

Urban-scale energy simulations using building archetypes: methodological insights and limitations from a case study

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Abstract. Urban-scale energy simulations deal with significant challenges, mainly the lack of comprehensive building datasets and the selection of a suitable simulation tool capable of accurately reflecting the complex interactions between urban buildings. In fact, available datasets are often either incomplete or obtained from the combination of multiple sources, thus requiring the homogenization of different data that can lead to errors or inaccuracies. Additionally, although urban-scale energy simulation tools often share a set of common inputs, the approach adopted for the simulation can require peculiar variables for each tool, thus potentially compromising the reliability of the results. This study, conducted within the PRIN project URBEM, focuses on the critical use of building archetypes for urban-scale energy simulations, highlighting the main challenges faced by modelers. Simulations are carried out with two different simulation tools: UMI, based on the EnergyPlus engine, and EURECA, based on a thermal resistance-capacitance approach. The comparison of the results aims to provide advice concerning the strengths and limitations of each approach while highlighting possible drawbacks in the implementation of the building archetypes already defined within the URBEM project and offering valuable recommendations for future urban-scale energy simulation efforts. Furthermore, the findings can support more informed decision-making for urban planning and tailored energy efficiency strategies.

Keywords: Urban scale energy models, building archetypes, UMI, EURECA

1 Introduction

Urban Building Energy Modelling (UBEM), developed in recent years, is a critical tool for facing the global challenges of urban energy efficiency, climate resilience, and carbon emission reductions. Nowadays, several software tools help researchers and policymakers explore large-scale energy interventions, assess the impact of climate change on urban energy systems, and support the transition to more sustainable cities. However, the use of UBEM tools also hides significant challenges that affect the accuracy of these models [1]. Besides issues such as data quality and availability, each software requires a unique set of urban-scale input data [2]. This variability, ranging from building geometries and occupancy patterns to weather data and energy system details, often leads to the use of various different assumptions that make results hardly comparable across tools or contexts [3]. Similarly, key outputs related to energy performance and savings, or CO₂ emissions, can be obtained by applying different energy models, increasing or reducing the high computational demands of modeling large urban areas [4]. These differences, in addition to the limited real-world data available, pose other significant barriers to the validation, reliability, and replicability of outputs. This paper aims to highlight the lack of standardization, focusing on the application of two different UBEM tools to a case study in Southern Italy. The comparison will be held between EURECA [5], which implements two simplified dynamic models based on the electric resistance-capacitance approach, and UMI [6], developed by the Massachusetts Institute of Technology, which solves the thermal balance of the buildings relying on EnergyPlus. The comparison of the tools will investigate geometry implementation, input data, methodological aspects and limitations, and primary outcomes, showing the strengths and weaknesses of each approach upon implementation of building archetypes already defined within the URBEM research project [7]. This analysis will provide new perspectives to UBEM modelers for the correct use of urban-scale energy simulations, ensuring greater accuracy and adaptability across diverse urban contexts. Furthermore, these findings highlight the importance of harmonizing simulation tools to ensure comparability, reliability, and scalability to adequately address the complex dynamics of urban energy systems.

2 Description of the case study

2.1 Morphological and typological characteristics

This study applies to a neighborhood in the Catania Municipal Area, located in Southern Italy. Catania has a typical Mediterranean climate, with hot, dry summers often exceeding 30–35°C, and mild winters (883 heating degree days), which makes it a climate where cooling energy demand dominates over heating needs. The selected area is a district resulting from the expansion process that the city experienced in the 1960s and is almost entirely made of residential buildings. The investigated

area has a high building density and compact building fabric, with the prevalence of mid-rise residential buildings.

Fig. 1 shows the study area within the city (a), and a 3D Map of the investigated neighborhood (b). Moreover, Fig. 1c and 1d show the 2D digital maps for the buildings' typologies based on their age of construction and building type, respectively. About 63% of the buildings are apartment blocks, 6% are terraced houses, and single-family houses are almost absent. Buildings with different end uses have been represented within the "other" category (Fig. 1c) and have not been included in the simulations. The predominant construction period is between 1951 and 1970 ($\approx 69\%$), while only 30% of the buildings were built before 1951. Table 1 summarizes the main characteristics of the area investigated.

