Zoning Effects and Stochastic User Profiles: A Multi-Method Sensitivity Analysis for Residential Building Simulation

Kevin Waiz[1], Sharon Thomas[1], Jacob Estevam Schmiedt[1], Jana Stengler[1] und Bernhard Hoffschmidt[1,2]

[1] *Institute of Solar Research, German Aerospace Center (DLR), Jülich, Germany*

[2] *Chair of Solar Components, RWTH Aachen University, Germany*

Abstract

Building energy simulation can be strongly influenced by thermal zoning and coupling assumptions. However, zoning decisions are rarely assessed together with uncertainties from building data and user behavior. This work quantifies the influence of zoning granularity, layout, and stairwell representation for a multi-family building relative to physical input uncertainty and stochastic occupancy. Eight zoning variants of a single building are generated in a workflow for reduced-order building models. The uncertainty propagation samples construction state, age class, window-to-wall ratio, setpoints, internal gains, weather, and stochastic household profiles. In addition, Morris screening and Sobol analysis are used to rank influential input parameters and quantify first- and total-order effects. The results show that zoning acts as a structural uncertainty: it affects absolute KPI values, uncertainty ranges, and parameter sensitivities, but not equally for all outputs. For annual heating demand and peak heating load, the dominant structural effect is the transition from a single-zone model to explicit multi-zone representations, whereas overheating indicators are more sensitive to zoning resolution, layout, and retrofit state. Sensitivity rankings are target dependent: air change and construction assumptions dominate heating demand, whereas overheating is more strongly influenced by window, shading, solar, and weather effects.

Keywords: building simulation, sensitivity analysis, zoning layout effects, stochastic occupancy, Modelica

Introduction

In Germany, multi-family houses represent only a comparatively small share of the residential building stock, but they contain more than half of all dwellings and account for about 1.6 billion m^2 of residential floor area, corresponding to roughly 40% of the national total (Deutsche Energie-Agentur 2022). They also account for about 40% of greenhouse gas emissions from residential buildings (Bienert 2022). This highlights the relevance of robust simulation approaches for this building type. In large-scale applications, especially at district scale, however, building data are often only available in simplified form, for example from CityGML (Gröger et al. 2012) or OSM-based datasets, so construction age, use, window areas, thermal properties, and internal structure must often be assumed typologically (Blanco et al. 2023). One relevant but uncertain assumption concerns the internal zoning of the building. In stock or district applications, the external envelope and a few typological attributes may be known, while internal layout, apartment positions, and the thermal separation of circulation areas remain unavailable and have to be assumed. Zoning is therefore not only a question of the number of thermal zones, but also of their spatial arrangement and interzonal heat exchange. Previous studies show that zoning strategies and model detail can lead to substantial deviations in building performance simulation (Brès et al. 2017, Johari et al. 2022). For residential buildings, this issue is particularly relevant because dwellings, heterogeneous setpoints, occupant gains, and heat exchange between flats and circulation areas must be represented explicitly. For multi-family buildings, this structural modeling decision is particularly relevant under uncertainty. Kühn et al. (2024) show that these buildings differ from single-family and non-residential buildings because of their architecture and diverse occupancy patterns. Their approach also shows the central trade-off: reduced-order models can strongly

reduce simulation time, but annual heat demand at flat level may deviate substantially if zoning and interzonal heat exchange are simplified. Stairwells and circulation areas are a particularly critical simplification, since representing them as separate unheated zones or implicitly within adjacent residential zones changes apartment heat losses, interzonal heat flows, and temporal load distribution (Groesdonk et al. 2023). The aim of this work is therefore to assess the influence of structural zoning decisions relative to physical and user uncertainties in reduced-order simulations of a multi-family building. The focus is on zoning granularity, layout variants, stairwell representation, and their interaction with uncertain input parameters and stochastic occupancy profiles. By comparing model variants within a consistent workflow, the study treats zoning as a structural uncertainty and evaluates how it changes absolute results, uncertainty ranges, and sensitivity patterns relative to physical input uncertainty, weather variation, and stochastic occupancy.

