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Validating 'GIS-UBEM'—A Residential Open Data-Driven Urban Building Energy Model

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Abstract: The study of energy consumption in buildings, particularly residential ones, brings with it significant socio-economic and environmental implications, as it accounts for approximately 40% of CO_2 emissions, 18% in the case of residential buildings, in Europe. On a number of levels, energy consumption serves as a key parameter in urban sustainability indicators and energy plans. Access to data on energy consumption is crucial for energy planning, management, knowledge generation, and awareness. Urban Building Energy Models (UBEMs), which are emerging tools for simulating energy consumption at neighborhood scale, allow for more efficient intervention and energy rehabilitation planning. However, UBEM validation requires reliable reference data, which are often challenging to obtain at urban scale due to privacy concerns and data accessibility issues. Recent advances, such as automation and open data utilization, are proving promising in addressing these challenges. This study aims to provide a standardized UBEM validation process by presenting a case study that was carried out utilizing open data to develop bottom-up engineering models of residential energy demand at urban scale, with a resolution level of individual buildings, and a subsequent adjustment and validation using reference tools. This study confirms that the validated GIS-UBEM model heating and cooling demands and consumption fall within the confidence bands of ±15% and ±12.5%, i.e., the confidence bands required for the approval of official alternative simulation methods for energy certification. This paves the way for its application in urban-scale studies and practices with a well-established margin of confidence, covering a wide range of building typologies, construction models, and climates comparable to those considered in the validation process. The primary application of this model is to determine the starting point and subsequent evaluation of improvement scenarios at a district scale, examining issues such as massive energy rehabilitation interventions, energy planning, demand analysis, vulnerability studies, etc.

Keywords: bottom-up model; district scale; simulation model; urban energy assessment; residential energy use

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1. Introduction

The increasing importance of studying energy consumption in buildings, particularly residential ones, is indicative of many socio-economic and environmental issues, as buildings generally account for 40% of global CO_2 emissions, 18% in the case of residential buildings, in Europe. Energy consumption is also a common parameter in urban sustainability indicator systems or energy plans at various scales. Access to data on business and citizen consumption, recognized as essential to energy planning and management, can also serve as a tool for improving the generation, dissemination, and awareness of knowledge [1]. In energy transitions, access to free and reliable information on energy consumption is vital.

In the field of research and the development of energy plans and policies, there are calls to develop scenarios and projections for strategies for decarbonizing the residential sector, also taking into consideration possible climate change scenarios. These analyses can be carried out using predictive models, i.e., simulation-based models (bottom-up engineering models) [2] that estimate the residential energy consumption of a single building or set of buildings. This, in turn, makes it possible to predict the evolution toward the set objectives for greenhouse gas emission reduction while conducting exploratory analyses on possible climate scenarios for different mitigation strategies (building rehabilitation, renewables, system improvements, etc.). At the specific neighborhood or district scale, we find urban building energy modeling(UBEM), an emerging field associated with energy simulations, carried out using different tools, of a group of buildings, considering their interaction [3,4].

Urban building energy modeling is a relatively novel field of research which has accompanied the emergence of computing methods and algorithms for the optimization of energy simulation processes in aggregated building sets. A particularly notable center for research and development in this field is the Sustainable Design Lab at MIT, where researchers developed the "Shoeboxer" algorithm to simplify the simulation of building sets based on an analysis and discretization of the building mass in a city sector [5]. This led to the development of the energy consumption module of the Urban Modeling Interface (UMI) tool, based on the EnergyPlus calculation engine [6]. Among the earlier review articles, a notable primary contribution is that by Reinhart and Cerezo-Davila (2016) [4]. This paper identifies the tasks needed to create a reliable energy model of an urban sector: organizing simulation input data, generating the thermal model, execution (thermal simulation), and the validation of results. However, since then, this field has continued to evolve, as highlighted by the review publications authored by Ang et al. (2020) [7], T. Hong et al. (2020) [3], Flora D. Salim et al. (2020) [8], Li et al. (2017) [9], and, more recently, by Wang, C. et al. (2022) [10] and Ali et al. (2021) [11].

Physical UBEM has been used to document case studies of urban- or district-scale energy consumption. In 2016, the bottom-up physical energy model developed for Boston [12], based on a GIS and simulated with UMI version 3.0, was followed by experiences applying the same methodology in Lisbon [13]. Subsequently, in 2020, researchers from this same group conducted experiments to model existing residential stock by combining TABULA project typologies for building characterization templates, focusing on the city of Dublin [14–17].

Some of these noteworthy experiences are found in the context of Mediterranean cities, where UBEM are developed at individual building scale within a block or district, using open data records but without employing simulation tools specifically designed for the urban scale. This was the case in a study on the energy consumption of a residential block with aggregated individual building energy models (BEM)s of heritage buildings in a city center [18]. Also of interest are the bottom-up models of suburbs on the outskirts of Seville [19] created using energy certificate data or those in Madrid [20], with there being an algorithm for estimating thermal losses through the envelope study of residential blocks based on the use of cadastral data and Python scripts/coding.

The morphological and constructive variability of the residential stock is a complex factor to transfer to energy analysis models. However, initiatives such as TABULA define representative typologies of the stock in each European country or region [21,22], while UBEM-IO is used in the USA [7,23]. The variability of usage profiles is crucial in final consumption [3,24,25]. Therefore, in the context of neighborhood-scale analysis, the usage profile is standardized based on standard patterns, while surveys and statistics on the sector analyzed can be used to characterize the simulated usage profile, ensuring it is more closely aligned with the real one.

UBEMs present an advantage compared to building-scale energy models (BEMs), which require vast resource consumption when applied at an urban or neighborhood scale. Although these scales are the most appropriate for the development of energy intervention and rehabilitation plans, as with all simulation models, their reliability can only be adjusted and determined with a validation using reference data. For BEMs, reference data for model adjustment can be theoretical, using standardized patterns which were first established with BESTEST [26,27], while the use of DESTEST is preferable for UBEMs [28,29]. Real values obtained through the monitoring of existing modeled building consumptions can also be used for model validation [30]. However, while the existing legislative framework is conducive to easier access to energy consumption data, respecting data protection legislation [1], in actual fact, it is difficult to obtain real consumption data at an urban scale for validating UBEMs. Typically, these data are protected and managed directly by supply companies, which makes them difficult to access, even for research purposes [31,32].

The literature provides examples of attempts to validate/verify UBEMs with monitored consumption values (calibration), as was attempted in the work of Emmanuel and Jérôme (2015) [30], who used CitySIM, albeit for a single building. Bayesian methods for calibrating urban models are also described [33,34], and these methods are applicable when real consumption data are available.

A recent review article on the subject [35], which presented analyses of numerous UBEMs on real case studies, concluded that none of the many cases analyzed featured a specific calibration method and highlighted the lack of an accepted international UBEM metric standard.

Furthermore, a recent study in Borlänge and Uppsala (Sweden) [36] implemented the automation of a UBEM based on open data, using available energy certificates for the purposes of calibration and validation. Additional research on the city of Milan employed the open-source software QGIS version 3.28.8 to model and calculate various energy-related variables in order to predict space heating, domestic hot water consumption, and potential solar production [37].

