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Enhanced building-specific heat load prediction with limited information through an automated zoning algorithm

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SUMMARY
In urban development, buildings have a key influence on energy use and sustainability. Therefore, accurate building energy demand predictions are required to design climate neutral energy systems. GML models, common for city-scale energy simulations in Europe, often lack detailed building information about architecture and construction. This study addresses the challenge of predicting heat load profiles for buildings with limited available data, especially those characterized by multiple thermal zones and various use types. A Multizone Assignment Algorithm (MZA) is developed to improve load prediction by defining zoning strategies using the concept of Binary Space Partitioning (BSP). The MZA integrates an automated zoning approach, embedded into the TEASER-AixLib framework for seamless energy simulation. By incorporating adjacency relations and interzonal heat transfer, the methodology improves prediction accuracy while requiring minimal manual input. This novel approach accelerates and simplifies district-scale simulations, providing important insights into how different areas within buildings interact and improving the operation of energy systems with limited initial data.

Keywords: CityGML, heating demand simulation, zoning strategies

1. INTRODUCTION

Buildings account for up to 40 % of global energy demand, significantly contributing to climate change (Statista, 2022). Improving energy efficiency in buildings is crucial for sustainable development, with heat demand prediction playing a central role in optimizing design and operation. Thermal simulations often rely on public GML files, classified into Levels of Detail (LoD) that range from simple footprints (LoD0) to detailed volumetric models (LoD3) (Biljecki et al., 2016). However, most municipal data is typically limited to rudimentary information, resulting in reduced prediction accuracy and compromised thermal simulation quality.

Despite the frequent lack of information, there are approaches aimed at improving the accuracy of predictions. In addition to the estimation of material properties of the facade or the enrichment of building models with information from aerial images, the assumed structure within the building envelope also plays a decisive role. For example, unheated partial areas or heat transitions between neighboring zones influence the heat demand of a building. Through inadequate or inappropriate zoning techniques this results in deviations of up to 15 % for a single zone (Jansen et al., 2021; Kühn et al., 2024). In addition, the high diversity of occupancy profiles and, in this context, the behavior of the residents significantly influences energy consumption patterns. Not only do heat transitions into unheated neighboring zones affect the heat demand, but also heat exchanges between apartments and floors arise due to user-controlled setpoint temperatures. Hence, the decomposition of a single-zone model into a multi-zone model is suggested and has already been addressed in other works. Some approaches address this challenge by focusing on the expansive generation and zoning of interior floor plans. For instance, Lopes et al. (2010) present a flexible method for generating procedural interior room layouts that accommodate various building types, including those with multiple floors. In contrast, Dogan et al. (2016) and Johari et al. (2022) concentrate on subdividing larger buildings into subzones, both recommending detailed zoning for varying usage profiles.

In contrast to these advancements, many existing approaches do not adequately address the complexities introduced by multiple thermal zones and diverse usage types on a larger scale for multi-family houses or apartment blocks. Due to the lack of information, a time-consuming multiple zone modeling is not considered, leading to inaccuracies in energy demand predictions. This work addresses these challenges by enhancing heat demand estimation through an automated zoning algorithm, even when detailed architectural information is lacking. The methodology focuses on an automated heuristic approach that can generate individual apartments within multi-family buildings while adhering to predefined constraints. Although manual zoning and perimeter-core zoning have been integrated into the framework, the emphasis in the present study is on the automated zoning method.

2. METHODOLOGY

2.1. Data aggregation and preprocessing

In this work, we combine geodata from OpenStreetMap (OSM) (2024) with CityGML data (Remmen et al., 2016) as input in order to obtain detailed information about the buildings. The integration of OSM data enables the supplementation of the information contained in CityGML, specifically by using attributes such as building and roof type in OSM or the address point of a building. In addition, we integrate further data (Blanco et al., 2023), enriching the dataset per building with additional information, such as the classification of buildings into construction year typologies. The systematic analysis and processing of these combined sources ensures a consistent and sufficient database for subsequent applications.