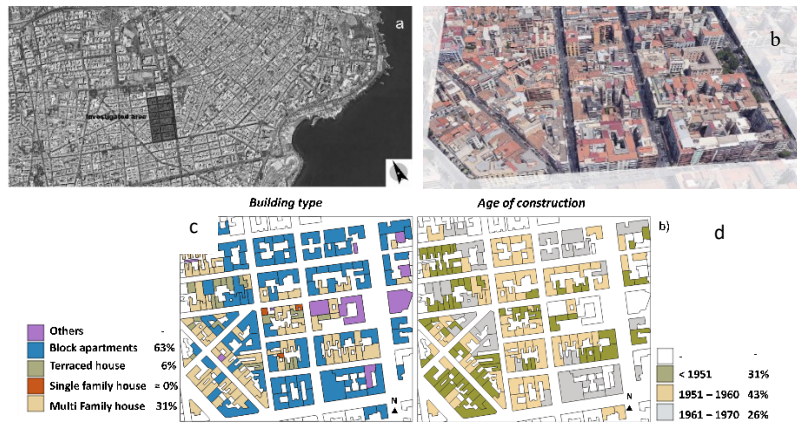


Fig. 1. Investigated neighborhood area: (a) Satellite image of the urban area; (b) 3D view; (c) 2D map of the building types; (d) 2D map of the construction periods.

Table 1. Geometric parameters and urban indexes of the investigated area.

Parameter	Symbol	Value	Unit
Site Ground Area	S_{site}	140,000	m^2
Total buildings gross volume	V_{Bldg}	795,785	m^3
Building's total gross floor area	S_t	390,756	m^2
Average building height	h_{wd}	17.10	m
Number of buildings	n_{bldg}	218	ND
Number of Dwelling Units	n_{ru}	2287	ND
Building to site area fraction	S_{bldg}/S_{site}	69%	m^2/m^2

2.2 Building Archetypes: envelope and HVAC systems features

Based on the detailed building information available, three age classes were identified (before 1951, 1951-1960, 1961-1970). Accordingly, three residential building

archetypes were defined based on the data available from surveys, municipal databases, project documentation, energy performance certificates, and expert assumptions.

The U-values of wall, roof slab, ground floor slab, and windows for RES_1951-60 and RES_1961-70 correspond to the median values resulting from the statistical analysis of the existing building components retrieved from various data sources such as survey data, municipal database, project documentation, energy performance certificates. For residential buildings included in RES_<1951 band, stratigraphy and U-values were retrieved from literature studies that investigated a series of buildings of the same age and typology near the study area [8, 9].

Internal heat gains (occupancy, lighting, and equipment) have been assumed from national standards and technical recommendations, according to the residential use of the buildings [9]. Likewise, air exchange rate has been set to 0.30 h^{-1} . Heating (from 1/12 to 31/03) and cooling (from 1/06 to 30/09) periods for HVAC system operations were defined according to the climate zone of Catania [10]. Daily profile usage includes three hours in the morning (7 AM-9 AM) and five hours in the evening (6 PM-11 PM) for the heating service, while an additional hour is added in the afternoon (5 PM-11 PM) for the cooling service. The efficiencies of heating, cooling, and DHW systems have been obtained from the statistical analysis of the available data. Table 2 summarizes the archetypes' data implemented in the simulations.

Table 2. Detailed data of residential building archetypes.

Data	Residential building archetypes			
	RES_<1951	RES_1951-1960	RES_1961-1970 electric heating	RES_1961-1970 thermal heating
Building Geometry	WWR _N (ND)	0.10	0.20	0.20
	WWR _S (ND)	0.10	0.10	0.30
	WWR _E (ND)	0.10	0.20	0.30
	WWR _W (ND)	0.10	0.20	0.20
Building Envelope	Wall type	Squared lava stone masonry	Hollow brick masonry	Hollow brick masonry
	U-value - wall [W/(m ² K)]	1.81	1.19	1.09
	Roof type	Floor with iron beams and hollow flat tiles	Reinforced brick-concrete slab	Reinforced brick-concrete slab
	U-value - roof [W/(m ² K)]	1.73	1.53	1.81
	Ground floor type	Concrete slab	Reinforced brick-concrete slab	Reinforced brick-concrete slab
	U-value - ground floor [W/(m ² K)]	1.44	1.62	1.62
	Window type	Single glazing, wood frame	Single glazing, aluminum frame	Single and double glazing, aluminum frame with and without thermal break
	U-value - window [W/(m ² K)]	5.10	5.87	4.32
Thermal system	Heating generator	Air-source Heat pump	Air-source Heat pump	Air-source Heat pump
	Heating efficiency, COP or η_H	3.12	3.12	3.12
	Cooling type	Air-cooled chiller	Air-cooled chiller	Air-cooled chiller

