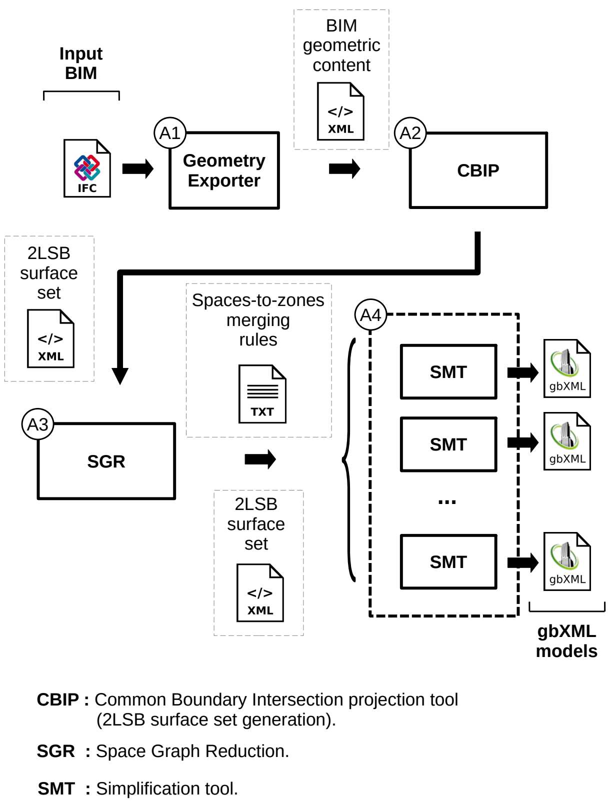

Figure 1: Block diagram of the BIM-based geometric processing stage of the proposed methodology.

These four processing steps and the software tools involved are analyzed in the following paragraphs.

A1. BIM geometry extraction

In this step, the geometric data from the input BIM IFC file is extracted using the Geometry exporter tool that is a part of the online tool bundle described in (Katsigarakis et al., 2021). This data include three-dimensional solid representations of the building's space and opening volumes. These representations are boundary representations, where the boundary polygons follow the outward normal rule, meaning the normal vectors of the boundary surfaces point outward from the volume of the space or the opening. These boundary representations are exported in a XML file, denoted as BIM geometric content in Figure 1.

A2. BEM geometry generation

To produce the geometric content for the BEM, the Common Boundary Intersection Projection (CBIP) process is employed (Lilis et al., 2017) on the geometric BIM data extracted in step A1. In general, the geometric content of the BEM consists of polygonal surfaces, termed second-level space boundaries (2LSB), through which thermal flows among building spaces and the external building environment (outdoor air or ground). The geometric definitions of these surfaces are exported in an XML file defined as a 2LSB surface set in Figure 1. The process is illustrated in Figure 2 where CBIP process is applied on three space volumes producing internal 2LSB surface pairs (illustrated with dashed lines) and external 2LSB surface (illustrated with solid lines).

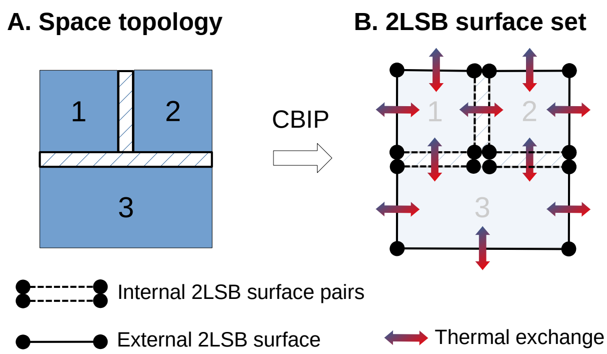

Figure 2: Illustration of the CBIP based 2LSB surface set generation process.

A3. Spaces-to-zones merging path formation

The internal second-level space boundary (2LSB) surface pairs created in step A2 identify adjacent spaces that are separated by internal building elements such as walls or slabs. This adjacency information can be represented as a space graph (see Part B in Figure 3). In this graph, each building space i corresponds to a graph vertex (v_i), while edges (e_ij) represent internal 2LSB surface pairs that connect spaces i and j. The relationship between the spatial topology of the building and the corresponding space graph is illustrated in Figure 3, where part A displays spatial topologies and part B shows the respective space graphs.