This work presents a number of innovations with respect to the situations previously described in the literature. In general, BESTEST cannot be applied to UBEM tools, which, by definition, consider a diversity of buildings, their mutual interaction, and interaction with the urban environment [4]. Furthermore, at present the DESTEST project [28,29] does not address the morphological, constructive, or usage profile variability of the buildings included in the model. Instead, it focuses on modeling energy systems at an urban scale (district heating networks), an uncommon solution in most cities in the Mediterranean area, where thermal systems tend to be individual or centralized at the building scale.

In this research, the GIS-UBEM workflow, which is based on the use of open data to develop the morphology and constructive characterization of a UBEM, is proposed. It can be easily replicated for any urban environment where administrative information about the age of buildings and their geometry in GIS format is available, such as the cadaster [20,38]. UMI version 3.0, the tool used for energy simulation, is publicly accessible and widely referenced in research articles and previous case studies. Finally, the confidence margin obtained is comparable to that required by official reference energy assessment tools in Spain (alternative methods to HULC [39]), providing support for future studies and research based on the implementation of the GIS-UBEM workflow.

Overall, this work aims to offer a standard procedure for adjusting and validating UBEMs at district scale according to reference methods and with known confidence intervals. This allows for the generation of bottom-up predictive models of residential energy demand in urban sectors that can be adapted to different regional realities and is based on the acquisition of open data. For this purpose, a case study was used to develop a validation process for this methodology.

The novelty of our approach can be summarized as follows:

1. The development of a workflow for validating urban sector models using UBEM tools (for urban-scale simulation) in conjunction with reference and accredited BEM tools (for single-building simulations) to construct models of individual buildings.
2. The incorporation of variability in building age and typology, as well as in the climates considered in the nine referencemodels, enables us to extend the reliability of validation to other regions or scales.
3. The selection of sample buildings and reference weather files for simulation with the reference BEM tools enhances the reliability of the process from single-building

assessments to encompass the entire regional housing stock with a known level of confidence and accuracy.

4. The entire process is built upon open datasets and utilizes open processes and tools, facilitating replication in any other location.

2. Materials and Methods

The methodology involved adapting adjustment and validation processes similar to those applied in the context of BEM, as well as previous initiatives for district-scale calibration. A UBEM of a real heterogeneous urban sector was chosen as a case study, covering a range of representative building typologies, each subjected to different reference climates. A sample of buildings representative of the sector was selected, and their energy performance was analyzed with the UBEM tool, as well as with two other well-established and validated BEM tools, HULC version 2.0.2253.1167 and CYPETHERM HE Plus 2019 version 2022.a [40].Various climatic scenarios were also considered in the analysis to determine the range of variability of the residential sector analyzed for the spectrum of extreme and intermediate climates characteristic of the reference region of Andalusia.

After modeling the different standard buildings in the different reference climates in the tool and the two control programs, results were analyzed and compared. The results obtained with the UMI fall within the confidence bands marked by the control tools and were thus considered validated. The predictive GIS-UBEM aimed to obtain, for each of the buildings in the study area, the energy demand for the heating and cooling services (residential) of an urban sector.

2.1. Case Study

In order to test the proposed methodology in terms of predicting residential energy consumption at an urban scale, a particular climate was chosen to highlight the effect of air conditioning demand and associated energy consumption, which also made it easier to visualize any differences between buildings of different periods and typologies.

Jaén, a historic medium-sized city in southern Spain, has a recorded population of 111,932 inhabitants, according to its 2021 census. It also has very diverse topography, as well as great morphological diversity in its urban fabric and building stock.

A wedge-shaped sector was chosen for this study (Figure 1), originating from the historic center and opening along two radial communication routes. These two routes straddle an area containing historical developments occurring throughout the 20th century. As a result, the set of residential buildings (around 1000 in total) covers a wide range of typologies and dates of construction, as well as a sequence of urban layouts characteristic of a growth pattern concentric to the original core, very common in historic European cities.

2.2. Model Characterization of District UBEM Based on Open Data

The cadastral database included within the boundaries of the sample was used as a starting point for the development of the UBEM model. The following step was to filter the cadastral data based on the "use" of the buildings, discarding any buildings without "residential" use and maintaining those where at least 50% of the properties or premises are dwellings. Finally, the buildings were filtered according to their state of conservation in the cadaster records. Thus, any buildings in ruins or with no data on the state of conservation were excluded from the outset, as it could not be assumed that they could meet the conditions to accommodate primary residences, a prerequisite for residential energy consumption to occur. These two filters were therefore used to identify all multi-family and single-family residential buildings within the selected sample in order to study energy demand.

The QGIS tool was then used to examine data from different fields relating to the residential building records, noting the construction date, which was used to assign the construction and operational template for building characterization in the UBEM model.

Figure 1. Boundaries of the urban sector analyzed as a case study (Jaén, Spain).

The next step involved the combined use of QGIS and the UMI through a Grasshopper plugin. Sector modeling was performed using the methodology described in the 'UBEM.io' platform [7]. This methodology used data from open GIS databases of the Spanish cadaster [38] acquired with QGIS, as well as any administrative data available for individual buildings in the sector, in order to carry out the semi-automatic generation of the set of buildings included in the sector, preserving the urban typology and approximate volume, as shown in Figure 2.

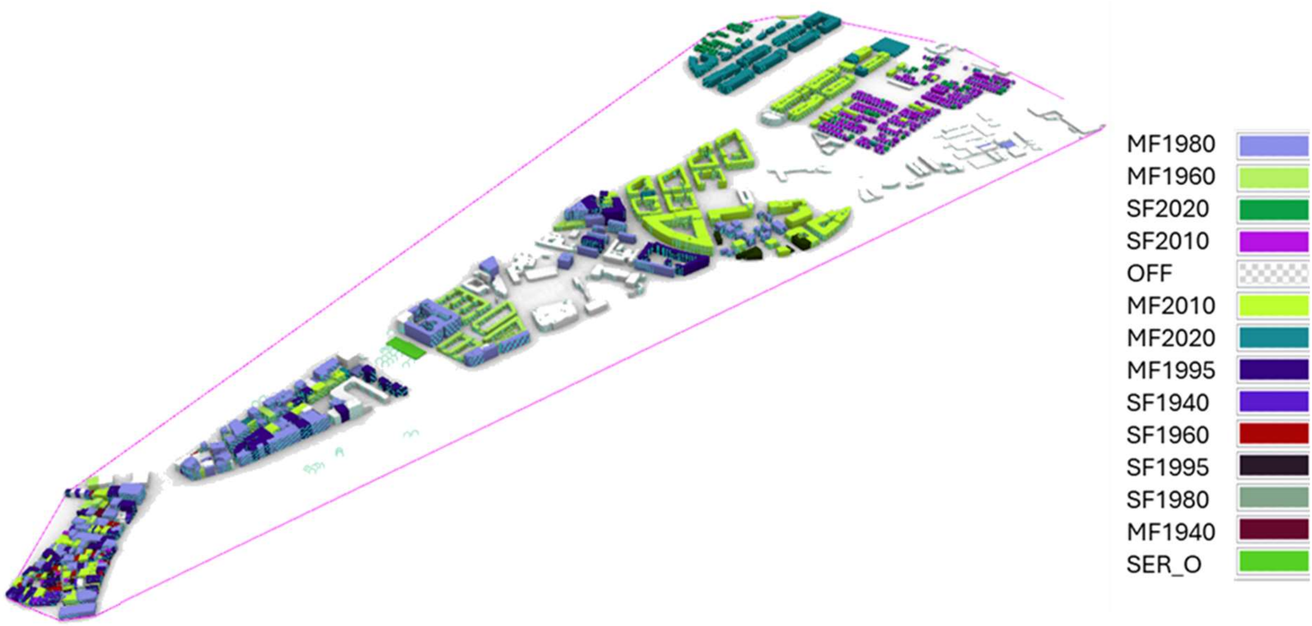


Figure 2. General overview of the UBEM model of the case study, modeled with UMI 3.0, Rhinoceros 6, and the UBEM.IO platform. The building typologies used are represented in color.

