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HEATING DEMAND AS AN INDICATOR OF RENOVATION DEPTH IN SOVIET-ERA APARTMENT BUILDINGS

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Abstract

Incremental renovation creates uncertain inputs for archetype-based UBEM, especially in Soviet-era apartment blocks with incomplete renovation records. This study proposes a dynamic archetyping methodology using heating demand as a diagnostic indicator for renovation depth (none/partial/deep). Simulating 44 buildings in Tallinn using the ReST (Renovation Strategy Tool), this study derives performance ranges rather than deterministic values, which account for uncertainties in user behavior and construction quality. Results show a proportional decrease in heating demand with respect to renovation depth. Deep renovation forms a distinct low-demand tier, while overlap among partial states limits identification of specific measures from energy data alone.

Introduction

In the European Union, the built environment accounts for roughly 40% of energy consumption and 36% of CO_2 emissions (Commission, 2020). Significantly reducing these numbers requires robust methods to estimate energy use across scales, from individual units to nationwide systems. While Urban Building Energy Models (UBEM) are essential for large-scale planning, their accuracy is frequently undermined by a lack of reliable, building-level input data. To address this, many UBEM studies utilize an archetype approach, grouping buildings by typology, construction period, and use (Ferrando et al., 2020; Verellen and Allacker, 2019). While archetype-based UBEM can be suitable for aggregated city-level analyses, it can be unreliable at the level of a district or individual buildings, where renovation history, system condition, and occupant behavior strongly influence energy use (Ferrando et al., 2020).

Renovation often occurs incrementally and unevenly over several decades, meaning that buildings of the same archetype often differ substantially in current envelope condition, system upgrades (such as air-to-air heat pump installation or ventilation system modification), and operational characteristics. Furthermore, national registries like the Estonian Building Register (EBR) frequently lack up-to-date records (Hamburg and Kalamees, 2019; Iliste et al., 2023). Although geometric information is often available, missing data on building service systems and envelope upgrades introduce substantial uncertainty into UBEM. Consequently, policies are often implemented based on limited information, despite significant variations in actual building conditions, rendering static, archetype-based solutions unreliable. To address this challenge, systematic data collection is essential to minimize modelling errors and uncertainty (Iliste et al., 2023).

This study addresses this gap by developing the methodological foundation for a dynamic archetyping framework that uses heating-demand distributions to infer renovation depth. To establish this framework, we adapted the European Commission's renovation depth classifications traditionally defined by primary energy savings as light (<30%), medium (30–60), and deep (>60) (European Commission, 2019) into operational renovation classes: baseline (no savings), partial (covering light and medium renovations, from (1%-60% savings), and deep (>60% savings).

This study analyzes how simulated heating demand varies across incremental renovation scenarios and evaluates whether these energy patterns can be translated into these operational renovation-depth tiers. The core research question is: Can heating demand be used to classify renovation depth (none/partial/deep) in Soviet-era apartment buildings? As a simulation-based proof-of-concept, this analysis establishes the classification logic and methodological structure required for future tool development.

Literature Review

Building envelope renovation is an effective way to reduce energy consumption and improve indoor comfort (Cai et al., 2025). Evidence from Northern European contexts: Ruokamo et al. (2025) analysed 416 Finnish housing companies' data and found that partial, maintenance-driven actions, such as window or door replacements, are significantly more common than deep renovations. These low-cost measures typically serve as the initial step in a renovation sequence, while capital-intensive upgrades like façade insulation and heating system modernization occur at later stages (Ruokamo et al., 2025).

Similar patterns are reported in Eastern Europe. Nowak-Dzieszko and Rojewska-Warchał (2015) found that many large-panel buildings in Poland have undergone basic modernization, like balcony glazing, which can reduce heating demand in adjacent rooms by up to 22% due to increased solar gains. Large-scale renovation studies confirm that multifamily renovation typically follows a stepwise, component-by-component sequence (Abdul Hamid et al., 2018). According to Abdul Hamid et al. (2018), renovation projects commonly start with envelope measures such as façade insulation, roof improvements, and window upgrades because they directly influence energy performance, durability, and indoor comfort. Next in the sequence are actions targeting ventilation and heating systems, particularly upgrades from existing natural ventilation to mechanical ventilation with heat recovery (MVHR) or installing heat pumps. Plumbing system upgrades appear further down the renovation order and are less frequently implemented (Abdul Hamid et al., 2018). The reviewed literature indicates that technical needs, such as façade degradation and energy-performance priorities, consistently establish envelope measures as the starting point in multifamily renovation pathways.