In order to reduce the computational effort and limit the number of possible solutions, a discretization of the building floor area is necessary. We carried out this reduction of the solution space using the Binary Space Partitioning (BSP) algorithm (H. Fuchs et al., 1980). This approach enables an automatic subdivision of the base surface up to a predefined granularity, efficiently dividing the solution space into smaller, manageable, and convex hyperplanes called leaves. The outcome is a recursive data structure in the form of a tree, as shown in Fig. 1.

Finally, further information is aggregated per leaf, such as direct neighboring leaves or connections to the outer edge of the building, which are essential for the functionality of the proposed methods and the placement of staircases. The latter is important for two reasons: Firstly, an unheated staircase influences the energy demand of a building and its individual zones, and secondly, the placement creates additional constraints that facilitate the automatic zoning. Consequently, the staircase for a building is aligned based on the address point and orthogonal to the nearest possible external wall. The dimensions of the staircase are currently determined by a proportion of the floor area and with respect to the standards (DIN 18065, 2011), but future iterations will adjust them according to the year of construction and building type.

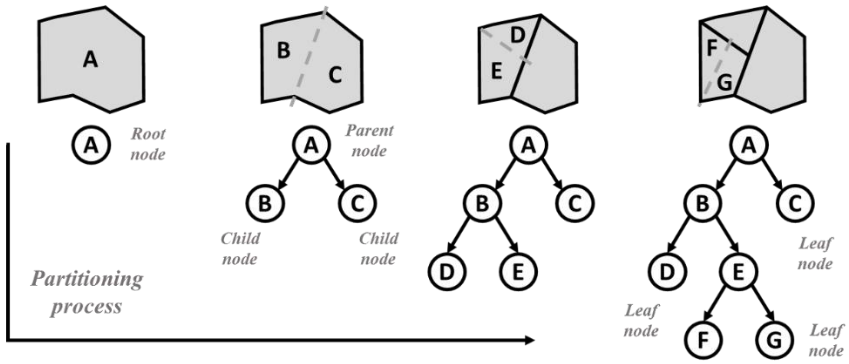

Figure 1. Partitioning process of a Binary Space Partitioning (BSP) tree with leaves as final partitions

2.2. Automatic zoning

The heuristic zoning algorithm presented here is based on a combination of random seed placement and subsequent regional allocation of areas, under adherence to predefined constraints. In the first step, the seeds — i.e., starting points — are generated along polygon boundaries. These boundaries correspond to the partition wall between the stairwell and the rest of the floor area along which the starting points are positioned. Each starting point represents a required zone per floor. The number of zones or apartments to be determined per building and per floor is derived from databases, using either the average apartment size or a predefined number of households per building volume (Census, 2011; Destatis, 2023). Subsequently, up to a defined iteration limit, a procedure with uniform spacing of the starting points is carried out. Beyond a certain threshold, random placements within or along the boundary line are allowed. For each iteration, all leaves are assigned to the nearest sub-area using a breadth-first search method, where multiple seeds act simultaneously in a queue. The subareas grow in parallel, assigning neighboring leaves (connected by an adjacency list) to the subarea that "captures" them first, which is comparable to the method described by Loga et al. (2016).

As soon as all leaves have been assigned, a constraints check is carried out to ensure minimum requirements are met. These relate to the number of leaves bordering the stairwell and an external facade in each sub-area or a maximum permissible deviation of the individual subarea areas from the specified average value. An assignment is only considered valid if these conditions are met.

$$Z = P_{\text{total}} + \alpha(\max(A_{\text{subarea}}) - \min(A_{\text{subarea}})) \tag{1}$$

The final step involves postprocessing to reduce local irregularities at the boundaries and smooth out potential "jagged patterns" in the subareas. For this purpose, each leaf is evaluated in the context of its neighborhood, where the majority subarea is determined based on the adjacent leaves. If flipping the respective leaf into this dominant subarea is feasible without violating global constraints, the adjustment is executed. Overall, this methodology combines a heuristic, random-based approach with multi-criteria evaluation and a local smoothing algorithm. It is primarily designed for an accelerated process and simpler building floor plans. However, for more complex geometries and additional boundary conditions, such as window positions specified in an LoD3 standard, a different algorithm is currently under development. This algorithm will employ graph partitioning to address the optimization problem.