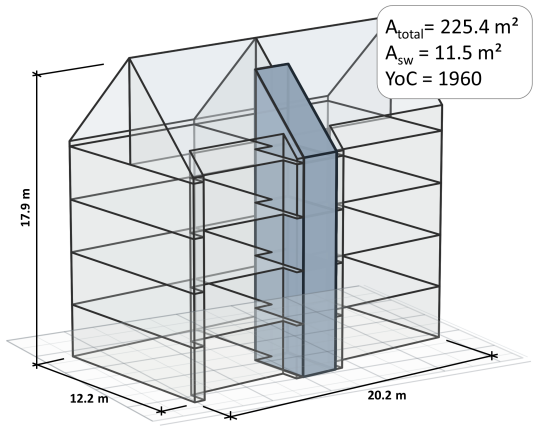
Simulation and sensitivity analysis workflow

Model generation and zoning variants

For this study, we use the TEASER-AixLib toolchain (Remmen et al. 2018, Müller et al. 2016) with TABULA-based typological parameters (Loga et al. 2016) to generate reduced-order Modelica building models. For each run, the selected zoning variant is exported and enriched with the specified input parameters. The use case is a free-standing multi-family building, which allows zoning assumptions to be evaluated without effects from adjacent buildings. How the variants differ is summarized in Figure 1. The variants were chosen to separate three uncertain modelling assumptions in stock and district-scale residential simulations: zoning granularity, layout, and stairwell representation. Zoning granularity ranges from a single aggregated building zone to models that distinguish floors, two dwellings per floor, or four dwellings per floor. Layout effects are tested by variants with the same number of zones but different spatial partitioning, especially 11Z/A versus 11Z/B and 21Z/A versus 21Z/B. Stairwell treatment is assessed by comparing an explicit unheated stairwell, no separate stairwell zone, and a heated stairwell. For variants with explicit stairwell representation, the stairwell geometry is included according to dimensioning assumptions based on DIN 18065. The unheated stairwell is used as the main representation because circulation areas are often thermally separated from dwellings but not actively conditioned, while 11Z/SWh represents an upper-bound assumption for conditioned core areas. The residential zones are divided into equal areas, which makes 21Z/B appear geometrically irregular. For the simulation, however, the effective separating area between neighboring zones is more relevant than the exact path of the dividing line. Unheated attic and basement areas are treated as fixed model assumptions. Interzonal heat transfer is considered because temperature differences between apartments and the stairwell, as well as between neighboring apartments, can influence zonal heat flows, loads, and comfort indicators. For this purpose, we use the ROM extension proposed by Groesdonk et al. (2023), which enables heat transfer between adjacent thermal zones.

Boundary conditions and input uncertainties

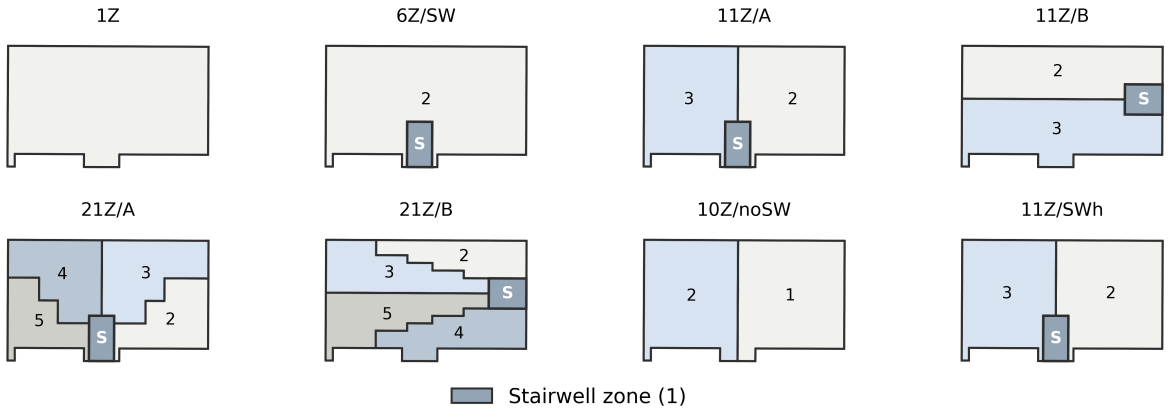
Uncertain input variables are varied directly in the simulation workflow. The value ranges and settings are given in Table 1 and were selected based on literature values, typological assumptions, and previous sensitivity studies. Construction age uncertainty reflects uncertainties in European building data and reported classification accuracies (Arcipowska & Mariottini 2016, Rosser et al. 2019). Residential setpoint limits follow typical comfort ranges, while the window-to-wall ratio (WWR) variation is interpreted as a parameterized façade and window area variation following the concept of Energy Design Measures (Hale et al. 2008). Internal gains are varied by ±20%, based on preliminary studies and corresponding parameterizations in Brès (2022). Weather is represented by two cases using Napoli 2011 and Munich 2015 weather data, to test whether zoning effects remain stable under different climatic conditions. The construction age class is treated as an uncertain TABULA class by retaining the original class or shifting it to an adjacent class. Heating setpoints are derived from a building-level mean value and, in multi-zone variants, an additional zonal spread. For 1Z, a uniform building setpoint is used. The zonal spread represents heterogeneous apartment temperature preferences and makes interzonal heat exchange effects visible. In addition to the building and