For the constructive and installation characterization of residential buildings in the sector, the criterion adopted was that of assigning typologies or templates based on segmentation by age and single-family or multi-family use for individual buildings. For this characterization, a series of reference works were consulted, including studies on thermal envelopes in social housing [41–43], typologies from the TABULA project [22,44], IECA Survey 2008–2018 [45] statistics, and recognized documents from the Spanish Technical Building Code, CTE ('Catalog of construction elements' [46]) and Energy Performance Certification of existing buildings [45,47].

For modeling in a Mediterranean climate, an integral constructive solution (envelope, partitions, roofs, installations, etc.) was defined for 12 distinct building typologies, along with a standard usage profile characteristic of residential use, common to all cases. However, as part of the adjustment and validation process, ventilation conditions were incorporated into the usage profile based on the building's purpose and age. The UMI tool can be used to customize natural ventilation operation parameters, such as the activation thresholds for outdoor temperature and zone setpoints. The validated model incorporates an infiltration rate determined by airtightness studies conducted in Spain [48,49]. The use of 12 templates corresponds to the segmentation by single-family/multi-family use and to 6 possible construction periods. Appendix A summarizes the information included in each template for all 12 types. According to the main bibliographical references and direct experience, a proportion between 10 and 20% was established for the window-to-wall ratio (WWR), depending on the use and age of the building.

2.3. Energy Modeling

2.3.1. UBEM Energy Modeling

For urban-scale energy modeling and calculation, the UMI tool, which is highly scientifically valid [6], based on an EnergyPlus calculation engine, was used. The Shoeboxer algorithm was used to apply it to a large set of buildings [5], while UBEM.io was used to accelerate the semi-automatic modeling process [7]. It has been incorporated into similar urban-scale studies in cities including Boston, Kuwait, and Dublin [12,15,50].

A methodology originating from the IEA BESTEST was chosen for model validation [26,27]. BESTEST compares the calculation results of a standard building using a new BEM software to be validated with the results of those obtained with a series of well-established programs for the same standard building. To this end, a preliminary calculation of the entire sector was performed, and the results obtained were then transferred to QGIS. This, in turn, enabled a statistical analysis to be carried out for the energy demand of the sample buildings in the study. Subsequently, the data obtained were used to generate a histogram where the distribution and range of results can be identified. This histogram was used to identify three control buildings to avoid biases in the model adjustments. The buildings selected represent the extremes and the average of the set, as well as three climatic zones present in Andalusia (A3, C4, and D2) (Table 1), aiming to cover the maximum variability of results at both regional and urban level. These buildings were used in the model adjustment and validation process using recognized BEM tools.

Table 1. Climates considered for regional variability study.

Climatic Zone	Koppen Climate	Description	Reference City in Spain
A3	Csa, Mediterranean	Mild winter, warm summer	Cádiz, Málaga
C4	Csa, Mediterranean continentalized/BSk, cold semi-arid	Moderate winter, hot summer	Jaén, Badajoz, Toledo, Cáceres
D2	Csa, Mediterranean continentalized/Csb, Mediterranean with mild summers, BSk, cold steppe	Harsh winter, mild summer	Valladolid, Zamora, Dólar (Granada).

2.3.2. HULC and CYPETHERM Modeling

The next step consists of the adjustment of the parameters of the tool and the individual building models (pre-established construction typologies by age). A comparison was carried out for the heating and cooling energy demand values, with a reference pattern obtained in each case with two reference simulation tools in Spain, HULC and CYPETHERM, using the S3PS and EnergyPlus calculation engines.

In the HULC and CYPETHERM programs, the spatial definition of thermal models was simplified to approximate it to the UBEM model in UMI so that only one zone per residential floor was considered without internal distribution. The surrounding buildings were defined as elements of nearby shadows in the UBEM, and the adjacent buildings were considered as partitions or party walls. In both programs, the envelope and interior partition elements were modeled according to the corresponding building templates. The heating and cooling systems were also modeled using constant performance systems.

After modeling, the models were calculated in HULC and CYPETHERM with the climatic files of zones A3, C4, and D2, respectively, in order to expand the comparison spectrum between the BEM models and their UBEM version. From the calculation results, the demands and final energy consumption values for heating and cooling were extracted for a comparison with the results of the UMI UBEMs.

According to the validation protocol adopted, the result of the UMI model was accepted as valid if it fell within the following established confidence ranges or bands around the average results of HULC and CYPETHERM:

- Heating and cooling demands: $\pm$15% bands.
- Total final energy consumption (Heating, Cooling, DHW): $\pm$12.5% bands.

After defining the validation pattern for individual building types in the three reference climates, a process involving the recalculation and adjustment of the models in UMI was carried out to approximate them as closely as possible to the validation ranges while maintaining cross-coherence between the models and the climate. This process followed a sequence of iterative calculations, including dozens of models with specific adjustments of their parameters (mainly ventilation rate, setpoints, and their corresponding schedules), to achieve the best fit of the UMI 3 $\times$ 3 series results (3 typologies in 3 different climates = 9 results) with the chosen control patterns (HULC and CYPETHERM HE Plus series (3 types $\times$ 2 BEMs $\times$ 3 climates = 18 reference patterns). Figure 3 shows the workflow followed for the validation of the GIS-UBEM.

2.3.3. Energy Simulation of the Validated Model

In the final step of this GIS-UBEM process, represented in Figure 3, the calibrated model was recalibrated using the EPW climate file for Jaén obtained from the PV-GIS database. In the case study, the sector with the validated UBEM included 1010 residential buildings with a total of 9301 dwellings. The purpose of the model was to help in estimating energy demand and consumption under real conditions for the climate of Jaén. Thus, a GIS layer with the results of the energy calculation from the GIS-UBEM was obtained. The SHP layer with the energy calculation results also served as a basis for obtaining the training dataset for predictive models at the urban scale using Machine Learning.

2.3.4. Limitations

This methodology is for the analysis of urban scales. The validation method does not aim to replace BEM tools for individual building analysis, as they do not serve the same function or intended use, nor does it aim to replace engineering calculations or official energy assessments at district scale (mass energy certification). Any templates assigned to characterize the residential stock remain a simplification of the constructive user profile and functional diversity (segmented by use and age), valid for representing the stock.

