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Assessing the reliability of archetype-based Urban Building Energy Simulations: A case study analysis in Turin (Italy)

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Abstract. The recently issued Energy Performance of Building Directive (EU 2024/1275) emphasises the importance of national building renovation plans, achievable by integrating building archetypes with Urban Building Energy Modelling (UBEM). However, UBEMs are often uncalibrated or unvalidated, and building archetypes are typically derived from energy certificates, which are known to have quality limitations. This research aims to assess the representativeness and reliability of data within building archetypes through a validation procedure, enhancing model credibility. Specifically, the proposed methodology introduces two new KPIs—the Validity of Representativeness Hours (*VRH*) and the Percentage of Representativeness Hours (*PRH*)—to evaluate how closely simulated energy demand aligns with real-energy consumption data within a defined tolerance range, given a set of inputs derived from the probabilistic building archetype schema. This methodology was applied to a residential case study in the municipality of Turin (Italy), composed by more than 300 apartment blocks and modelled in CitySim Pro. The validation procedure successfully identifies the most representative building archetype data, shaping and capturing the real energy performance of the building stock.

1. Introduction

1.1. Background analysis

The achievement of EU climate goals relies on the development of national building renovation plan. The newly released EPBD (EU 2024/1275) [1] emphasises the relevance of these plans in improving building stock energy efficiency and driving large-scale urban renovations. To support this transition, city-wide energy models are essential for assessing the energy performance of portfolio of buildings. This can be achieved by developing an Urban Building Energy Model (UBEM).

A key challenge in UBEM development is reducing uncertainty, which is particularly amplified at the urban scale compared to single-building energy modelling due to data accessibility, availability, and quality limitations [2]. To bridge this uncertainty gap, building archetypes (BAs)—along with of UBEM calibration and validation—play a crucial role. When combined in a UBEM framework, archetypes provide a reliable and realistic picture of the simulated building energy performance. They are widely used as a trade-off between reducing model complexity and enhancing model accuracy. BAs encapsulate the non-geometric properties needed to represent the energy performance of similar real buildings. However, most UBEMs in literature remain uncalibrated or unvalidated [3] due to limited monitoring data and the high computational effort requested for bottom-up physical based model verification. Improving model accuracy is essential for effective urban energy planning and for assessing the potential impact of energy efficiency measures.

In most cases, BAs are developed using energy performance certificates (EPCs), meaning that the non-geometrical properties of representative buildings reflect the limitations of existing EPCs. These constraints include restricted data availability, static energy performance assessments, limited energy-related insights, and low-quality parameters [4].

1.2. Aim of the research
The credibility of national building renovation plan depends on the reliability of large-scale energy models, which depends on reducing of the gap between simulated and actual building stock energy performance. BAs, often developed using unreliable and inaccurate EPCs, play a crucial role in reducing this uncertainty. Therefore, a validation approach is necessary to evaluate their actual representativeness.

This research introduces two new metrics—the Validity of Representativeness Hours (*VRH*) and Percentage of Representativeness Hours (*PRH*)—to assess, at each simulation step, how effectively the probabilistic BA schema captures real operational building conditions. Using CitySim, the methodology was applied to a residential district in the municipality of Turin (Italy), consisting of apartment blocks segmented into three construction periods. The results demonstrate that BA inputs can accurately represent the real energy performance of the building stock. By iteratively varying sensitive input variables within their statistical range, different *PRH* values were compared to evaluate representativeness.

The study aims to provide valuable recommendations for two key audiences. For UBEM developers, it offers insights on optimising BA data by identifying the most representative values. For policymakers, it enhances awareness of the actual building stock energy performance, supporting more informed decision-making in urban energy planning.

2. Methodology
BAs are deterministic or probabilistic sets of non-geometrical properties designed to characterise the building energy performance by capturing different technological aspects and usage patterns. This methodology is aimed at assessing the effectiveness of BA inputs in accurately modelling the actual energy performance of the building stock, based on their representativeness.

The proposed approach comprises the following steps:

1. identify and extract relevant input from the BA schema,
2. establish the probability function and variation range for each selected variable,
3. employ a UBEM tool to conduct scenario analyses with varying input parameters, and
4. calculate for each simulation the *VRH* and *PRH* metrics.

2.1. Validity of Representativeness Hours and Percentage of Representativeness Hours
This methodology introduces two correlated new KPIs, namely the Validity of Representativeness Hours (*VRH*) and Percentage of Representativeness Hours (*PRH*), to assess how closely simulated energy demand aligns with real energy consumption data within a defined tolerance range, given a set of inputs derived from the probabilistic building archetype schema.