(a) 3D model for variant 11Z/A with highlighted stairwell (facing east).

(b) Variant zoning and stairwell (SW) treatment.

Variant	Thermal zones	Residential zoning	SW	SW state
1Z	1	Aggregated building	–	–
6Z/SW	6	One zone per storey	✓	Unheated
11Z/A	11	Two zones per storey, Layout A	✓	Unheated
11Z/B	11	Two zones per storey, Layout B	✓	Unheated
21Z/A	21	Four zones per storey, Layout A	✓	Unheated
21Z/B	21	Four zones per storey, Layout B	✓	Unheated
10Z/noSW	10	Two zones per storey	–	–
11Z/SWh	11	Two zones per storey, Layout A	✓	Heated



(c) Layout variants showing the zoning concepts.

Figure 1: Overview of the building model and zoning variants. Dark blue indicates the stairwell zone and light blue/grey indicates residential zones.

zoning structure, occupant behavior influences the simulation results through internal gains. The LoadProfileGenerator (LPG) (Pflugradt et al. 2022) is used to represent stochastic occupancy and internal gains. Household profiles are assigned to apartments or zones in a seed-based manner so that usage variability can be evaluated separately from physical input uncertainties. Depending on the variant, 10 or 20 household profiles are used.

Setup and result evaluation

The analysis consists of three sequential steps. Step 1 compares the zoning variants and propagates input, weather, and LPG seed uncertainty. Step 2 applies Morris screening to identify dominant input variables, while Step 3 uses Sobol analysis to quantify first-order and total-order variance contributions for the reduced parameter set. The associated variants, sampling designs, and parameter ranges are summarized in Table 1. The results are evaluated at building, zone, and time-series levels to capture aggregated demand, local comfort, and temporal load effects. This allows structural zoning effects to be compared with physical input uncertainty and stochastic profile variability rather than being interpreted as isolated model differences.

Table 1: Sensitivity analysis design and uncertain inputs used in the simulation workflow.

Setting / input	Main uncertainty propagation	Morris screening and Sobol decomposition
Variants	1Z–11Z/SWh	Morris: 1Z, 11Z/A, 21Z/A; Sobol: 11Z/A
Sampling	Variant × building × uncertainty sample × LPG seed.	Morris: $r = 16$, levels $= 6$, $s_m = 1$; Sobol: Saltelli design with $N = 128$, $K = 6$, $(K + 2)N = 1024$ runs per weather case.
Usage profiles	Multiple LPG seeds for stochastic household/profile variability.	Controlled representative LPG realization.
Construction	Standard/retrofit with $p_{\text{standard}} = 0.75$.	Standard fixed.
YoC	Correct or neighbouring TABULA age class.	Age-class shift: $-1, 0, +1$.
Setpoints	Mean: 20.5–21.5 °C; spread: 0.5–2.0 K; limits: 18–24 °C.	Mean: 20.5–21.5 °C; spread included in Morris.
Envelope / gains	WWR factor: 0.8–1.2; gains factor: 0.8–1.2.	WWR and gains in Morris; gains retained in Sobol.
Ventilation	Not varied.	Base air change rate: Morris: 0.05–0.8 h^{-1}; Sobol: 0.05–0.5 h^{-1}.
Solar / window	Covered by WWR factor.	Shading: 0.3–1.0; window g-value: 0.45–0.75; further window parameters in Morris only.