In the Estonian context, heating energy use is strongly influenced by envelope condition, service-system operation, renovation quality, and occupant behavior. Iliste et al. (2023) show that actual wall thermal performance often deviates from calculated values due to air leakage, insulation gaps, and workmanship defects. Operational factors such as indoor temperature settings, ventilation airflow, and air leakage can further affect heating demand (Hamburg et al., 2020; Hamburg and Kalamees, 2019). Even buildings with similar typology can therefore display substantial variation in energy use.

Based on the reviewed studies, renovation in multifamily apartment buildings typically follows a sequential and incremental pathway. Moving from window replacement and minor envelope repairs, followed by roof and façade insulation, while more complex upgrades such as ventilation and heating-system improvements are generally implemented at later stages or within coordinated deep-renovation projects. This gradual evolution produces uncertain intermediate renovation states. Because heating demand may not uniquely distinguish between specific renovation combinations, this study assesses whether these patterns can instead be used to reliably infer overall renovation depth in Soviet-era buildings.

Methodology

The primary objective is to evaluate whether heating demand can be used to classify renovation depth (none/partial/deep). To demonstrate and validate this approach, a pilot study was conducted in a residential neighborhood in Mustamäe, Tallinn, Estonia. The dataset includes 44 multifamily apartment buildings (Figure 1), of which 26 belong to the 464A series and 18 to the 317A series. In Estonia, buildings are grouped by series, reflecting the industrialized, standardized designs used to address post-WWII housing shortages. (Iliste et al., 2023). Series-level classification is more reliably available and widely used in practice. While each series contains subtypes (Type) varying by story count or minor details, this study adopts the series level as the primary analytical unit. This choice ensures the tiering approach remains practical and applicable even when building registries lack granular subtype data. To verify that the proposed heating-demand tiers reflect physical renovation depth rather than modeling artifacts, a subset of 12 buildings belonging to subtype 1-464A-1kE is analyzed separately as a validation case.

Figure 1: Study area in Mustamäe, Tallinn, apartment buildings

Modelling approach

All buildings were modelled in ReST tool (Renovation Strategy Tool) (Hallik et al., 2024). Each model was based on building-specific as-built data obtained from the Estonian Building Register (EHR). Input parameters include building geometry, net heated floor area, envelope properties, window areas, and façade orientation.

Although buildings are grouped by series, they are not treated as identical archetypes; each building retains its specific physical characteristics. Therefore, baseline heating demand may still vary within the same series due to subtype-driven differences in geometry, heated area, and façade orientation. To isolate the effect of envelope modifications, all non-envelope assumptions (including user behavior, ventilation settings, air leakage parameters, and heating-system settings) were held constant across simulations. At the subtype (type) level, buildings sharing identical geometric and envelope inputs produce single baseline values. However, unless geometric and orientation-specific inputs are identical, variation in baseline heating demand can still occur between buildings.

Renovation scenarios and input parameters

Renovation scenarios were generated by systematically modifying selected envelope thermal properties within each building model. Specifically, thermal transmittance values for windows (U_{window}), walls (U_{wall}) and roof (U_{roof}) were applied according to the combinations described in Table 1. For renovation-depth classification *Table 1*, scenarios were grouped into three categories: (i) non-renovated, (ii) Partial (one or two envelope measures), and (iii) Deep (full envelope upgrade: windows, walls, and roof). No ventilation system upgrades (e.g., heat-recovery ventilation) or HVAC system modifications were modelled in this study. In this study, 'Wall insulated' refers exclusively to full envelope insulation to ensure a consistent comparison of renovation depth. To represent typical incremental renovation pathways in Soviet-era apartment buildings, a set of envelope scenarios was defined by varying insulation thickness and the corresponding thermal transmittance (U-values) of walls and roofs.