2.3 Enrichment and simulation

For the thermal simulation of buildings, the methodology presented in 2.2 is embedded in the TEASER framework (Remmen et al., 2018) and the Modelica library AixLib (Müller et al., 2016). TEASER, a Python-based program, automates the parametrization of building models according to VDI 6007-1 (2015) and utilizes data such as construction type, year, and material properties derived from the German TABULA typology (Loga et al., 2016). Additionally, features such as the set temperature and the usage conditions of each zone are defined. Through its interface with AixLib, the model is converted into a Reduced-Order Model (ROM), which represents thermally conductive components using resistance-capacitance (RC) elements. To allow heat exchange between zones, we follow the approach of Groesdonk et al. (2023), which extends the ROM by adding an additional RC element per zone. This enables the simulation of interzonal heat transfer in cases of temperature differences or adjacent unheated zones. If the building model lacks window information, window areas are determined by considering wall-to-window ratios from the TABULA database and the available external walls, taking adjacent buildings into account. Furthermore, internal gains can be provided via an external model for residential energy consumption as an alternative to the standardized approach. The LoadProfileGenerator (LPG) (Pflugradt et al., 2022) determines profiles for occupants, machinery, or lighting based on Markov chains, allowing a more accurate representation of human behavior and the associated internal gains. The LPG simulates the activities of individual households, which we then distribute across the zones, allowing us to assign each household to a specific subarea. Fig. 2 provides an overview of the study’s workflow.

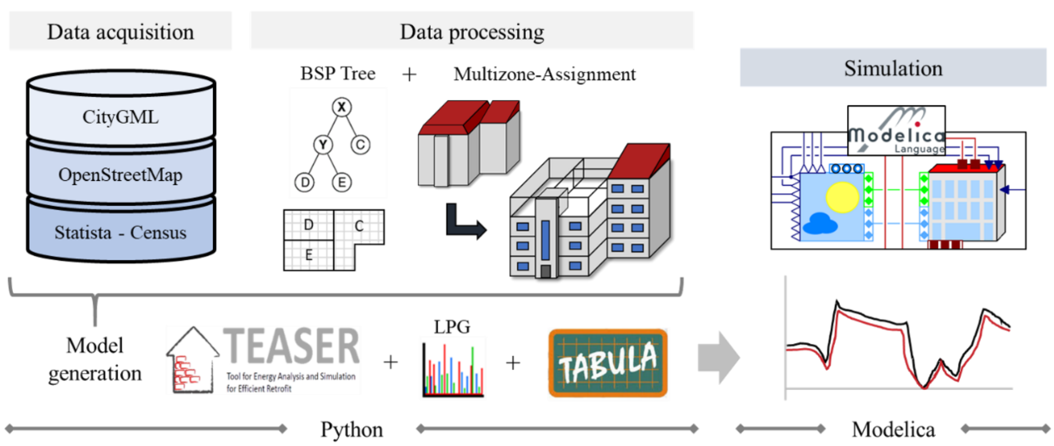

Figure 2. Schematic overview of the process.

3. FIRST RESULTS AND DISCUSSION

The partitions shown in Fig. 3 represent the results of applying the previously discussed sequence of methods for automatic zoning. We processed the GML models of three different apartment blocks (A-C) and three different apartment buildings (D-F). Additionally, a second version was created for each floor plan (specified as "-2"), either generating a predefined number of partial areas or applying a different weighting factor for the objective function. All samples were generated with a total of 200 iterations for the assignment of leaves, as determined through experiments. Increasing the number of iterations beyond this value does not generally improve results, while reducing it, for structures such as in example C, fails to produce sufficiently valid results for satisfactory zoning (e.g., isolated inclusions). The algorithm demonstrates its ability to produce consistent zonings for most base areas. The equality of areas is preserved across all samples, although certain zone boundaries tend to exhibit irregularities. These include narrow elements, as observed in A-1 and B-1, as well as unsatisfactory handling of the "jagged pattern," as seen in F-1 and E-2. The postprocessing step requires further refinement to better identify and adapt these cases more effectively and accurately.