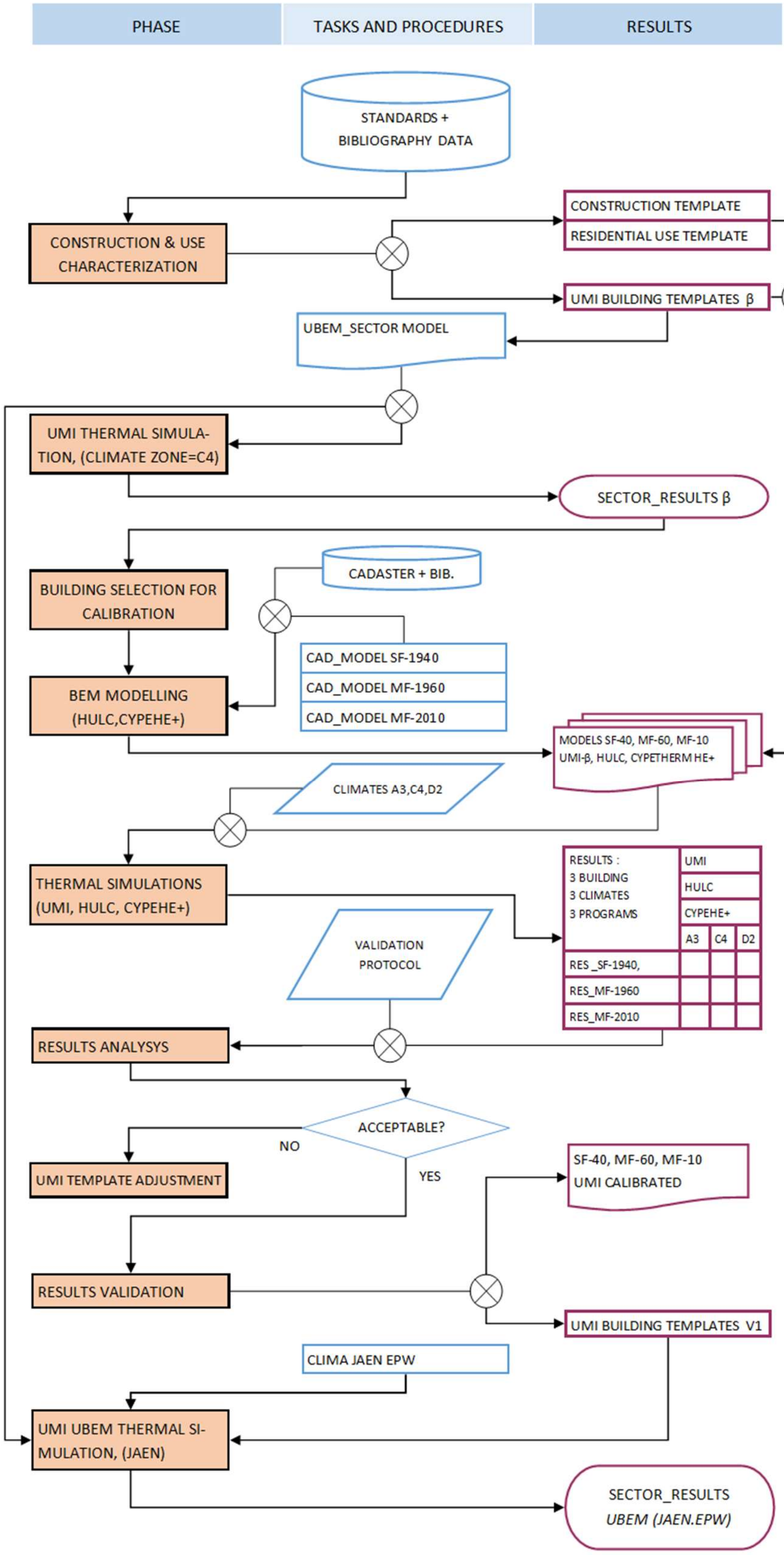
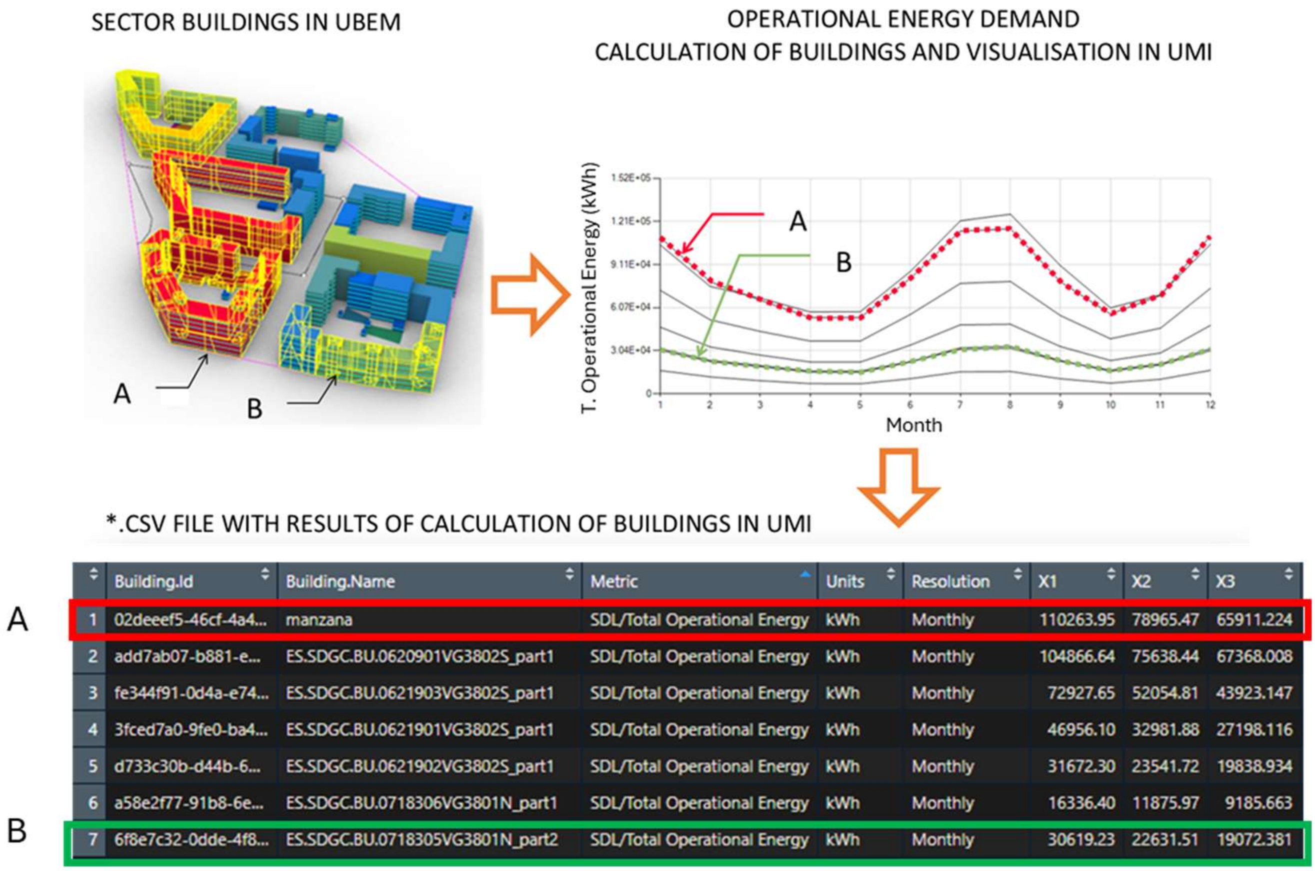


Figure 3. Workflow for the validation of the GIS-UBEM.