Table 1: Renovation scenarios and renovation-depth labels used in the ReST simulations

Scenario	Envelope measures applied	Renovation depth
None	Baseline	None
Single measure	Windows replaced	Partial
Single measure	Roof insulated	Partial
Single measure	Wall insulated (full)	Partial
Double measure	Window and roof	Partial
Double measure	Window and wall	Partial
Double measure	Wall and roof	Partial
All Combined	Window, roof, and wall	Deep

For both building series, insulation thicknesses of 150 mm and 250 mm were applied to both walls and roofs. This corresponds to a range between $U_{wall,max}$= 0.21 W/m²K and $U_{wall,min}$ = 0.17 W/m²K, and for roof $U_{roof,max}$= 0.21 W/m²K and $U_{roof,min}$ = 0.17 W/m²K, respectively, to represent a practical minimum-maximum range for heating demand. Window performance was modelled using $U_{window,max}$ = 1.8 W/m²K (improved condition) and $U_{window,min}$ = 0.9 W/m²K (best-case performance). In this study, all existing windows were assumed to be replaced in window upgrades involved in renovation scenarios. To complement the absolute heating-demand ranges, the impact of each renovation scenario is expressed as a percentage reduction relative to the non-renovated baseline $HD_{baseline}$. Percentage reduction is calculated as:

$$\%\Delta HD = \frac{(HD_{baseline} - HD_{scenario})}{HD_{baseline}} \times 100 \qquad (1)$$

Where HD represents annual heating demand. This proportional view supports comparison across buildings with different baseline levels and clarifies the practical effect of each renovation package.

Results

Across both building series (317A and 464A) (Table 2), window-only and roof-only measures deliver modest heating-demand reductions. Full window replacement results in reductions of 12–14%, while roof insulation yields 13–28%. In contrast, wall insulation produces significantly larger reductions, ranging from 45% to 55%. Combinations involving wall insulation result in even higher performance gains. For both series, double measure (e.g., window and wall) achieves reductions of 57–64%, while full-envelope renovation reaches the highest overall savings at 68–75%.

Table 2: Heating demand reduction (%) relative to non-renovated baseline min/max range across buildings per series.

Scenario	464A (%)	317A (%)
Windows replaced	12–14	12–13
Roof insulated	14	13–28
Wall insulated	47–50	45–55
Window and roof	24–26	23–24
Window and wall	59–61	57–64
Wall and roof	58–62	56–66
Window, roof, and wall	68–73	69–75

The intervals in Table 2 show the minimum and maximum heating reductions across the entire building series (n=44), accounting for variations in geometry, orientation, and the 150-250 mm insulation thickness used in the simulations. The pattern observed in Table 2 is consistent with the incremental renovation sequence identified in the literature review. Window-only measures result in relatively modest reductions in heating demand and are typically associated with early-stage, maintenance-driven interventions.

In contrast, wall insulation and full envelope renovation lead to substantially larger reductions, reflecting their more comprehensive and capital-intensive nature. This gradual increase in reduction levels across measures supports the interpretation of heating-demand performance as an indicator of renovation depth.

Analysis of renovation impacts on heating demand (464A series)

Figure 2 summarizes the heating-demand distributions (kWh/m²·yr) for the 464A building series.

The reported intervals and violin densities represent the overall results obtained across the entire dataset of 26 buildings, capturing the full range of performance variations caused by building-specific geometry and orientation. Heating demand decreases consistently as renovation measures accumulate, indicating a consistent correlation between renovation depth and energy performance. The violin plots provide deeper insight into the data. The "width" of each violin illustrates the probability density of the data, while the median values identify the typical performance for a building in this series under each scenario.

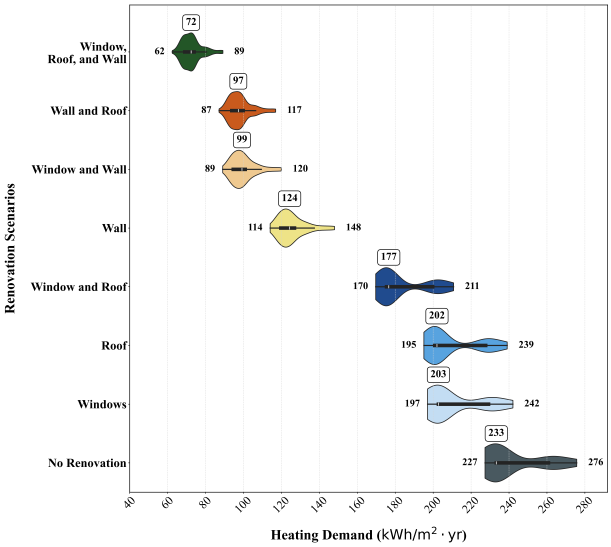

Figure 2: Heating-demand distributions (kWh/m²·yr) for renovation scenarios (464A series). The intervals and violin densities represent the overall results obtained across the entire building dataset.