When all physical building cavities (e.g., rooms enclosed by walls, slabs, or other constructions) are

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modeled as separate spaces, the resulting spatial configuration is referred to as a *full 2LSB surface set*. Correspondingly, the graph representation of this configuration is defined a *full space graph*.

From the full-space topology, a 2LSB surface surface set can be derived as detailed in Step A2 (referred to as the 2LSB surface set in Figure 1). This topology acts as a foundational reference for subsequent simplification processes, defined as space-to-zone merging paths (illustrated with a vertical down arrow in the example of Figure 3).

Each merging path consists of a finite series of space graph reduction steps. In each step, a single space graph edge, (e_i, e_j), is collapsed, resulting in the merging of the edge's corresponding nodes, n_i and n_j, into a single node, (n_i, n_j). This process simplifies the building space topology by consolidating adjacent space volumes into single zones. Simultaneously, the associated 2LSB surface set is updated, as described in Step A4.

As illustrated in Figure 1, the completion of Step A3 results in the definition of a finite number of space-to-zone merging paths. The corresponding space graph reduction steps for these paths, are encoded as execution commands, recorded line by line in an output text file indicated in Figure 1 as Spaces-to-zones merging rules. This encoding is performed by the Space Graph Reduction (SGR) tool also indicated as a processing block in Figure 1.

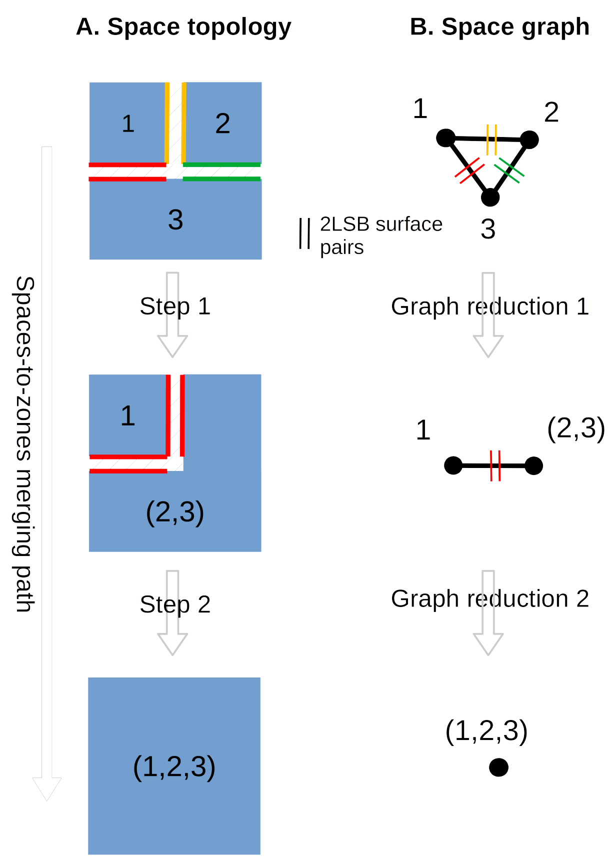

Figure 3: Illustration of a spaces-to-zones merging path and the respective space graph reduction.

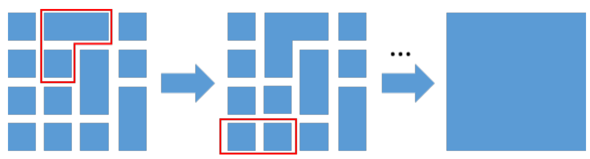

Figure 4: Illustration of a merging path following Method 1

Introduced space merging methods

In this study, three methods of space merging are being analyzed.

Method 1: Full space topology to monozone topology

In *Method 1*, the starting point is the *full space topology*. From this initial configuration, adjacent spaces are merged together by collapsing their respective 2LSB surface pairs, in a purely random way. The final output of this method is a monozone after the merging of all adjacent spaces and collapsing all respective 2LSB pairs of the building, as displayed in Figure 4.