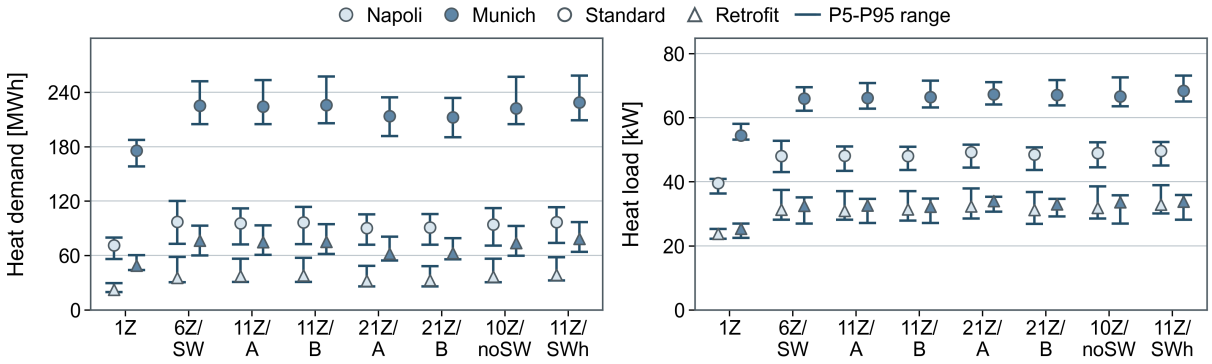
Simulation results

Variant effects on heating demand and overheating

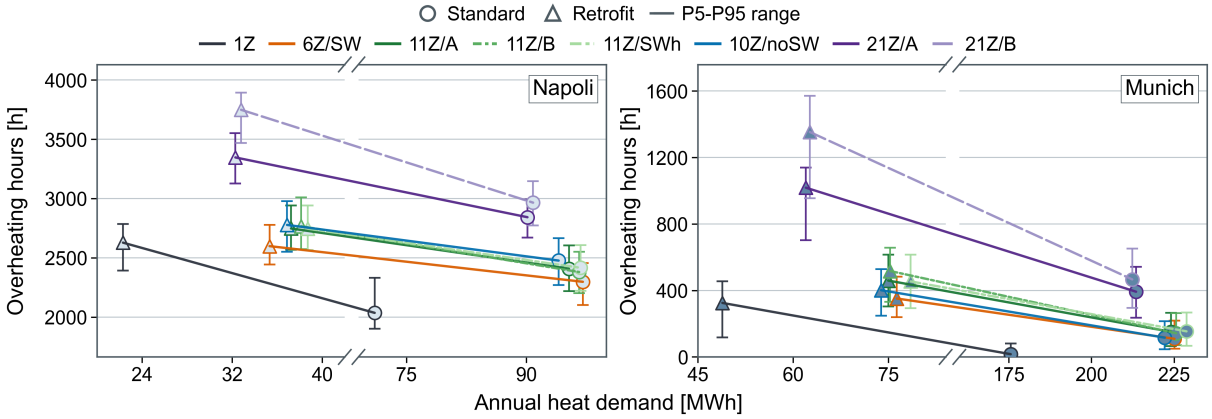
Figures 2a and 2b show that zoning is not a uniform source of model uncertainty; its influence depends strongly on the evaluated output, construction state, and weather case. For annual heating demand, the main difference remains the transition from the fully aggregated 1Z model to explicit multi-zone representations. The 1Z variant shows the lowest medians, while the multi-zone variants form a comparatively narrow range. This pattern is visible in both weather cases, although the absolute demand level is much higher for Munich than for Napoli. The P5–P95 ranges partly overlap between the multi-zone variants. Thus, for annual demand, zoning mainly shifts the absolute level between aggregated and multi-zone modeling, while the remaining layout choices are partly masked by the propagated input uncertainty. Retrofit shifts all variants to a substantially lower demand level without changing the relative ordering. At the same time, the P5–P95 range becomes larger relative to the median in the retrofit cases, because the demand level is reduced more strongly than the remaining variability. The 1Z variant also shows consistently narrower uncertainty bands for annual demand, suggesting that aggregation smooths part of the variability resolved in the multi-zone models.