3. Results and Discussion

This section presents the results obtained during the adjustment and validation process and the subsequent recalculation of the urban model. The workflow using confidence bands, based on BESTEST adapted to urban building energy modeling, ultimately serves the intended purposes, as an energy model with a known variability range was obtained through the analyzed reference benchmark buildings.

After the initial calculation of the model, the results extracted for analysis included heating and cooling demands (Figure 4). These data were then used to prepare a histogram of the preliminary calculation results for the energy consumption of the sample buildings (Figure 5).



	Building.Id	Building.Name	Metric	Units	Resolution	X1	X2	X3
1	02deeef5-46cf-4a4...	manzana	SDL/Total Operational Energy	kWh	Monthly	110263.95	78965.47	65911.224
2	add7ab07-b881-e...	ES.SDGC.BU.0620901VG3802S_part1	SDL/Total Operational Energy	kWh	Monthly	104866.64	75638.44	67368.008
3	fe344f91-0d4a-e74...	ES.SDGC.BU.0621903VG3802S_part1	SDL/Total Operational Energy	kWh	Monthly	72927.65	52054.81	43923.147
4	3fced7a0-9fe0-ba4...	ES.SDGC.BU.0621901VG3802S_part1	SDL/Total Operational Energy	kWh	Monthly	46956.10	32981.88	27198.116
5	d733c30b-d44b-6...	ES.SDGC.BU.0621902VG3802S_part1	SDL/Total Operational Energy	kWh	Monthly	31672.30	23541.72	19838.934
6	a58e2f77-91b8-6e...	ES.SDGC.BU.0718306VG3801N_part1	SDL/Total Operational Energy	kWh	Monthly	16336.40	11875.97	9185.663
7	6f8e7c32-0dde-4f8...	ES.SDGC.BU.0718305VG3801N_part2	SDL/Total Operational Energy	kWh	Monthly	30619.23	22631.51	19072.381

Figure 4. Sample output of results of buildings A and B from a UBEM model in UMI. Exploration of consumption results by different uses on a monthly basis. The results were imported in CSV format for processing and statistical analysis in R-Studio 2022.02.0. Note: *.CSV is used to represent an undefined (*) output file with '.csv' extension.

Figure 6 displays the locations of the three benchmark buildings chosen for the calibration and validation process. These buildings are a row house in the historic center of Jaén dating back to the 1940s; a multi-family building from 1955 with a linear block typology in the expansion area; and a recently constructed multi-family building in a newly developed area to the north of the city. These three buildings represent the extremes and center in terms of possible consumption and energy demand results. They were used to adjust and validate the model using recognized BEM tools. Appendix B of this article provides a detailed description of the selected benchmark buildings, also providing their respective UBEMs and BEMs.

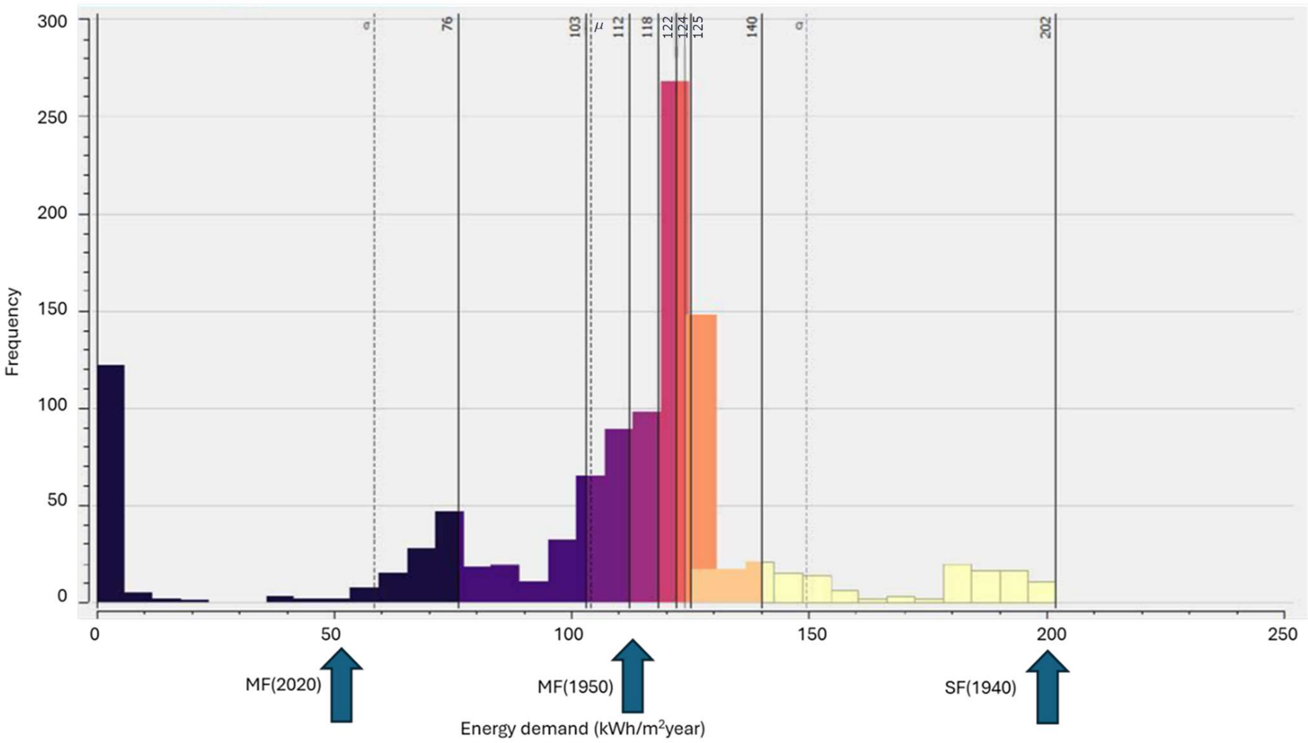


Figure 5. Histogram of preliminary calculation results of consumption for the buildings in the study sample. Colours represent deciles of the building population.