Method 2: Full space topology to physics based topology

In *Method 2*, the starting point is also the *full space topology*, but the merging process is governed by rules based on building physics. It is assumed that intermediate floors with a high inertia have a greater thermal decoupling capacity than lightweight vertical partition walls, and that window orientation is the factor with the greatest influence on thermal behavior among all boundary conditions. Thus only spaces with the same window orientation and located on the same floor can be merged. As for *Method 1*, paths are generated by merging randomly 2LSB surface pairs compatible with these rules. This method is illustrated in Figure 5. The final output of this method, after the application of all possible mergings, is called the *physics based topology* and is the same for all paths generated through *Method 2*.

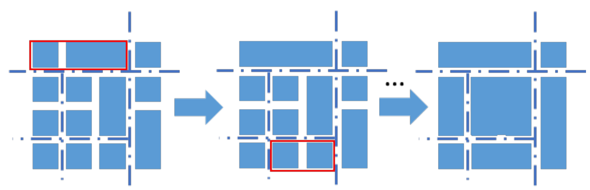

Figure 5: Illustration of merging path following Method 2

Method 3: Physics based topology to monozone topology

In *Method 3*, the starting point is the *physics based topology*, that is the final step of any path gener-

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ated through *Method 2*. From this starting point, the merging of spaces continues randomly without any specific rule, as in *Method 1*. In the final step the *monozone topology*, is obtained, as illustrated in Figure 6.

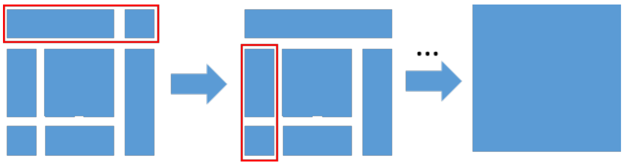

Figure 6: Illustration of a merging path following Method 3

The aim of defining these three methods is to assess the reliability of rules based on building physics for simplifying the geometry of BEMs. Several paths of the three methods will be evaluated after the generation of the corresponding BEMs. This will enable measuring how well the building physics expertise used for geometric simplification helps in achieving a good performance in terms of both computation time and accuracy of simulation results.

A4. Simplified BEM geometries

Every space graph reduction step defined in step A3 corresponds to a simplified 2LSB surface set which in turns can generate a simplified BEM geometry defined in a corresponding gbXML file. The generation of the simplified 2LSB surface set and the respective gbXML file is performed using the Simplification Tool (SMT) defined by Lilis et al. (2019) and used by Sayegh et al. (2024).

B. BEM-stage

The second processing stage is the automated generation and simulation of BEMs from the gbXML files supplied in the BIM stage. This process is carried out using three tools gathered in MyBEM, a simulation platform dedicated to building energy modeling:

- **HelioBIM**, a gbXML pre-treatment tool (Bouquerel et al., 2021)
- **PyRosette**, a python package for automated generation of a Modelica BEM from a gbXML (Bouquerel et al., 2019, 2021)
- **BuildSysPro**, a Modelica library for building energy modeling (Plessis et al., 2014)

The workflow applied relies on five steps detailed below :

B1. Data completion of BIM with HelioBIM.
B2. Solar calculation with HelioBIM.
B3. Generation of the Modelica BEM with PyRosette.
B4. Simulation of the Modelica BEM with Dymola.
B5. Calculation of simulation results accuracy and production of a Pareto front.

B1. Data completion of BIM with HelioBIM

Each gbXML provided at the end of the BIM stage contains the geometrical description of the building, but some physical properties required for energy analysis are missing. In particular, the properties of construction materials and windows, needed for the calculation of heat transfer through the building envelope, are missing. Thus, at this step, a so-called building configuration is applied to each gbXML, in order to add the thermal properties of all walls, floors, roofs, doors and windows. HelioBIM is used for this data completion step.

B2. Solar calculation by ray tracing with HelioBIM

HelioBIM also provides a detailed calculation of solar irradiance for each building envelope component (opaque or transparent) and for each hour of an annual scenario, taking into account reflections and masking effects. This calculation is performed using an advanced backward ray tracing method, and calculates direct irradiance from solar direction, diffuse irradiance from the sky, and reflected irradiance from all surfaces in the scene (building elements and ground). These data are exported in the form of CSV tables.