Cooling efficiency, EER	2.90	2.90	2.90	
DHW generator	Electric boiler	Electric boiler	Electric boiler	Natural gas boiler
DHW efficiency, COP or η_w	0.75	0.75	0.75	0.89

3 Models overview

3.1 EURECA and the resistance-capacitance approach

EURECA (Energy Urban Resistance Capacitance Approach) is a UBE platform based on lumped-parameters thermal networks developed by Pratavia et al. [5]. EURECA is designed to simulate both individual buildings and entire neighborhoods based on two lumped-parameter models: (i) a 5R1C thermal network based on ISO 13790 Standard [11] and (ii) a 7R2C thermal network from VDI 6007 German Standard [12]. The tool processes CityJSON and GeoJSON data related to building geometry and assesses urban dynamics, such as mutual shading and heat island effects. The simulations carried out in this study applied the 7R2C model, according to the greater accuracy for daily peak load calculations previously shown [13], considering a single thermal zone per building. Meteorological variables are provided by an EnergyPlus Weather File (EPW). The shapefile processed for the simulation must include information related to:

- Buildings' geometry: window-to-wall ratio (WWR), height, and floors number;
- Building age and envelope: to assign the corresponding archetype;
- Building ID and use to assign operating schedules based on the end use;
- Heating and cooling systems types.

The tool provides as outcomes detailed timestep variables concerning the building and the system's operation, including DHW demand, tank charge, solar thermal production, photovoltaic production, space heating/cooling demand, zone temperature, air handling unit demand, and energy carrier consumption. The tool also provides an annual and monthly report for energy carrier consumption, both as a CSV and as a new shapefile.

3.2 UMI and Energy Plus

The Urban Modeling Interface (UMI) is a Rhinoceros-based urban design modeling software package that can simulate the end-use energy needs of a building stock at an urban scale using EnergyPlus as the simulation core engine [6]. UMI can calculate the annual end-use energy needs for space heating, space cooling, and domestic hot water (DHW) preparation, as well as the energy consumption of equipment and lighting both at the individual building scale and at neighborhood and city scales [6]. Climatic data are provided by an EnergyPlus Weather File (EPW).

To overcome the computational demand needed when simulating large groups of buildings, UMI uses an algorithm that automatically creates thermal zones named "shoeboxes" based on the preliminary definition of perimeter and core zones. The shoeboxes minimize the geometric complexity of the thermal models, and allow

reasonable calculation time since the energy balances are solved just for each shoebox. [14]. The input generation and organization phases are based on implementing geometric data by means of closed polysurfaces (boundary representations or BREP) and associating a “zone archetype” to each BREP. The zone archetype contains non-geometric building data such as construction assemblies, internal gains, occupancy schedules, and HVAC settings (Table 2). BREP units are then reduced to a minimum number of shoeboxes aggregated into different clusters based on a preliminary solar radiation analysis of the different facades. As a final step, the shoebox models are converted into an input file for EnergyPlus [15], and the detailed timestep simulation results of each shoebox are aggregated by weighing them according to the floor area of its associated cluster. The same input data were used for UMI and EURECA. Both utilise the same climatic file, physical and geometrical parameters of buildings, as well as identical efficiencies, system types, and schedules.

4 Discussion

This section will present a detailed discussion of the results of EURECA and UMI. The comparison will investigate the outputs of final energy consumptions related to Space Heating (SH), Domestic Hot Water (DHW), Heating (the sum of SH and DHW), and Cooling (C). The following discussion clarifies the unique characteristics of each UBEM and identifies the reasons for potential discrepancies in simulated energy consumption.