However, despite the clear decrease in heating demand, most partial renovation states are not uniquely identifiable because their heating-demand ranges and densities overlap significantly. The yellow-orange shade range has been assigned to visualize wall measures better.

Influence of individual renovation measures

Wall (façade) insulation produces the most significant reduction in heating demand, forming a clearly lower performance band (114–148 kWh/m²·yr) compared to the non-renovated baseline (227–276 kWh/m²·yr). As shown in Table 2, this separation corresponds to a substantial 47–50% reduction. This shift is visually captured by the yellow-orange-shaded violins in Figure 2, where the sharp drop in the median to 124 kWh/m²·yr from 202-203(roof and window) highlights wall insulation as the key driver for lower heating demand.

In contrast, window replacement and roof insulation deliver more modest improvements. Full window replacement results in reductions of 12–14% (spanning 197–242 kWh/m²·yr with a median of 203 kWh/m²·yr), while roof insulation yields a 14% reduction (195–239 kWh/m²·yr with a median of 202 kWh/m²·yr). The blue-shaded scenarios exhibit substantial distribution overlap with each other and the baseline. The wide, irregular violins in Figure 2 show that single-measure upgrades affect buildings differently. Because of variations in size and orientation across the dataset, the impact of an upgrade can vary. This high variability makes these partial states (except wall insulation) difficult to distinguish from unrenovated buildings using heating-demand data alone.

Effects of combined renovation measures

Combining renovation measures further reduces heating demand, though several partial combinations remain difficult to distinguish. In particular, the window and wall (89–120 kWh/m²·yr) and wall and roof (87–117 kWh/m²·yr) scenarios fall within a nearly identical band. The medians for these two scenarios, 99 kWh/m²·yr and 97 kWh/m²·yr, respectively, indicate that once wall insulation is included, adding a second measure provides limited additional separation in heating-demand ranges. However, the distinct clustering of these two-measure scenarios provides strong evidence that wall insulation is present, making heating demand a reliable indicator for identifying wall-involved renovations. Although window replacement is common in practice, in this analysis, window upgrades are treated as a distinct scenario and are not assumed to be universally present across the building stock.

In contrast, full envelope renovation (window, wall, and roof) forms a clearly isolated, low-demand tier (62–89 kWh/m²·yr). With a median of 72 kWh/m²·yr, this scenario shows no overlap with any single-measure case. This clear separation indicates that deep renovation can be robustly identified from heating-demand data alone. These results align with the percentage reductions in Full window replacement results in reductions of 12–14%, while roof insulation yields 13–28%. In contrast, wall insulation produces significantly larger reductions, ranging from 45% to 55%. Combinations involving wall insulation result in even higher performance gains. For both series, double measure (e.g., window and wall) achieves reductions of 57–64%, while full-envelope renovation reaches the highest overall savings at 68–75%.

Table 2, where full envelope upgrades consistently deliver the highest performance gains across the entire building series.

Analysis of renovation impacts on heating demand (317A series)

Figure 3 shows broader ranges and stronger overlap across the partial renovation scenarios compared to 464A. Despite this increased variability, the data follow a consistent trend: heating demand decrease is proportional to the increase in renovation measures. The "width" of the violins in Figure 3 highlights higher densities, while the median values identify the typical performance for a building in this series.

Effects of Individual and Combined Measures (317A)

Wall (façade) insulation remains the primary driver of heating demand, shifting the median demand from 242 kWh/m²·yr(baseline) down to 137kWh/m²·yr, causing a reduction of approximately 45–55%. While combined measures yield larger absolute reductions, they remain partially non-unique (Figure 3). For instance, the window-and-roof scenario displays a wide range (163–240 kWh/m²·yr) that overlaps heavily with both the window-only state and the non-renovated baseline. This reinforces the finding that envelope upgrades excluding wall insulation are difficult to identify reliably from heating demand data alone. In contrast, wall-involved combinations reduce demand more substantially and consistently. Scenarios such as window-and-wall (76–136 kWh/m²·yr) and wall-and-roof (73–140 kWh/m²·yr) occupy nearly identical low-demand tiers. This suggests that once wall insulation is implemented, adding a secondary measure provides limited additional separation in the demand range. However, full envelope renovation (window, wall, and roof) forms the lowest and most distinct band (54–104 kWh/m²·yr).