B3. Generation of the Modelica BEM with PyRosette

PyRosette is a Python package designed for the automated generation of BEMs in Modelica. It takes as inputs a gbXML, a weather data scenario, and the precomputed solar irradiance scenarios provided by HelioBIM. It provides a multizone BEM corresponding to the building described in the gbXML. This model is based on BuildSysPro, an open source Modelica library for building energy model.

For this automated generation process, PyRosette parses each gbXML, retrieves the list of building components (thermal zones, envelopes, usage scenarios...) and their relationships (adjacencies, membership...), and, in the Modelica model, generates for each component the corresponding model, and for each relationship the corresponding model interaction.

B4. Simulation of the Modelica BEM with BuildSysPro and Dymola

BuildSysPro provides a comprehensive set of elementary Modelica classes for modeling building envelope

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and energy systems components. Each class is designed to simulate the static or dynamic energy behavior of these components through 0D/1D modeling patterns.

The building energy models based on BuildSysPro are simulated with Dymola, a commercial modeling and simulation environment for Modelica.

B5. Calculation of simulation results accuracy

The simulation of a BuildSysPro BEM in Dymola provides time series of different variables in each thermal zone such as air temperature, and power demand for heating and cooling when the temperature regulation is activated. Only free-floating behavior of the model is considered in this paper, for the sake of simplicity. So in the study presented here, only the air temperature is used to evaluate the accuracy of BEMs with a simplified geometry.

The objective is to measure the impact of geometry simplifications on the simulation results' accuracy for each zone of the full space topology. To do so, for each zone of index j of the full space topology, the zone k of the simplified geometry, where this individual zone has been merged, is selected. Then the air temperature of these zones are compared, using the zonal Root Mean Square Error (RMSE_j):

$$\mathrm{RMSE}_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(T_{ij} - \hat{T}_{ik}\right)^2} \qquad (1)$$

where:

- m is the total number of time steps (for an annual simulation with a time step of 1h, m=8760),
- i is the index representing the time step,
- j is the index representing a zone of the full space topology,
- k is the index representing the zone of the simplified topology that contains zone j after the merging process,
- T_{ij} is the air temperature of the i^{th} time step in zone j of the full space topology BEM,
- $\hat{T}_{ik}$ is the air temperature of the i^{th} time step in zone k of the simplified geometry BEM.

The lower RMSE_j is, the better the simplified model's performance for zone j within the full space topology. To assess the overall performance of the building, a global RMSE is computed by aggregating the RMSE values from all zones, ultimately yielding a single RMSE for the BEM. To achieve this, the RMSE values of all zones are averaged, using the floor area of each zone as a weighting factor. This weighting ensures that each zone is represented fairly according to its size, reflecting its overall impact on the building. The global RMSE is calculated using the following equation:

$$\mathrm{RMSE}_{global} = \frac{\sum_{j=1}^{n} w_j \cdot \mathrm{RMSE}_j}{\sum_{j=1}^{n} w_j} \qquad (2)$$

where:

- n is the total number of zones of the full space topology,
- j is the index representing a zone of the full space topology,
- w_j is the weight of zone j, typically the floor area of the zone,
- RMSE_j is the zonal RMSE of zone j.

Results

Case Study

The case study is a 2,700 m² office building constructed in the 1980s and located at EDF Lab Les Renardières (Moret-Loing-et-Orvanne), in Paris area (France). The Revit model of this building is displayed in Figure 7.

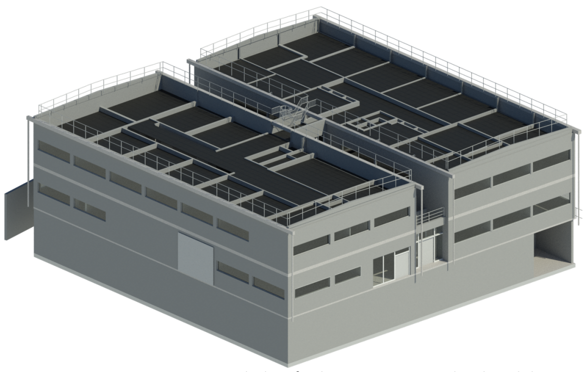

Figure 7: Revit model of the case study building.