Since no monitored data were available for the investigated building, the absolute annual heating demands cannot be interpreted as validated prediction errors. As a plausibility check, the median annual heating demands were converted to specific values using the summed floor area over all storeys of approximately 1127 m^2. The standard Munich cases correspond to roughly 155–205 kWh m^{-2} a^{-1} and are therefore in the same order of magnitude as published German residential building benchmarks and metered multi-family house consumption data (Deutsche Energie-Agentur 2022, Techem Energy Services GmbH 2023). The Napoli and retrofit cases are lower, as expected from the warmer weather file and the assumption of improved envelopes. This supports the plausibility of the simulated heating demand levels, but does not replace building specific validation.

Peak heating load shows a similar but less pronounced behavior. The 1Z model again produces the lowest medians and bandwidths, whereas the multi-zone variants cluster closely. In the standard case, their medians are around 48–50 kW in Napoli and 66–68 kW in Munich; under retrofit assumptions, they decrease to roughly 31–34 kW. The P5–P95 ranges overlap strongly between variants with similar zoning resolution. Differences between 11Z/A and 11Z/B, as well as between 11Z/A, 10Z/noSW, and 11Z/SWh, remain secondary for aggregated heating indicators, showing that stairwell and layout



(a) Annual heating demand and peak heating load by zoning variant, construction state, and weather case. Markers show P50; error bars indicate the P5–P95 range.



(b) Retrofit trade-off between annual heating demand and any-zone overheating hours above 26 °C by zoning variant and weather case. Markers show P50; error bars indicate P5–P95.

Figure 2: Variant results for aggregated heating indicators and the retrofit trade-off between heating demand and overheating.

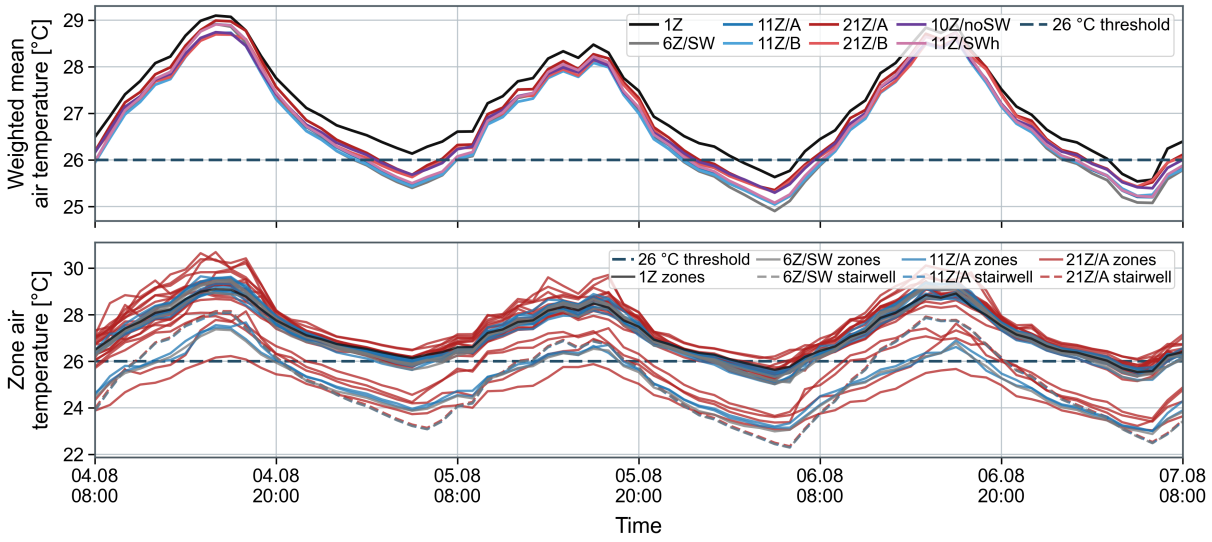


Figure 3: Three day event window: The upper panel shows the area weighted mean air temperature across zoning variants; the lower panel compares zone temperatures of selected detailed variants.