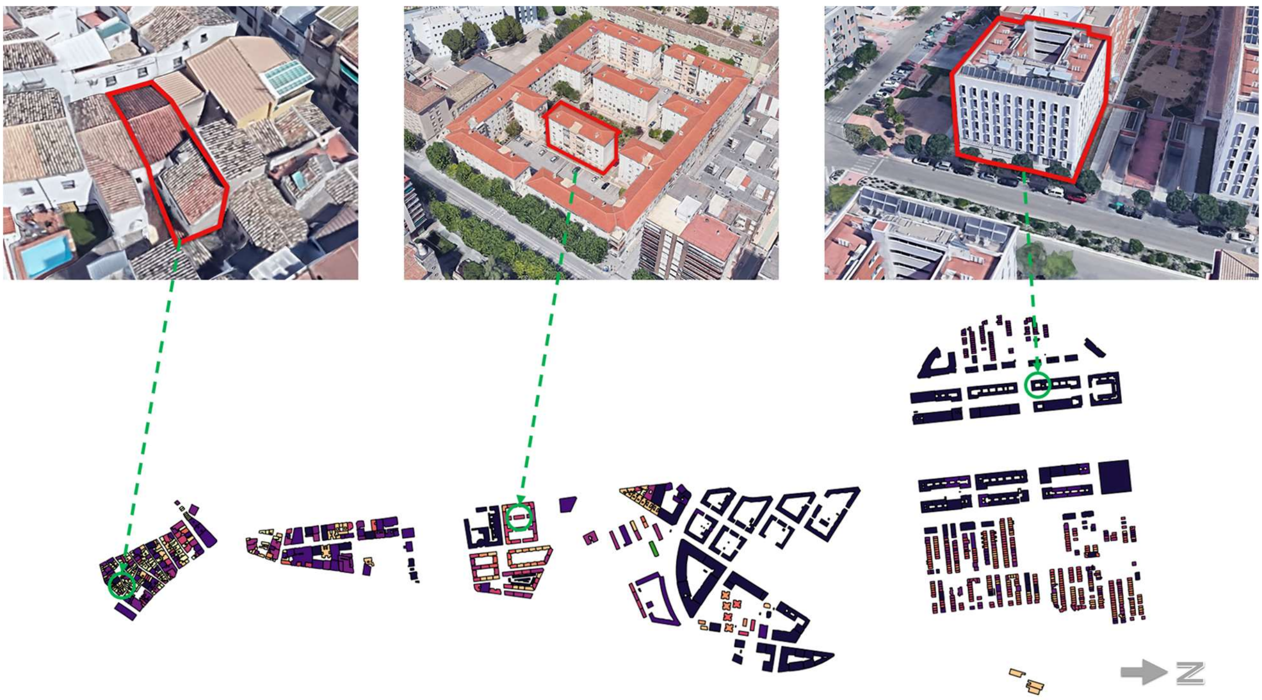


Figure 6. Selected benchmark buildings. Aerial view from Google Earth and location within the case study area in Jaén. Color ramp represents building's heating demand per m^2.

The calibration process involved creating various model variations to approximate the heating and cooling demand results of the buildings in the UMI (UBEM tool) to the reference benchmark values obtained through using HULC and CYPETherm HE Plus (BEM tools) for their counterpart models in each program. The parameters used to adjust the results are primarily linked to the configuration of the ventilation profile, as well as the heating and cooling setpoints, which cannot be programmed hourly in the UMI. The parameters defining ventilation and its configuration in the UMI with the best fit, including the infiltration rate, the programming of nighttime natural ventilation, and the setpoint temperatures at which cross-ventilation operates, based on the outdoor temperature, are summarized in Table 2. Another crucial adjustment parameter was correcting the proportion of facade openings to match the model's geometry, as UMI models adopt the WWR (%) proportion assigned to their template by default.

Table 2. Natural ventilation and setpoints in the validated reference models in the UMI.

Building	Climatic Zone	Nat. Ventilation: Min./Setpoint/ Max Tª, °C	Scheduled Night Ventilation: Setpoint Tª, °C	Scheduled Night Ventilation: ACH	Infiltration Rate: ACH	Heating Setpoint °C	Cooling Setpoint °C
MF 2020	A3	20.5/21.0/27.0	10	4.0	1.0	20	27
	C4	20.5/21.0/27.0	10	4.0	1.0	20	27
	D2	20.5/21.0/27.0	10	4.0	1.0	20	27
MF 1960	A3	20.5/21.0/27.0	10	4.0	1.5	20	27
	C4	20.5/21.0/27.0	10	4.0	1.5	20	27
	D2	20.5/21.0/27.0	10	4.0	1.5	20	27
SF 1940	A3	20.5/22.5/27.0	10	4.0	2.0	20	27
	C4	20.5/22.5/27.0	10	4.0	2.0	20	27
	D2	20.5/22.5/27.0	10	4.0	2.0	20	27

Once the maximum degree of convergence was achieved for all three models and all three climatic zones, these values were ultimately transferred as data from thecai-brated models for the next validation phase.

In Figure 7, it can be observed that dispersion increases as demand increases. In all cases, the differences are accentuated in the heating demands, especially for the MF 1960 model. The results of the SF-1940 model show greater dispersion in climate A3. The results of the MF-2020 model are very similar in terms of cooling but not in terms of heating.

In all cases, there is a very high affinity between the results of HULC and CYPETherm, while, depending on the case, the UMI value tends to be found around the center of the reference results.

As pointed out in the methodology, in order to validate the values in all cases of the TOTAL energy consumption, the results had to be within the tolerance band of ±12.5%, which is the band used to validate alternative procedures for CALENER for the CEE.

Figure 8 shows a graphical representation of the model's output results. After the validation process and the inclusion of the climatic data for Jaén, through a simulation with the reference EPW weather file, the overall results of the GIS-UBEM calculated for the sample sector were as follows:

- Total annual heating demand: 31.7 GWh = 31,744,275 kWh; (20 kWh/m^2).
- Total annual cooling demand: 17.5 GWh = 17,481,886 kWh; (11 kWh/m^2).

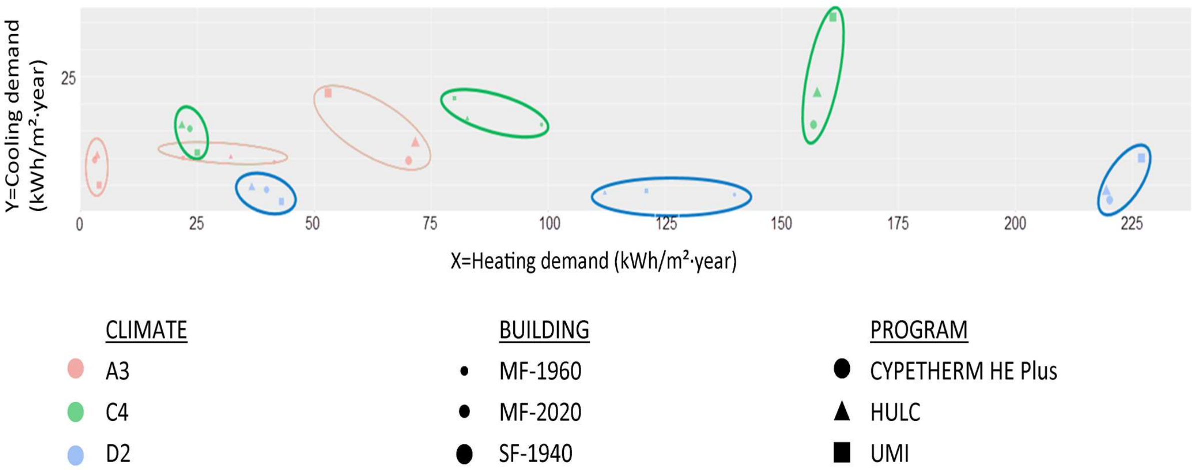


Figure 7. Graphical representation of the heating and cooling demand results from the three models in the three climates and using the three programs.