The building is part of the European project DigiBUILD, aiming to transform it into a fully equipped smart building with energy meters, indoor air quality monitoring, and smart HVAC systems. A detailed BIM was used to generate a building energy model, calibrated with heterogeneous data measurements. This BEM serves as a digital twin of the real occupied office building.

The detailed BIM serves as the starting point for the proposed methodology, which was successfully applied in the three aforementioned methods. To illustrate the geometry simplification process, three key 2LSB topologies used to create the corresponding BEM geometries are shown: the *full space 2LSB surface set* (80 spaces) in Figure 8, the *physics based 2LSB surface set* (28 spaces), which is the final configuration of Method 2 and the initial configuration of Method 3, in Figure 9, and the *monozone 2LSB surface set* in Figure 10. Roof surfaces were excluded in these figures to better visualize the interior 2LSB surfaces.

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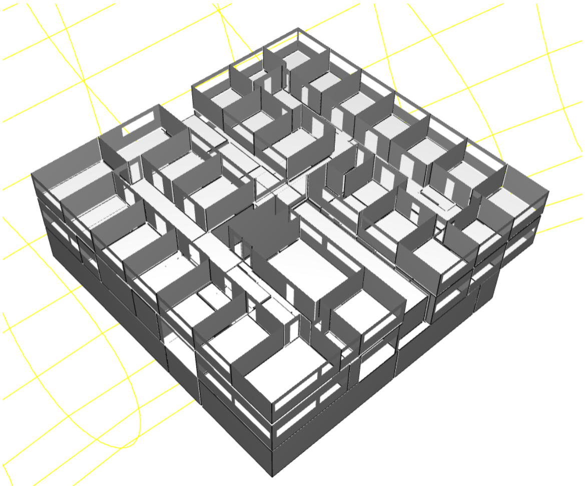

Figure 8: BEM geometry for the full space topology (80 spaces)

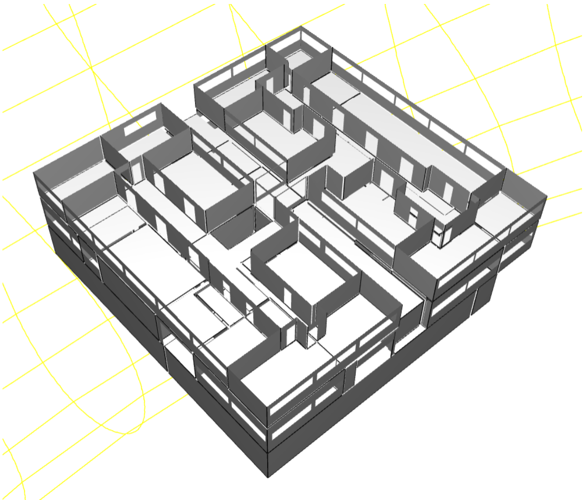

Figure 9: BEM geometry for the physics based topology (28 spaces)

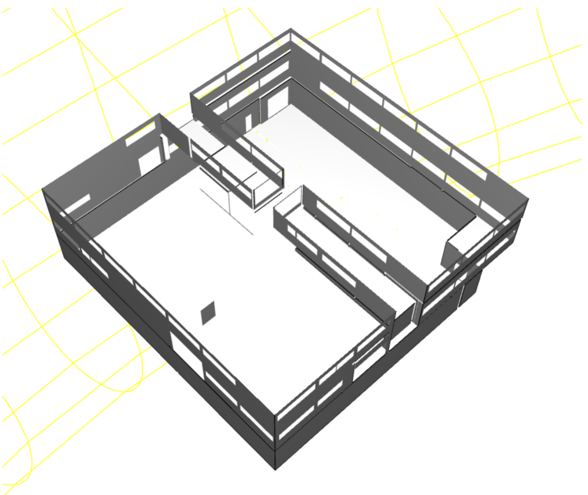

Figure 10: BEM geometry for the monozone topology

Performance of BIM stage process

For each method, a batch of 50 paths have been generated at the BIM stage. The total number of simplified geometries is:

- Method 1: 50 paths × 79 geometries per path = 3950 simplified geometries
- Method 2: 50 paths × 52 geometries per path = 2600 simplified geometries
- Method 3: 50 paths × 27 geometries per path = 1350 simplified geometries

To assess overall process performance, execution times for Method 1—applied to the case study building—were recorded, as it is the most complex approach, involving 50 simplification paths from the full model to a monozone model. In multi-threaded mode on an 8-core i7-6700 CPU, the BIM stage A achieved the following execution times:

- A1: 6 sec for the BIM geometry extraction.
- A2: 40 sec for the BEM full model generation
- A3: 184 sec for the space-to-zone merging paths formation.
- A4: 8572 sec for the generation of the simplified 3950 gbXML models (50 paths × 79 simplification steps from full 80-zone model to monozone model). On average, each gbXML model generation took $8572 \div 3950 \approx 2.17$ seconds.

Pareto front for BEM performance

To analyze the trade-off between simulation accuracy and computation time, a Pareto front is shown in Figures 11 (full plot) and 12 (zoomed plot of RMSE in the range [0,0.5]). Each BEM is marked based on the geometry simplification method used, with colors indicating the number of spaces (ranging from 1 to 79 in eight intervals). The black markers in the upper left of Figure 11 represent monozone topology, while those in the bottom left of both Figures 11 and 12 represent physics-based topology.

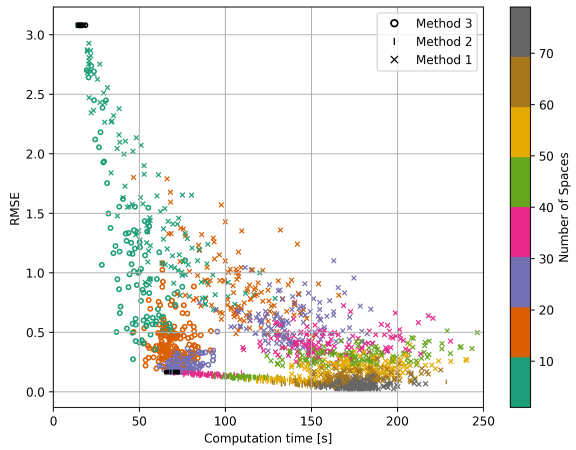

Figure 11: Pareto front of BEM performance

Simulations were run in multiprocessing mode on an 8-core i7-11850H CPU @ 2.50 GHz. The reported computation time includes both the initialization and the one-year free-floating simulation, using Dymola 2024x Refresh 1 as the Modelica environment and Cvode as the variable-order, variable-step solver. To

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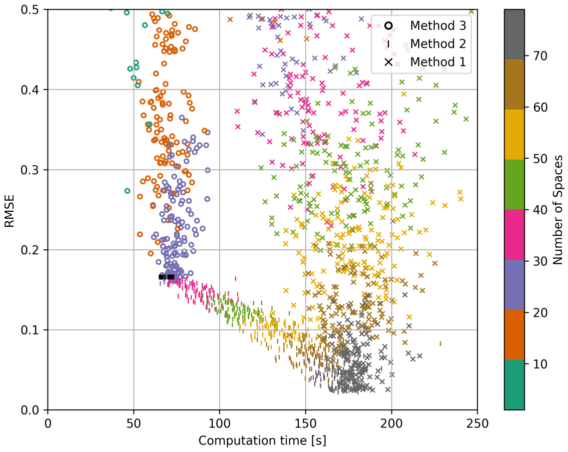

Figure 12: Pareto front of BEM performance (zoomed)

reduce the number of BEMs on the Pareto front, only one out of three geometries per path from the BIM stage was simulated and displayed, while preserving the first and last geometries. This required three mergers per step instead of one. The impact on the analysis is minimal, as the studied paths remain unchanged, with only a slightly coarser discretization.