For different sets of inputs, *VRH* (-), defined in Equation (1), assesses whether the simulated delivered thermal energy to the generation sub-system (index gen;in;sim), calculated using a UBEM tool, at the *i*-th timestep (sub-hourly, hourly, or daily) falls within the established lower (index lw) and upper (index up) consumption limits (index lim) for the assessed building (index *bldg*). Depending on the availability and reliability of measured data, this equation can be applied to various energy services, including space heating (index H), space cooling (index C), and/or domestic hot water (index W), either separately or in combination (e.g., delivered energy as the sum of space heating and DHW demands). The upper and lower consumption limits can be statistically defined, incorporating a tolerance margin based on monitored data accuracy, or set as the maximum and minimum values of the building consumption dataset, respectively.

Subsequently, *PRH* (%) quantifies the effectiveness of the simulated BA inputs in capturing the building's representativeness. As defined in Equation (2), *PRH*, expressed as percentage, is the ratio of *VRH* to the total number of timesteps (*N*) over the calculation period. This metric provides an aggregated measure of how the tested combination of inputs, extracted from the probabilistic BA schema, reflects real operational conditions.

$$VRH_{\mathrm{H/C/W};bldg;i} = \begin{cases} 1, & Q_{\mathrm{H/C/W;gen;in;lw;lim};i} \leq Q_{\mathrm{H/C/W;gen;in;sim};bldg;i} \leq Q_{\mathrm{H/C/W;gen;in;up;lim};i} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

$$PRH_{\mathrm{H/C/W};bldg} = \frac{\sum_i^N VRH_{\mathrm{H/C/W};bldg;i}}{N} \cdot 100 \quad (2)$$

This approach offers flexibility, enabling scalability across different contexts with measurements at varying spatial and temporal resolutions. Spatial flexibility allows the procedure to be applied to energy consumption at both disaggregated (building-level) and aggregated (block- or district-level) scales. Similarly, temporal flexibility enables the aggregation of simulated building energy consumption on a sub-hourly, hourly or daily basis, depending on the resolution of measurements.

3. Application

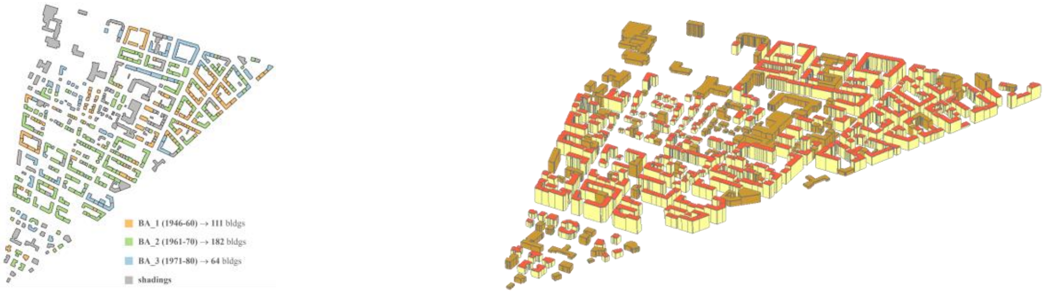
This methodology has been applied to a case study in the municipality of Turin (Italy), mainly composed by apartment blocks and modelled in CitySim. To assess the archetype reliability on a building-by-building basis, thermal characteristics of the opaque and transparent building envelope components, as well as space heating set-point temperatures, have been varied in five discrete steps within their statistical ranges. The simulated energy use for space heating has been compared to real upper and lower limits, derived from anonymised hourly district heating energy consumption from over 100 substations serving apartment blocks in Turin. For each simulation and building, *PRH* were calculated over the space heating period specified by Italian legislation.

3.1. CitySim Pro

CitySim is a widely recognised and utilised UBEM tool, developed by the Solar Energy and Building Physics Laboratory at École Polytechnique Fédérale de Lausanne (EPFL) [5]. Its calculation engine, CitySim Solver, underpins the KAEMCO graphical user interface CitySim Pro. CitySim operates as a dynamic hourly energy model, employing a Resistive-Capacitive system that discretise opaque and transparent building envelope components into temperature nodes, thermal resistances, and heat capacities [6].