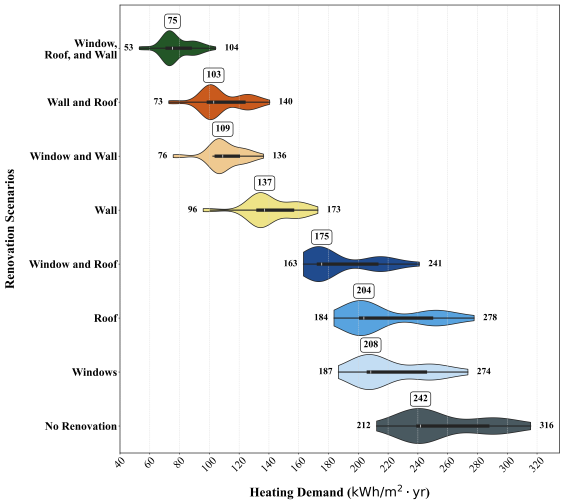

Figure 3: Heating-demand distributions (kWh/m²·yr) for renovation scenarios (317A series). The intervals and violin densities represent the overall results obtained across the entire building dataset.

Energy-Based Tiering and Classification Logic

The heating-demand distributions across both series (Figure 2 and Figure 3) indicate that while renovation depth generally correlates with heating demand reduction, specific partial renovations often overlap. To translate these simulated distributions into a practical screening tool, a consistent classification logic was applied to both the 464A and 317A series. While building-specific geometry and orientation create overlapping ranges, the following two rules were established to ensure robust categorization:

Prioritization of Common Practice: Since window replacement is the most frequent initial renovation measure in Estonia, the overlapping intervals between the non-renovated baseline and window-only ranges are intentionally assigned to Tier 2. By setting a high threshold for Tier 1, we minimize the risk of misclassifying partially renovated buildings as entirely unrenovated.

Median-Based Classification: For deeper renovations (Tiers 3 and 4), where ranges often intersect, boundaries are defined using median values rather than absolute ranges. Medians provide high-confidence statistical centers that allow for distinct classification despite the overlapping "tails" of the distributions. For the 464A series, the Tier 3 wall-involved median (99 kWh/m²·yr) is significantly higher than the Tier 4 deep-renovation median (72 kWh/m²·yr) (Figure 2). Similarly, for the 317A series, the wall-involved median (103 kWh/m²·yr) is clearly distinguished from the full-envelope median (72 kWh/m²·yr). Using this logic, typology-specific thresholds were established to categorize buildings into four distinct operational tiers (Table 3).

Table 3: Heating-demand tiering ranges (kWh/m²·yr) for renovation depth classification

Renovation Tier	464	317
Tier 1	≥242	≥275
Tier 2	170-240	163-274
Tier 3	87-147	104-162
Tier 4	<87	<103

From Table *3*, the tiers are as follows:

- **Tier 1** = None: non-renovated baseline
- **Tier 2**= Partial: Window and/or roof only
- **Tier 3** = Partial: Wall-involved renovation
- **Tier 4** = Deep: Full envelope renovation

Robustness of Heating-Demand Tiers

To ensure that the identified heating-demand tiers and their overlapping boundaries reflect the physical relationship between envelope measures and renovation depth rather than modeling artifacts, we performed two targeted checks on the 464A building series. First, we tested the stability of the boundaries against highly optimistic envelope-performance assumptions. Second, we isolated the effects of geometric variability by analyzing a subtype with identical inputs.

Impact of Optimistic U-Values

To verify the stability of the identified heating-demand tiers, we performed a robustness check on the 464A building series. We evaluated the theoretical best-case scenario for the same buildings from the 464 series using optimistic envelope values (U_{window} = 0.9; $U_{wall,min}$= 0.17 and U_{roof} = 0.08 W/m²K). Figure 4 shows the largest absolute reductions occurring in combined renovation scenarios.

Figure 4 demonstrates that every renovation scenario involving wall insulation (green) results in a non-overlapping heating-demand tier. This isolation is more pronounced under optimistic assumptions than in the realistic ranges (grey). While overlaps continue in the orange categories, the actual area of overlap is significantly reduced compared to the grey. Despite these absolute shifts, both cases follow a consistent logic: as envelope renovations intensify, heating demand decreases. This proves that the relationship between renovation depth and demand reduction is a stable physical property of the building series, rather than an artifact of specific U-value inputs.