From the pareto front we can observe the following:

- Method 2 significantly reduces computation time, by up to 2.7× (from ∼186 sec to ∼69 sec for the physics-based topology vs. full-space topology), with minimal accuracy loss (RMSE < 0.2).
- Compared to Method 1, Method 2's geometry simplification has a much smaller impact on RMSE. For 30–40 spaces, Method 2's mean RMSE is 0.15 (range: 0.12–0.17), while Method 1's is 0.41 (range: 0.23–0.73). This is expected, as Method 2 merges spaces with similar thermal behavior, preserving accuracy.
- Method 2 also reduces computation time more effectively than Method 1. In the 30–40 space range, its mean time is 86.6 s (range: 69.5–123.0 s), nearly half of Method 1's 162.1 s (range: 110.3–240.0 s). The reason for this unexpected efficiency gain requires further investigation.
- Method 3, like Method 1, fails to reduce computation time without a significant RMSE increase.
- The physics-based topology offers one of the best trade-offs between computation time and accuracy.

Additionally, the computation time for initialization and simulation may vary when the same BEM is run multiple times. Thus, trends in Methods 1, 2, and 3 are more indicative than exact computation times. For an overall perspective on this case study, Table 1 presents the mean, standard deviation, and min/max values for the three most representative topologies.

Finally, compilation time is required to convert the Modelica code into an executable model, varying with

Table 1: Computation time variability

Computation time [s]	Mean	Standard deviation	Min	Max
Full space topology	185.7	4.1	178.2	196.0
Physics based topology	69.2	2.6	64.8	73.2
Monozone topology	15.5	0.7	14.3	18.7

model size: ∼60 sec for the full-space topology and ∼25 sec for the monozone topology. However, once compiled, the model can be re-simulated without recompilation if its structure remains unchanged and only boundary conditions (e.g., weather data, occupancy schedules) are modified.

Limitations and future work

In the BIM stage, the process used to simplify the gbXML models occasionally results in small erroneous surfaces or artifacts. For example, the small door in the basement of the case study building is incorrectly included in the Building Energy Model (BEM) geometry under the monozone topology, as illustrated in Figure 10. These artifacts could be eliminated in future versions of the simplification tool through the application of appropriate geometric processes.

In the BEM stage, this study solely examines the accuracy of air temperature calculations in a free-floating simulation. The methodology can also be extended to energy performance indicators, particularly if simulations involving temperature regulation using active energy systems, such as HVAC systems, are considered. For instance, future work could explore the impact of space-to-zone merging on BEM models, on the total energy demand calculations, when active temperature regulation is considered.

Regarding the overall methodology, combinatorial reasoning shows that the number of potential space-to-zone merging scenarios increases exponentially with the number of physical spaces in a building. As a result, the search space for finding an optimal merging scenario—balancing simulation execution time and accuracy—becomes extremely large in buildings with numerous physical spaces, making exhaustive search methods impractical.

In this study, we focused on comparing only two merging scenarios: random merging and expert-based merging using building physics knowledge. The results demonstrated the advantages of using building physics expertise to define merging rules *a priori*. However, the BIM and BEM stages were conducted sequentially: first, the geometries were generated, followed by the generation and simulation of BEMs, without feedback between the two stages. A future improvement could involve integrating feedback from the BEM evaluation process into the BIM simplification process at each merging step, allowing the optimization of each merging step based on the BEM's actual performance. This could involve using optimization techniques to explore the solution space effectively, minimizing a cost function that balances computation time with global RMSE.

Conclusion and perspectives

In this paper, we presented a workflow that combines a novel BIM-to-BEM model generation method with BEM geometry simplification techniques. The goal was to evaluate the trade-off between simulation accuracy and computational time across various space-to-zone merging scenarios.

The approach was successfully applied to a large office building with 80 physical spaces. We tested two geometry simplification strategies: purely random and expert-based using building physics knowledge, within the context of free-floating simulations. The results involving pairs of computation times and accuracy metrics—measured by the RMSE between the full (unmerged) and simplified (merged) models—were plotted on a Pareto front. The front's shape clearly demonstrates that, for a given reduction in computation time, higher accuracy is achieved when building physics expertise is used to guide the merging process. This methodology offers great potential for application to larger buildings and other simulation types, particularly those involving temperature regulation for calculating heating or cooling needs.

Acknowledgments

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