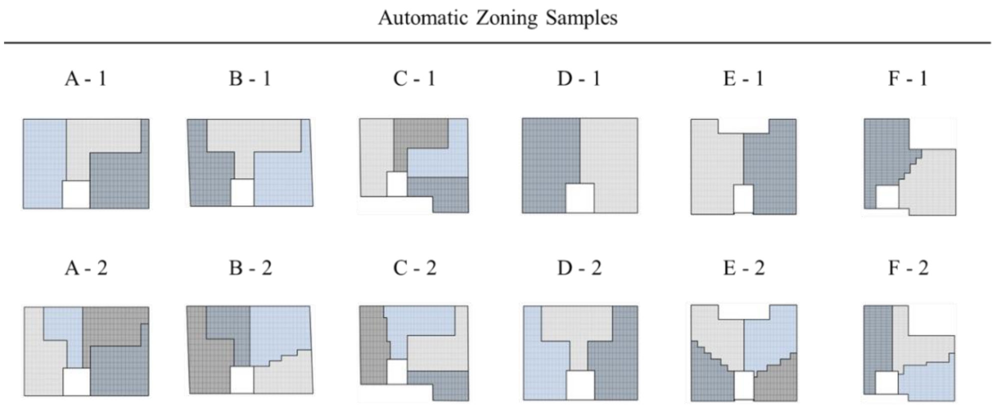

Figure 3. Results for the automatic zoning process for six different floor plans (staircase in white) with α = 2.0 (except for C - 2 (α = 1.0)) and predefined number of subareas for "-2".

Although the advantages of zoning with dynamic occupancy profiles and variable setpoints per dwelling have been extensively discussed in other studies (see, e.g., Kühn et al. (2024) for a detailed analysis of zoning effects and LoD variation), the results of a dynamic thermal simulation for the building depicted in Fig. 3 (E-1) are presented in Fig. 4-6. We simulated a total of four variants: Variant Multizone A corresponds to the partitioned building with an unheated stairwell, Multizone B includes a heated stairwell, Variant C incorporates usage profiles from the LPG with an unheated stairwell, and the final variant represents a single-zone model. For the weather data, a Test Reference Year (TRY) for the city of Aachen from 2015 was used. Unless otherwise specified, a setpoint temperature of 20 °C was assumed for all zones. An ideally operating heater was modeled for all variants, combined with a standard construction type from the Tabula database. An ideal cooler was not considered, since we primarily focus on the heating demand. The modeling (data acquisition and processing) as well as the simulation were executed on an i7-1370P CPU (1.90 GHz, RAM 16 GB). The figures show that the Multizone models exhibit a heat demand curve with an increased number of steep demand peaks. Notable peaks, particularly around midday, are clearly visible, whereas the single-zone model does not display these peaks to the same extent. It is evident that the single-zone model has the lowest annual heat demand of all versions. This may be attributed to the Reduced-Order Model for larger buildings, which tends to underestimate the internal mass of the building, thereby reducing the heat demand (see also Jansen et al., 2021). Additionally, significant differences in simulation time are apparent. While the modeling remains below 20 seconds for all models, the simulation time for the Multizone model, including heat transfer, increases substantially up to 750 %. This can pose challenges when simulating a large number of buildings. Nonetheless, considering the Multizone model offers advantages for scenarios with varying occupancy profiles and setpoints.

It accounts more accurately for demand peaks and provides a more precise representation of dynamic processes (as demonstrated in variant C), both of which are critical for the design and operation of an energy system, such as ensuring sufficient capacity during high-demand periods in winter when heating requirements significantly increase. It is evident that the individual zones contribute not only differently to the peak demand during colder periods (see Fig. 5) but also, particularly on summer days (Fig. 6), to an increased overall heat demand. The zoning also indicates that cooling specific areas is becoming more important due to a spread in overheating zones. Temperatures exceeding 28 °C are reached for certain zones, while in the single-zone model, values above 25 °C are rarely found during the same period.