Impact on Type-level (1-464A-1kE)

To isolate the effect of geometric variability, the same renovation scenarios were applied to subtype 1-464A-1kE. Because buildings within this subtype share identical geometric and envelope parameters, the baseline heating demand remains constant at 233 kWh/m²·yr (Table *4*).

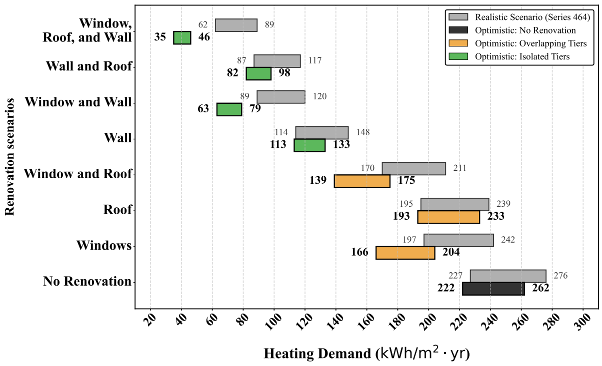

Figure 4: Robustness check (464A series) heating-demand tiers. Grey bars (realistic) vs. colored bars (optimistic U-values) show a consistent lower demand proportional to renovation scenarios. Orange signifies overlapping tiers, and green bars are non-overlapping tiers. Values represent min/max heating demand (kWh/m²·yr).

This deterministic result confirms that the wide variability observed at the broader series level is fundamentally driven by building-to-building geometric differences rather than modeling artifacts. For the renovated states, the remaining "Highest-Lowest" variation shown in Table *4* reflects envelope-performance levels (U-values). The "Highest" demand values corresponds to standard performance inputs ($U_{window,max}$ = 1.8; $U_{wall,max}$= 0.21 and $U_{roof,max}$ = 0.21 W/m²K), while the "Lowest" demand scenario corresponds to higher-performance specifications (U_{window} = 0.9; $U_{wall,min}$= 0.17 and $U_{roof,min}$ = 0.17 W/m²K).

Table 4: Heating demand (kWh/m²·yr) for subtype 1-464A-1kE, with identical geometric inputs and varying envelope U-value.

Variables	Highest	Lowest
No Renovation Applied	233	233
Windows Replaced	203	182
Wall insulation	125	120
Roof insulation	202	198
Window Replaced and Wall Insulated	99	74
Window Replaced and Roof Insulated	177	152
Wall Insulated and Roof Insulated	98	90
Window, Roof, and Wall	73	45

While real-world buildings certainly show performance variation due to partial window replacements, workmanship quality, and operational differences, those exact mechanisms are not explicitly modelled here. Instead, the high-low U-value intervals are used to represent those plausible real-world performance variations and construct realistic heating-demand ranges for each envelope upgrade.

Compared to the broader series level, the type-level analysis demonstrates significantly fewer overlapping ranges (green colors for non-overlap scenarios in Table 4), allowing for cleaner renovation tiering. However, even at this more granular type level, some overlaps remain. As marked in Table 4, these fall into two groups: single-measure overlaps (orange: windows [182–203 kWh/m²·yr] vs. roof [198–202kWh/m²·yr]) and combined-measure overlaps (blue: window and wall [74–99kWh/m²·y] vs. wall and roof [90–98kWh/m²·y]). This persistent overlap confirms that heating demand alone is insufficient to uniquely identify specific renovation states, suggesting that supplementary information (e.g., renovation records or imagery) may be required to distinguish between overlapping states.

Small Vignette:

The proposed workflow (Figure 5) is the first step of a decision-support pipeline using a rule-based classification. The tool takes building data (ID, series, and heating demand) as inputs, maps typology-specific rules, and assigns each building to a renovation-depth tier (none/partial/deep). To assist in decision-making, the output includes a confidence proxy based on the building's proximity to the nearest typology threshold. The workflow can classify a national (or large-scale) building stock into heating-demand tiers, supporting identification of deeply renovated buildings and prioritization of renovation targeting across large scales.