assumptions are less visible in building heating KPIs than in local thermal indicators. Overheating hours show a different pattern. Here, the spread between variants is larger and the P5–P95 ranges reveal clearer zoning and layout effects. Napoli leads to much higher overheating levels than Munich, while retrofit further increases overheating hours despite reducing heating demand and peak load. Figure 2b condenses this target conflict by relating annual heating demand to overheating hours for the standard and retrofit cases. Across both weather files, retrofit shifts the variants toward lower heating demand, while most variants move toward higher overheating levels. This is most pronounced for the finer 21-zone variants, with 21Z/B being the most critical case in all four weather–construction combinations. The layout effect between 21Z/A and 21Z/B is particularly visible in retrofit Munich, where median overheating hours increase by about 33%. This layout sensitivity is much stronger than for annual heating demand, indicating that overheating hours capture local spatial effects that are smoothed in aggregated energy indicators. In Figure 3, the temperatures of the hottest zones are consistently above the area-weighted mean indoor temperatures. The area-weighted mean curves remain similar between the variants, while the curves of the individual zones differ more clearly from one another. The 21-zone variants reach the highest local peak values, while ground-level zones, including the stairwell, are up to 4.5 K cooler.

Input sensitivities from Morris and Sobol analysis

Figure 4 summarizes the Morris screening and the subsequent Sobol analysis for annual heating demand and overheating hours. Morris screening identifies air change rate as the dominant input for heating demand across the investigated zoning resolutions, followed by construction year shift, mean setpoint, and shading. The ranking remains broadly similar for 1Z, 11Z/A, and 21Z/A, indicating that the main heating-demand sensitivities are driven more by physical input uncertainty than by zoning resolution. The Sobol indices confirm this pattern for annual heating demand. Air change rate has the largest first-order and total-order indices in both weather cases, while construction year shift, shading, and mean setpoint form a second group of relevant inputs. For overheating hours, the ranking changes clearly: shading becomes the dominant parameter, followed by the window g-value, especially under colder Munich weather. Air change rate and heating setpoint are much less relevant for overheating. Total-order indices exceed first-order indices for several inputs, particularly for the dominant parameters, indicating interaction effects between input assumptions and the thermal response of the building.

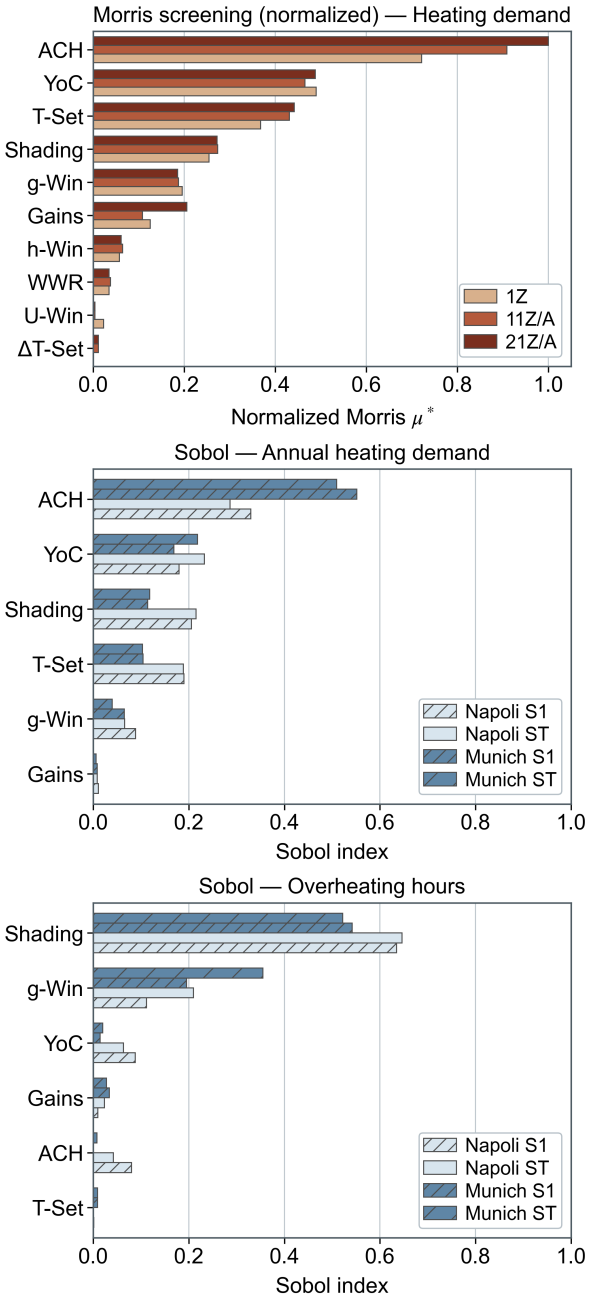


Figure 4: Morris screening and Sobol first-order and total-order indices for annual heating demand and overheating hours. Sobol indices are shown for the representative 11Z/A variant.