3.2. Case study

The case study examines a real residential block sited in Turin (heating degree days: 2162 °C d), consisting of 357 buildings segmented into three construction periods: 1946-60 (BA_1), 1961-70 (BA_2), and 1971-80 (BA_3). The building ages and heights were obtained from the open database of the Geoportal of Turin [7]. The Level of Detail (LoD) for the analysed urban block is LoD1, i.e., buildings represented as shoeboxes. Figure 1a-b illustrates the segmentation of buildings based on their different construction periods and depicts the 3D urban scene, modelled using CitySim Pro. Non-residential buildings, as well as residential buildings with different ages, were considered as shading objects. This part of the city of Turin is connected to the district heating network.



(**a**) (**b**)

Figure 1. Case study segmented per BAs (**a**); CitySim model of the urban block (**b**).

The procedure involves varying four parameters to assess how different input combinations impact the evaluation of *PRH*. The BA data were sourced from the Italian research project URBEM (Urban Reference Buildings for Energy Modelling) [8]. Table 1 provides thermal transmittance of walls (U_{wl}), roof ($U_{\mathrm{fl;up}}$), window (U_{w}) and heating set-point temperature ($\theta_{\mathrm{H;set}}$) for each BA group. Specifically, the thermal characteristics of the building envelope were discretised into five steps. Similarly, $\theta_{\mathrm{H;set}}$ values, derived from the EN 16798-1 standard [9], were also defined in five discrete set-points.

Table 1. BA characteristics per construction period.

	BA_1 (1946-60)					**BA_2 (1961-70)**					**BA_3 (1971-80)**				
U_{wl} W/(m^2 K)	0.82	0.93	1.05	1.16	1.27	0.89	0.98	1.06	1.15	1.23	0.93	1.01	1.09	1.16	1.24
$U_{\mathrm{fl;up}}$ W/(m^2 K)	0.75	0.92	1.10	1.28	1.45	0.91	1.04	1.16	1.29	1.42	0.77	0.93	1.09	1.25	1.42
U_{w} W/(m^2 K)	2.33	2.88	3.42	3.97	4.51	2.32	2.89	3.45	4.02	4.58	2.28	2.83	3.39	3.94	4.49
$\theta_{\mathrm{H;set}}$ °C	18.0	19.0	20.0	20.5	21.0	18.0	19.0	20.0	20.5	21.0	18.0	19.0	20.0	20.5	21.0

3.3. *From theory to practice: configuration steps*

This section details the application of the proposed methodology. For the *i*-th hour the lower and upper limits, calculated using Equation (3), were statistically derived by aggregating sub-hourly anonymised measurements from 2021 recorded at 105 substations connected to apartment blocks in Turin. A 10 % tolerance, based on ASHRAE Guideline-14 [10], was included in the assessment of measurement limits based on the 1st and 3rd quartiles (Q_1 and Q_3) and the interquartile range (*IQR*). For privacy reasons, the building addresses served by the district heating network were obscured by the provider.

$$\begin{cases} Q_{\mathrm{H;gen;in;lw;lim};i} = Q_{\mathrm{H;gen;in};Q_1;i} - (1.5 + 0.1) \cdot Q_{\mathrm{H;gen;in};IQR;i} \\ Q_{\mathrm{H;gen;in;up;lim};i} = Q_{\mathrm{H;gen;in};Q_3;i} + (1.5 + 0.1) \cdot Q_{\mathrm{H;gen;in};IQR;i} \end{cases} \tag{3}$$

In line with the case study, Equations (1) and (2) were adapted to calculate *VRH* and *PRH*, considering only the space heating energy service. This adaptation was necessary to align with the available measurements. The summation in the *PRH* assessments extends over the heating period, as defined by Italian legislation: from mid-October to mid-April.

The algorithm for testing all possible input sets in combination with CitySim Pro is available online [11]. A discrete uniform distribution was applied to the four independent variables reported in Table 1. Consequently, for each archetype group, 5^4 = 625 runs were performed, assessing *PRH* at each simulation phase and for each analysed building. Within each simulation group, the target BA cluster was thermally simulated, while the other two archetype groups were considered as shading elements.

4. Results and discussion

The results presented in this section are a part of a broader research study. Figure 2 shows the probability associated with the discrete levels of the considered variables that maximise *PRH* for the first building archetype BA_1. According to the results, for this cluster of buildings constructed between 1946-60, insulating the opaque building envelope components and setting the space heating set-point to 21 °C result in the highest *PRH* value. The probability assigned to the thermal transmittance of windows is nearly evenly distributed between the first and last discrete levels. Based on the formulated hypotheses, this suggests that lower opaque *U*-values and a higher $\theta_{H;set}$ are better aligned with the actual operation of the building stock. This assumption should be verified with the district heating network provider, particularly with regard to the delivered supply temperature. The *PRH* values for the buildings shown in Figure 2 range between 85-94 %, meaning that for approximately 220 to 660 hours over 183 days, the simulated energy demand falls outside the measurement range.