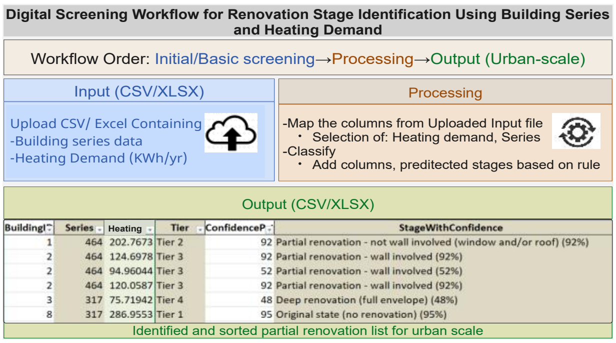

Figure 5: Digital screening workflow to classify renovation stage from building series and energy use (CSV/XLSX input and output)

By automatically post-processing heating-demand patterns as output, this workflow fills gaps in missing renovation records and establishes the operational logic for a dynamic archetyping framework.

Discussion

The findings demonstrate how simulated heating-demand patterns can be translated into renovation-depth indicators at the stock level. By combining series-level modelling, subtype validation, and robustness testing, the study establishes the analytical basis of a dynamic energy-profiling framework.

Across both building series, heating demand decreases proportionally with renovation depth, supporting a coarse renovation-depth (none/partial/deep) classification. However, substantial overlap among partial renovation scenarios shows that heating demand alone cannot uniquely identify specific intermediate measures (e.g., window-only vs roof-only). This happens because an average 1 °C increase in indoor temperature can raise heating demand by 15% (Hamburg et al., 2020), thereby masking the 12-14% savings gained from window replacement. Consequently, when demand falls within overlapping ranges, use the logic from Table 3, or use the interactive evidence-based extension (Figure 6) to refine the classification.

A key finding is that wall insulation represents the clearest threshold intervention. In both 464A and 317A, wall-involved scenarios consistently shift buildings into a lower heating-demand tier than window-only or roof-only upgrades. While heating demand cannot fully resolve intermediate measures, it provides strong evidence for identifying wall-involved renovation states.

The robustness analysis further demonstrates that while optimistic envelope assumptions shift absolute heating demand downward, the qualitative patterns remain stable: wall insulation remains the dominant threshold intervention, deep renovation remains identifiable, and the overlap among shallow partial renovation states persists. This indicates that uncertainty among partial renovation states is not an artifact of a specific parameter choice, but rather a structural limitation of energy-only classification.

The type-level analysis is included as a controlled validation case and demonstrates how the approach could be refined when reliable subtype data are available. Because the subtype buildings share identical geometric and envelope input parameters, the baseline heating demand remains constant and does not form a range. Under these conditions, renovation scenarios also produce single deterministic values, as non-envelope assumptions are held constant (Table 4). The only remaining variation reflects differences in envelope U-value levels, resulting in a narrower and clearly defined performance range. This confirms that the broader ranges observed at the series level arise from building-to-building geometric and input heterogeneity rather than modelling instability. When reliable subtype data are available, the tiering approach can be applied at that level to improve classification accuracy. While absolute tiering ranges are series-specific, the methodology is transferable to other building stocks by using specific building geometry as the primary analytical unit to derive new, series-specific medians.

Limitations

This study is a simulation-based proof-of-concept using ReST-derived heating demand under predefined envelope scenarios. Ventilation system type can significantly affect heating demand; incorporating alternative ventilation strategies (e.g., exhaust vs balanced with HRV) may change absolute demand values. Here, ventilation was held constant to focus on envelope measures. In this study, operational and behavioural assumptions were held constant across buildings, which can affect heating consumption. Furthermore, in real buildings, uncertainty arises from (i) EBR data inaccuracies (Iliste et al., 2023), (ii) operational and occupant behavior (e.g., thermostat setpoints, ventilation operation, window airing) (Hamburg et al., 2020; Hamburg and Kalamees, 2019), and (iii) physical degradation and workmanship-related performance gaps (Hamburg et al., 2020; Hamburg and Kalamees, 2019; Iliste et al., 2023) (e.g., air leakage, insulation defects). These factors can shift heating demand from one renovation tier to another. Finally, as tier thresholds are series and heating-demand-dependent, transferability requires typology data and is limited in cooling-dominated regions, such as Southern Europe, without first adjusting the models.