4.1 Variation in UMI outputs

Unlike EURECA, the stochastic nature of the UMI shoebox model generates unique building representations by randomly sampling parameters such as geometry, occupancy, and internal loads. As a result, each simulation differs from the previous one. To assess the impact of this variability, several UMI simulations were run with the same input values to understand the impact on the results. The boxplot in Fig. 2 illustrates the percentage variation of space heating (SH) and cooling (C) energy consumption across multiple UMI simulations. This is calculated by considering the minimum and maximum SH and C demand relative differences among six simulations for each building. Moreover, the Perimeter Offset (PO) that determines the length of the perimetral zone of the shoebox was changed between 3 m and 1.5 m.

Both SH and C energy consumptions change randomly when the simulation is run multiple times. Focusing on the SH (PO = 3m) boxplot, the median difference is 11.5%, but there are some buildings where this variation is over 30%. This effect is even more noticeable in C (PO = 3m), with a median variation of 14.6 % and a difference of over 40% in some cases. Such randomness in the results is due to the shoebox thermal zoning strategy of UMI, which creates a prototypical thermal zone according to solar radiation-based clustering [14].

Shoebox dimensions also impact the fluctuation of simulated energy consumption, even if in a less relevant way. In particular, the impact of PO is higher in SH than in C. Looking at the boxplots obtained with $PO = 1.5m$, the median in SH decreases to 9.1%, while in C, it remains almost constant (14.4%).

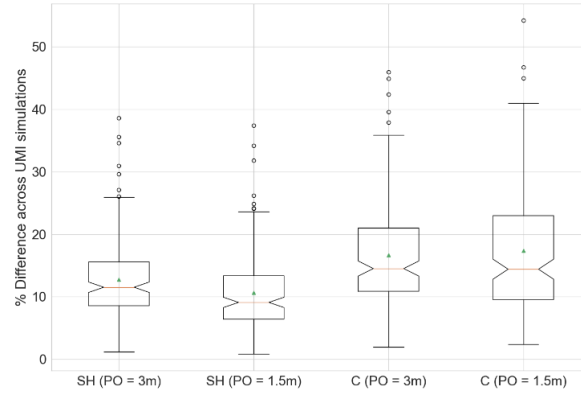


Fig. 2. Boxplot representing the percentual difference among SH and C energy consumptions across multiple UMI simulations.

4.2 Comparison of the final energy consumption

Table 3 shows the relative differences between EURECA and UMI final energy consumption, based on the characteristics presented in Table 2. The table presents both the relative deviation of the entire district's consumption and the average relative deviation of each building. This is for Space Heating (SH), Domestic Hot Water (DHW), total Heating (H), and Cooling (C). Positive signs must be interpreted as an overestimation by EURECA compared to UMI. A grouping based on the Archetype is also proposed. On the other hand, the average relative deviation between EURECA and UMI for specific heating consumption is 10.9%, while the difference in the district's total heating demand is almost 12%. This is observed only in the demand for SH, and not in the case of DHW preparation. Indeed, the two tools, by default, would assume different water grid temperatures; for this reason, this assumption has been forced in EURECA to be the same as UMI, giving almost equal DHW demand.

On the other hand, simulated cooling energy consumption of the entire district is almost the same in EURECA and UMI, with a difference of 0.2%, as reported in Table 3. However, the nearly equal total district cooling energy consumption is a result of compensation between the average EURECA overestimation of consumption for buildings built before 1951 and the average underestimation for buildings constructed between 1951 and 1970. At single building scale, differences are generally higher compared to SH because cooling energy consumption is more

dependent on solar heat gains and, consequently, on the shoebox's positions and dimensions.

Table 3. Average of percentual differences (Avg) and percentual difference on entire district (Tot) between final energy consumption simulated with EURECA and UMI. Every building has an air-cooled chiller as cooling system.

KPI		Residential building Archetypes				Entire dataset
		RES_<1951	RES_1951-1960	RES_1961-1970 Electric heating	RES_1961-1970 thermal heating	
H	Avg	2.0%	6.3%	34.5%	47.8%	10.9%
	Tot	0.9%	2.6%	7.1%	25.9%	11.9%
SH	Avg	2.5%	9.5%	32.9%	49.1%	11.9%
	Tot	2.4%	11.5%	34.6%	51.1%	34.8%
DHW	Avg	0.01%	-2.1%	0.6%	-1.3%	-0.9%
	Tot	0.4%	-0.05%	0.1%	-1.6%	-0.3%
C	Avg	23.8%	-19.1%	-35.0%	2.5%	0.5%
	Tot	18.9%	-7.4%	-15.7%	2.9%	0.2%