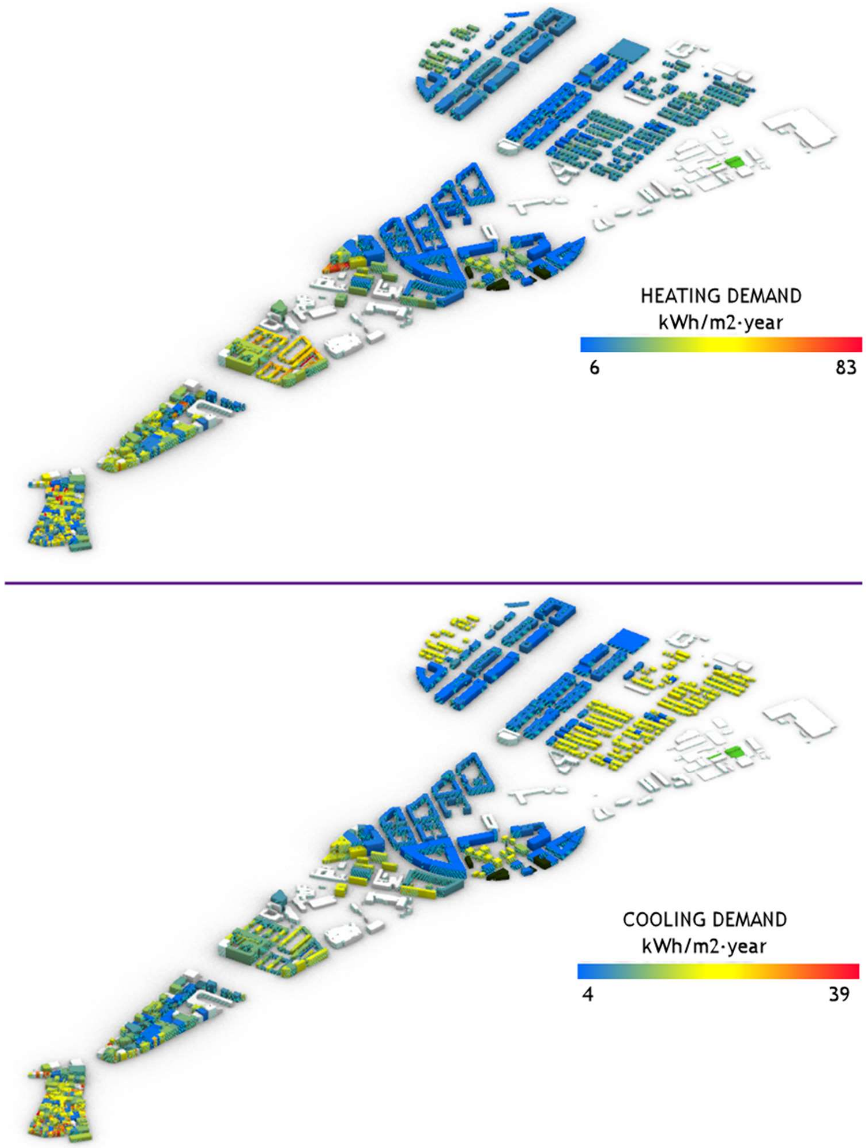


Figure 8. False color representation of heating and cooling demands normalized per square meter in the Jaén sector. Results from the GIS-UBEM obtained with the UMI.

4. Conclusions

Based on the results obtained, we can deduce that the model used in this study to predict the demand generated at district scale based on open data is reproducible for other urban areas in the Mediterranean region. Once adjusted, the application of the types to the entire reference sector allowed for the calculation of 1004 buildings, with the total annual heating demand being 31.7 GWh = 31,744,275 kWh; (20 kWh/m^2) and the total annual cooling demand being 17.5 GWh = 17,481,886 kWh; (11 kWh/m^2). The study has validated the UBEM methodology against traditional reference thermal analysis methods, given that the analyzed types fall within the confidence bands for reference demand and consumption.

A predictive model called GIS-UBEM (referring to the methods used for its generation), which is based on open data, has been proposed. This model allows for the estimation of the demand or potential consumption of an urban sector of a city with a resolution level of individual residential buildings for the sector analyzed, shown herein as a case study in the city of Jaén

The application of these predictive models at urban scele, generated from open data and validated according to the methodology described, allows for, among other actions, the generation of urban maps with the distribution of the prediction of the normalized residential energy demand or consumption demand in the buildings of a city and its correspondence with, for example, the age, typology, and morphology of residential buildings. It also makes it possible to identify the most energy-vulnerable areas, thus opening up interesting lines of research for the future, given the model's potential to provide level of resolution of individual buildings.

The validation of the reference typologies allows for the accurate calculation of larger urban sectors. It also paves the way for the creation of urban-scale predictive models based on training with large datasets of buildings obtained through UBEM for application to entire cities with affordable computing resources.

The possibilities for implementing the proposed model and exploring its results offer opportunities to use this novel analytical tool, which is based on the aforementioned methodology and open data and has multiple applications for both knowledge generation in the fields of research and urban planning and aiding in decision making. Therefore, the results obtained at the urban scale present a high potential for application in the fields of policy making and building stock management and decision making by public and private bodies, as well as in the field of research and the development of applications at different scales for energy performance improvement strategies aimed at building stock and achieving decarbonization in cities by 2050.

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Data Availability Statement: In the documentation repository, the following files related to the computer models used in this work can be downloaded: UMI sector GIS-UBEM file; template for 12 building typologies model GIS-UBEM; Jaén climatic data file (EPW format) (source: PV-GIS/TMY; ground temperature obtained from C4.EPW climate of CYPETherm HE Plus 2019); calibration model versions for CYPETherm HE Plus 2019 and HULC. Direct download link: https://personal.us.es/javigalo/TESIS/ANEJOS/ANEJO-E_MODELOS_INFORMATICOS.rar (accessed on 20 February 2024).

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Appendix A

Table A1. Summary of the constructive characterization of the residential typologies considered for the GIS-UBEM.