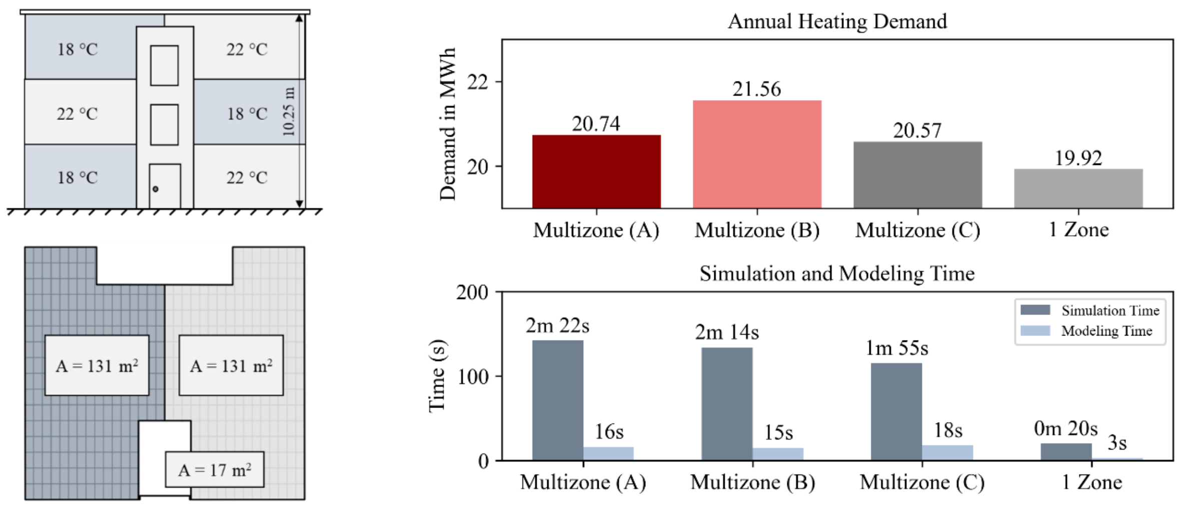

Figure 4. Front and top view of the building with varying set temperatures (left), annual heating demand, simulation and modeling time (right).

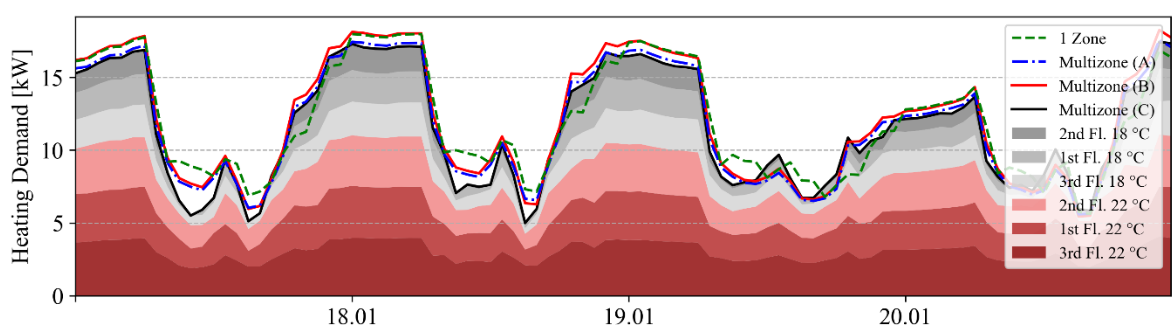

Figure 5. Heating demand comparison over a four-day time span for four different variants and stacked heating demand for the Multizone (C). Multizone (C) demand contributions are ordered from highest (dark red) to lowest (dark gray).

Regarding the zoning methodology and its functionality, some additional points require discussion. There are regional and age-related differences in the layout and construction of apartment buildings, including variations in staircase and corridor dimensions, as well as differences in apartment size and orientation. These assumptions must be carefully considered, as they significantly influence the simulation results. Furthermore, the most advantageous granularity of the zones must be considered in terms of the trade-off between accuracy and effort. While

Jansen et al. have already analyzed this for an office building, they, like Kühn et al., refer only to more complex models as a reference. However, a comprehensive examination and validation of this aspect for residential buildings using real measurement data remains open and should be pursued in the future. Moreover, the location of the stairwell can vary, potentially being positioned away from the street-facing side or located in a corner of the building.