4.3 Specific SH consumption

Fig. 3 shows the specific yearly SH final energy consumption in kWh/(m²·y) of every building in the case study. UMI results are reported in blue, while EURECA ones are in orange. The highest differences are in 1961-1970 building archetypes, with an average and total deviation of 32.9% and 34.6% for heat pumps and 49.1% and 51.1%, respectively, in the case of a natural gas boiler. Although these values are significant, the impact on the average difference for the entire district is low due to the limited number of buildings associated with these archetypes: 10 for heat pumps and 20 for natural gas boilers.

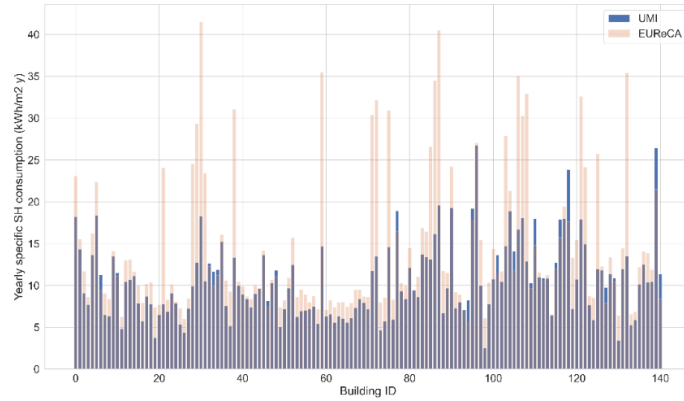


Fig. 3. Yearly specific SH energy consumption estimated with UMI (blue) and EURECA (orange)

Modifying the archetype associated to these buildings had no significant impact on the results, leading to the conclusion that such overestimation can be due to the particular geometries of this set of buildings, and not to the archetype itself. Indeed, most of them showcase unconventional shapes, including horseshoe shapes, internal courtyards, and varying heights among different building zones. These geometries affect the positions of the shoeboxes in UMI and most likely impact adjacent unheated environments, conductive heat transfer, and solar radiation. Moreover, the random nature of UMI does not allow for further comparison. Despite the differences in SH final energy consumption, both outputs are reliable, and it is not clear which could be closer to actual consumption. In fact, cooling dominant climates such as Catania result in small SH heating demand, not allowing a reliable comparison with benchmark data.

5 Conclusions

This study has provided a first attempt towards a comprehensive comparison between two UBEM tools, UMI and EURECA, applied to a residential district in Catania, Southern Italy. Through the critical evaluation of both tools, several key observations have emerged.

Firstly, the study highlighted the variability in the input data requirements and the methodologies adopted by each tool. EURECA employs a thermal resistance-capacitance approach to simulate the buildings individually. Conversely, UMI relies on EnergyPlus, representing every building with multiple shoeboxes to simplify and speed up simulations.

Both tools yield similar outputs, yet UMI shows random fluctuations in space heating and cooling energy estimates due to the randomized algorithm for shoebox creation. The results showed discrepancies between the energy consumption predictions: EURECA tended to overestimate the specific heating consumption compared to UMI, with an average difference of 10.9% across the district. This overestimation was significant for buildings with complex geometries that are likely causing inaccuracies in UMI shoeboxes' positioning. In terms of cooling energy consumption, the differences between the two tools were less pronounced on average, with a negligible total difference of 0.17% for the entire district. However, EURECA's overestimation for pre-1951 buildings and underestimation for 1951-1970 buildings highlighted a substantial difference in cooling energy demand calculation at building scale. Discrepancies are likely related to the UMI model of solar heat gains and the shoeboxes' positioning and dimensions.

This comparative analysis underscores the importance of harmonizing simulation tools to ensure consistency, reliability, and scalability in urban energy modeling. The findings suggest that a combined approach that takes advantage of EURECA's detailed thermal modeling and UMI's computational efficiency could enhance the accuracy and applicability of UBEM applications. Future research should focus on a systematic comparison of the way the two simulations tools manage the input data, while also performing a deeper analysis of the discrepancies

between space heating and cooling energy consumption across the tools and on the randomness deriving from UMI modeling and simulation approach, potentially comparing the results with measured data in different climates.

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