Discussion

The results confirm that zoning should be interpreted as a structural model uncertainty rather than only as a level-of-detail choice. The low median heating demand of the 1Z model should therefore not be interpreted as higher accuracy or efficiency. Aggregation can compensate for or obscure local effects, since gains, losses, and setpoints are averaged over a larger volume. This is reflected not only in the lower medians, but also in the narrower uncertainty bands for annual demand and peak load. For aggregated heating indicators, the transition from 1Z to explicit multi-zone models is therefore more relevant than most layout differences within the multi-zone group. At the same time, the overlapping P5–P95 ranges show that input, weather, and user-profile uncertainty can be of similar magnitude to the structural layout effect. After retrofit, the absolute heating demand and peak load decrease, but the uncertainty range becomes larger relative to the median, which makes residual input and usage assumptions comparatively more important.

A higher zoning resolution can increase the detected thermal risk. This does not necessarily mean that the real building physically overheats more strongly. Rather, the model is able to resolve smaller thermal zones in which local gains, façade orientation, and limited thermal averaging produce higher maximum temperatures. This is particularly relevant for the 21-zone variants and for the layout difference between 21Z/A and 21Z/B. The results therefore show that the number of zones alone is not sufficient; the spatial arrangement and façade allocation of the zones also matter. This effect is clearer in overheating hours than in mean temperatures, because temporal exceedance indicators preserve local peak behavior that is averaged out in building-level temperature metrics. Retrofit further illustrates a target conflict: it reduces heating demand and peak load, but can increase overheating hours when local temperature peaks are resolved and heat losses are reduced.

The sensitivity analysis supports this target-dependent interpretation and shows that structural uncertainty does not affect all sensitivity conclusions equally. Heating-demand rankings remain comparatively robust across the screened zoning resolutions and are mainly driven by air change rate or construction year shift, whereas overheating is dominated by solar-control and window parameters such as shading and window g-value. Model detail should therefore be selected according to the assessment target rather than by a fixed number of zones. For annual heating demand, a multi-zone model with explicit stairwell representation appears sufficient, since the medians of the multi-zone variants are close and the uncertainty bands overlap. For overheating and local comfort indicators, finer zoning and layout assumptions become more relevant. The benefit of resolving this structural uncertainty must therefore be balanced against computational cost: mean runtime increases from 0:26 min:s for 1Z to 12:42 min:s for 21Z/A and 10:47 min:s for 21Z/B.

Without measured reference data, the analysis quantifies structural differences and sensitivity patterns rather than absolute prediction errors. The numerical results are specific to the investigated case study and should therefore not be transferred directly to other residential building types. However, the qualitative pattern is likely more general: annual heating indicators are mainly affected by the transition from 1Z to explicit multi-zone models, whereas overheating and zone-temperature indicators are more sensitive to layout and stairwell assumptions.

Conclusion

The results show that thermal zoning acts as a model uncertainty whose relevance depends on the assessment target. For heating indicators, the main effect is the shift from the fully aggregated 1Z model to explicit multi-zone models, while differences within the multi-zone group remain comparatively small. For overheating and local comfort indicators, zoning resolution, layout, and stairwell treatment become more relevant, since stronger aggregation smooths spatial temperature differences and can hide local overheating risks. The sensitivity analysis further shows that dominant input parameters are target-variable dependent: air change rate and construction assumptions dominate heating demand, whereas overheating is mainly influenced by shading, window properties, solar gains, and weather. Model choice should therefore follow the research question and the relevant KPI rather than a fixed zoning rule.

Declaration of generative AI use

During manuscript preparation, the authors used an AI-based language tool for readability, grammar, and clarity. The authors reviewed and edited the

output and take full responsibility for the manuscript content.