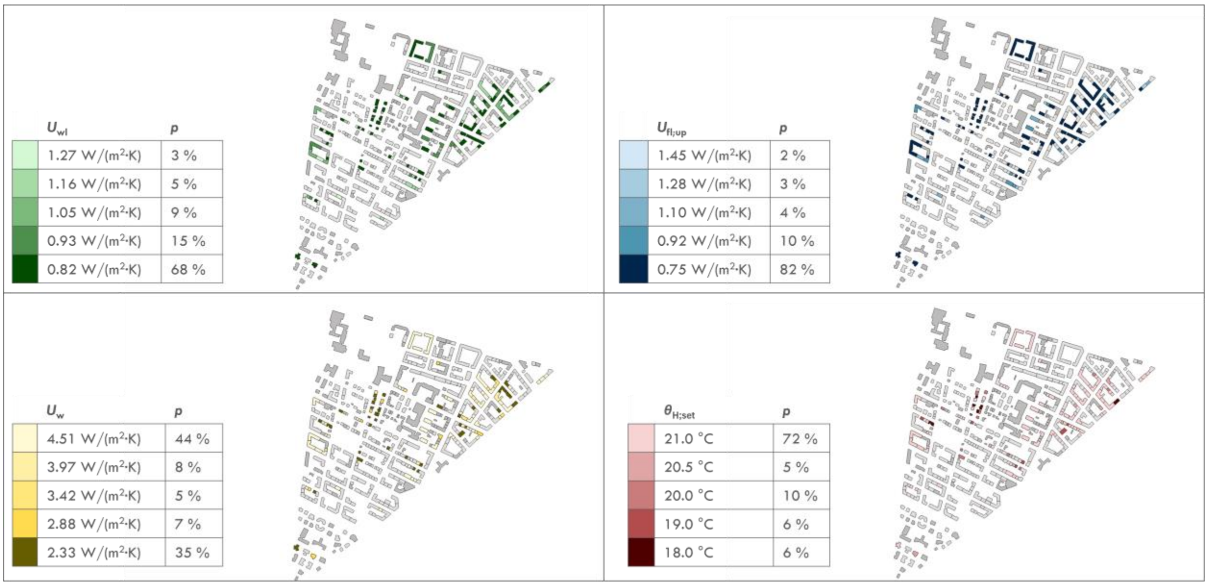


Figure 2. Probabilities (*p*) of independent parameters maximising *PRH* for BA_1.

5. Conclusion

This research aims to demonstrate the representativeness and reliability of data within BAs through a building-by-building comparison procedure.

BAs are often generated from EPCs, which are unreliable and inaccurate, necessitating a validation approach to assess whether these limitations are reflected in the BAs. By introducing two metrics—Validity of Representativeness Hours (*VRH*) and Percentage of Representativeness Hours (*PRH*)—this flexible approach can be adapted to different contexts with varying spatial-temporal measurements.

According to the reported results for BA_1, located in a residential district in the municipality of Turin, lower opaque thermal transmittances and a higher space heating set-point better align with the actual operation of the building stock indicating possibly an on-going renovation process.

5.1. Recommendations

The outcomes of this work provide recommendations for different target groups, namely UBEM developers and policymakers. Maximising *PRH* enhances energy representativeness with respect to the actual operational performance of the building stock. For UBEM developers, this research introduces a procedure to validate BA and identify discrete values, within the probabilistic BA schema, that better reflect real building stock energy performance. This approach lends credibility to national building renovation plans, aiding policymakers in meeting climate goals.

5.2. Future works
Using a bottom-up archetype-based approach, future steps will focus on calibrating the space heating and DHW demands of a Swiss case study in a UBEM model through a building-by-building process with the evolutionary algorithm CMA-ES/HDE. Additionally, the same optimisation will be applied to multi-building shared meters to calibrate the urban block in an aggregated manner.

Nomenclature
Symbols

PRH	percentage of representativeness hours (%)	*VRH*	validity of representativeness hours (–)
Q	areic (or volumetric) amount of heat (kWh/m^2) or (kWh/m^3)	θ	temperature (°C)
U	thermal transmittance ($W/(m^2\ K)$)		

Subscripts

bldg	building id	in	input, inlet	set	setpoint
C	cooling	*IQR*	interquartile range	up	upper
fl	floor	lim	limit	W	domestic hot water
gen	generation	lw	lower	w	window
H	heating	Q_1, Q_3	first and third quartile	wl	wall

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