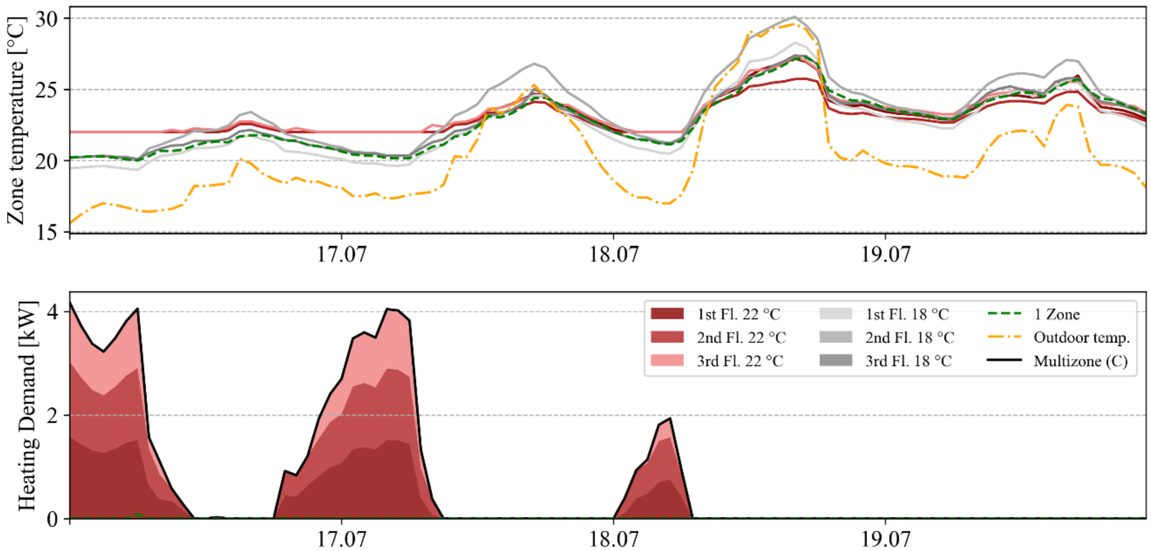

Figure 6. Zone temperature curves (above) and heating demand comparison over a four-day time span Multizone (C) and single zone (below).

These variations affect the zoning configuration and may distort heat demand results. Large apartment blocks present a significant challenge due to the increased number of apartments, which substantially raises simulation effort. Additionally, LoD2 models lack window areas in their GML data, leading to inaccuracies when assigning windows to walls that do not actually have them. Addressing this issue without image evaluations is not feasible.

4. CONCLUSION AND FUTURE WORK

This study focuses on the automatic partitioning of building models into individual residential units to improve heat load calculations. The Multizone Assignment Algorithm utilizes open-source data to enhance building models and is integrated into a thermal simulation environment within the TEASER-AixLib framework. The methodology is primarily designed for analyzing heat demand in smaller areas or specific applications, rather than large districts or entire cities. From a computational perspective, the single-zone model is the most resource-efficient option for large-scale observations. In contrast, the zoning approach targets small to medium-sized districts emphasizing dynamic factors like varying temperature setpoints and diverse occupancy profiles. This methodology aims to simplify building partitioning, especially when architectural data is limited, allowing users to model and parameterize buildings more easily. Future enhancements could include synergies with other algorithms, such as refurbishment status recognition or weather-related factors. Application scenarios may involve energy efficiency assessments for retrofitting buildings or demand response strategies for managing peak loads in urban planning. Further work will primarily focus on refining the methodology's structure and conducting extensive validation using real buildings. Additionally, an export function for the generated models is planned, enabling not only the preservation of model configurations but also ensuring applicability beyond the scope presented in this study.

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