References

Arcipowska, A. & Mariottini, F. (2016), The EU Building Stock Observatory: A New Tool to Support Europe's Building Policies, *in* 'Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings', American Council for an Energy-Efficient Economy, Pacific Grove, CA, USA, pp. 9–1–9–12.

Bienert, S. (2022), Klimaneutralität vermieteter Mehrfamilienhäuser – aber wie?, Technical report, IREBS Universität Regensburg. Accessed: 2026-05-21.

Blanco, L., Aditya, M., Schiricke, B. & Hoffschmidt, B. (2023), Classification of building properties from the german census data for energy analysis purposes, *in* 'Proceedings of Building Simulation 2023: 18th Conference of IBPSA', Shanghai, China, pp. 816–823.

Brès, A. (2022), Estimating the Frequency of Part Load Ratios in Building Energy Simulation Using Parametric Models, *in* 'Proceedings of BauSIM 2022', Weimar, Germany.

Brès, A., Judex, F., Suter, G. & de Wilde, P. (2017), Impact of zoning strategies for building performance simulation, *in* 'Digital Proceedings of the 24th EG-ICE International Workshop on Intelligent Computing in Engineering 2017', Nottingham, England, pp. 35–44. 24th EG-ICE International Workshop on Intelligent Computing in Engineering 2017, 10–12 July 2017.

Deutsche Energie-Agentur (2022), 'dena-Gebäudereport 2023: Zahlen, Daten, Fakten zum Klimaschutz im Gebäudebestand'. Accessed: 2026-05-21.

Groesdonk, P., Jansen, D., Estevam Schmiedt, J. & Hoffschmidt, B. (2023), Integration of heat flow through borders between adjacent zones in aixlib's reduced-order model, *in* 'Proceedings of the 15th International Modelica Conference', number 204 *in* 'Linköping Electronic Conference Proceedings', Modelica Association and Linköping University Electronic Press, pp. 577–587.

Gröger, G., Kolbe, T. H., Nagel, C. & Häfele, K.-H. (2012), OGC city geography markup language (CityGML) encoding standard, version 2.0.0, Technical Report OGC 12-019, Open Geospatial Consortium.

Hale, E. T., Leach, M., Hirsch, A. & Torcellini, P. (2008), Technical Support Document: Development of the Advanced Energy Design Guide for Medium Box Retail—50% Energy Savings, Technical Report NREL/TP-550-42828, National Renewable Energy Laboratory, Golden, CO, USA.

Johari, F., Munkhammar, J., Shadram, F. & Widén, J. (2022), 'Evaluation of simplified building energy models for urban-scale energy analysis of buildings', *Building and Environment* **211**, 108684.

Kühn, L., Zoumba, B., Spratte, T., Maier, L. & Müller, D. (2024), Level of detail in dynamic simulation models – a comparison for multi-family houses, *in* 'Proceedings of BauSim 2024: 8th German-Austrian IBPSA Conference', Aachen, Germany, pp. 215–222.

Loga, T., Stein, B. & Diefenbach, N. (2016), 'TABULA building typologies in 20 european countries–making energy-related features of residential building stocks comparable', *Energy and Buildings* **132**, 4–12.

Müller, D., Lauster, M., Constantin, A., Fuchs, M. & Remmen, P. (2016), AixLib – an open-source modelica library within the IEA-EBC annex 60 framework, *in* 'Proceedings of CESBP Central European Symposium on Building Physics and BauSIM 2016', Dresden, Germany, pp. 3–10.

Pflugradt, N., Stenzel, P., Kotzur, L. & Stolten, D. (2022), 'LoadProfileGenerator: An agent-based behavior simulation for generating residential load profiles', *Journal of Open Source Software* **7**(71), 3574.

Remmen, P., Lauster, M., Mans, M., Fuchs, M., Osterhage, T. & Müller, D. (2018), 'TEASER: An open tool for urban energy modelling of building stocks', *Journal of Building Performance Simulation* **11**(1), 84–98.

Rosser, J. F., Boyd, D. S., Long, G., Zakhary, S., Mao, Y. & Robinson, D. (2019), 'Predicting Residential Building Age from Map Data', *Computers, Environment and Urban Systems* **73**, 56–67.

Techem Energy Services GmbH (2023), 'Techem verbrauchskennwerte-studie 2022'.