Future Work

Future research will focus on calibrating this classification logic against real-world performance gaps by validating simulated results against measured heating data. This will include refining typology definitions through automated façade feature recognition and testing

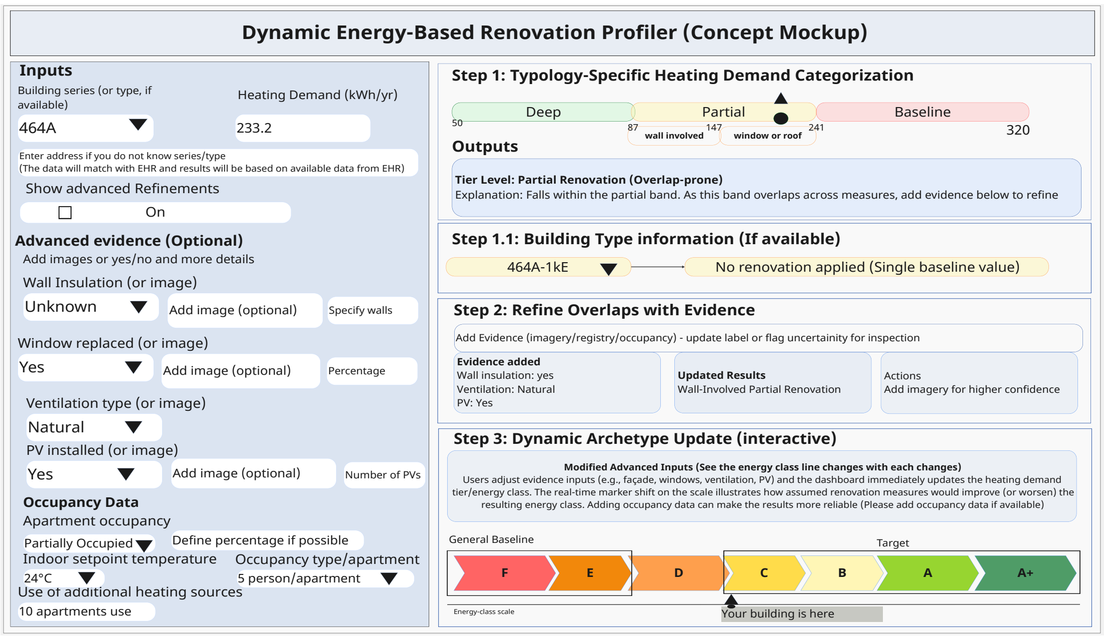

Figure 6: Concept mockup of an interactive Energy-Based Renovation Profiler

a wider variety of ventilation strategies (e.g., heat recovery variants). Furthermore, integrating heterogeneous data such as occupancy data and imagery-based assessments, through Bayesian calibration, offers a promising pathway to reduce UBEM performance gaps further (Wang et al., 2020). These steps will transition the current proof-of-concept into a reliable, multi-source decision-support tool for large-scale renovation.

Interactive heating-demand based tiering (mock-up)

The proposed heating-demand tiering provides a practical first step for archetype updating when renovation records are missing: buildings can be assigned a typology-specific renovation-depth tier from heating demand, with deep renovation being the most reliably detectable. However, overlap among partial renovation states means that energy-only classification should not be used to confidently infer specific measures (e.g., window-only versus roof-only). To address this limitation, we outline a conceptual interactive heating-demand-based tiering dashboard (Figure 6). The interface translates typology-specific thresholds into a decision-support workflow: users enter a building series and baseline heating demand to obtain an initial renovation-depth tier (none/partial/deep). Optional evidence inputs (e.g., ventilation type, registry attributes, occupancy behavior, or image-based façade) can then be incorporated to refine the classification. Users may test alternative renovation assumptions (façade, windows, roof, ventilation, PV) and observe how the assigned tier changes. This interactive layer allows rapid comparison of scenarios and highlights how additional evidence or renovation choices influence the inferred renovation status and energy class. This illustrates how typology-specific thresholds and supplementary evidence could be combined within a practical decision-support setting.

Conclusions

This study demonstrates that heating demand can be used to classify renovation depth (none/partial/deep) in Soviet-era multifamily buildings. Series-level analysis captures realistic stock heterogeneity, while subtype-level validation confirms deterministic model behaviour under identical inputs. The findings are a practical step toward establishing the methodological foundation for a dynamic archetyping framework, defining the analytical logic required for future integration with measured energy data and auxiliary building information within a decision-support environment.

Acknowledgments

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