Template	Façade	Ground Floor	Partition Floor	Structure	Party Wall
SF-1940	36 cm SB	Slab	Timber joist floor slab	Load-bearing walls	12 cm SB
SF-1960	24 cm SB	Slab	One-way RC slab	Load-bearing walls	12 cm PB
SF-1980	Cavity wall	Slab	One-way RC slab	RC beams and columns	12 cm PB
SF-1995	Cavity wall + 3 cm TI	Slab	One-way RC slab	RC beams and columns	12 cm PB
SF-2010	Cavity wall + 5 cm TI	Cavity floor	One-way RC slab +	RC beams and columns	12 cm PB +TI
SF-2020	Cavity wall + 7 cm TI	Cavity floor + TI	One-way concrete slab	RC beams and columns	12 cm PB +TI
MF-1940	36 cm SB wall	Slab	Timber joist floor slab	Load-bearing walls	12 cm SB
MF-1960	24 cm SB wall	Slab	Unidirectional HA slab	RC beams and columns	12 cm PB
MF-1980	Cavity wall	Slab	Unidirectional HA slab	RC beams and columns	12 cm PB
MF-1995	Cavity wall + 3 cm TI	Sanitary slab	Unidirectional HA slab	RC beams and columns	12 cm PB
MF-2010	Cavity wall + 5 cm TI	Sanitary slab	RC waffle slab	RC columns and slabs	12 cm PB +TI
MF-2020	Cavity wall + 7 cm TI	Cavity floor + TI	RC waffle slab +TI	RC columns and slabs	12 cm PB +TI
Template	**Roof**		**Window**	**Partitions**	**WWR %**
SF-1940	Pitched wooden roof		Wood+Single g.	10 cm HB	15
SF-1960	Flat RC one-way slab		Steel +Single g.	10 cm HB	15
SF-1980	Flat RC one-way slab		Steel +Single g.	10 cm HB	20
SF-1995	Flat RC one-way slab + 3 cm TI		Alu. +Single g.	10 cm HB	20
SF-2010	Flat RC one-way slab + 5 cm TI		Alu. +Double g.	10 cm HB	20
SF-2020	Flat RC one-way slab + 8 cm TI		Alu. TB+ Double low-e g.	10 cm HB	20
MF-1940	Pitched wooden roof		Wood+Single g.	10 cm HB	15
MF-1960	Flat RC one-way slab		Wood+Single g.	10 cm HB	15
MF-1980	Flat RC one-way slab		Steel +Single g.	10 cm HB	20
MF-1995	HA unidirectional roof AT 3		Single metal V	10 cm HB	20
MF-2010	Flat RC one-way slab + 5 cm TI		Alu. +Single g.	10 cm HB	20
MF-2020	Flat RC one-way slab + 8 cm TI		Alu. TB+ Double low-e g.	10 cm GYDW	20

GYDW: Gypsum Drywall; HB: Hollow Brickwork; MF: Multi-Family Building; PB: Perforated Brickwork; RC: Reinforced Concrete; SB: Solid Brickwork; SF: Single-Family Building; TB: Thermal Break; TI: Thermal Insulation.

Table A2. Summary of hot water, air conditioning, and ventilation installations for the residential typologies considered in the GIS-UBEM.

Template	Hot Water (DHW)	Ventilation	Heating	Cooling
SF-1940	Electric heater	Natural	Electric radiator	None
SF-1960	Gas boiler	Natural	Electric radiator	Split A/C EER 1.8
SF-1980	Gas boiler	Natural	Individual gas boiler	Split A/C EER 1.8
SF-1995	Gas boiler	Natural	Individual gas boiler	Split A/C EER 1.8
SF-2010	Gas boiler	Natural	Individual gas boiler	Split A/C EER 2.5
SF-2020	Gas boiler + solar Thermal	Mechanical	Split A/C COP 2.7	Split A/C EER 2.5
MF-1940	Gas boiler	Natural	Electric radiator	Split A/C EER 1.8
MF-1960	Gas boiler	Natural	Collective gas boiler	Split A/C EER 1.8
MF-1980	Gas boiler	Natural	Collective gas boiler	Split A/C EER 1.8
MF-1995	Gas boiler	Natural	Collective gas boiler	Split A/C EER 1.8
MF-2010	Gas boiler	Natural	Individual gas boiler	Split A/C EER 2.5
MF-2020	Gas boiler + solar Thermal	Mechanical	Split A/C COP 2.7	Split A/C EER 2.5

Appendix B

Detailed descriptions of the selected benchmark buildings for the validation process, as well as their respective UBEMs and BEMs.

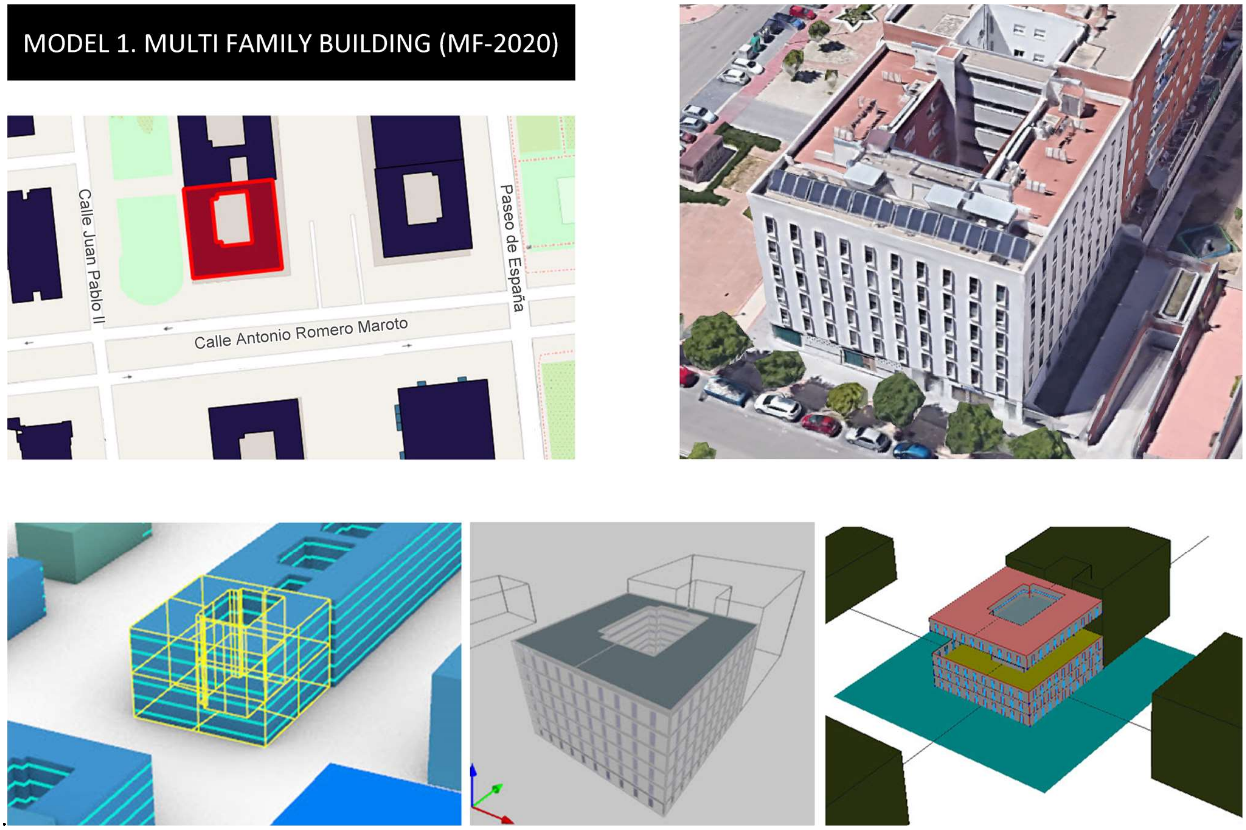

Figure A1. MULTI-FAMILY BUILDING IN BLOCK (MF-2020) UMI, CYPETHERM HE PLUS and HULC models.

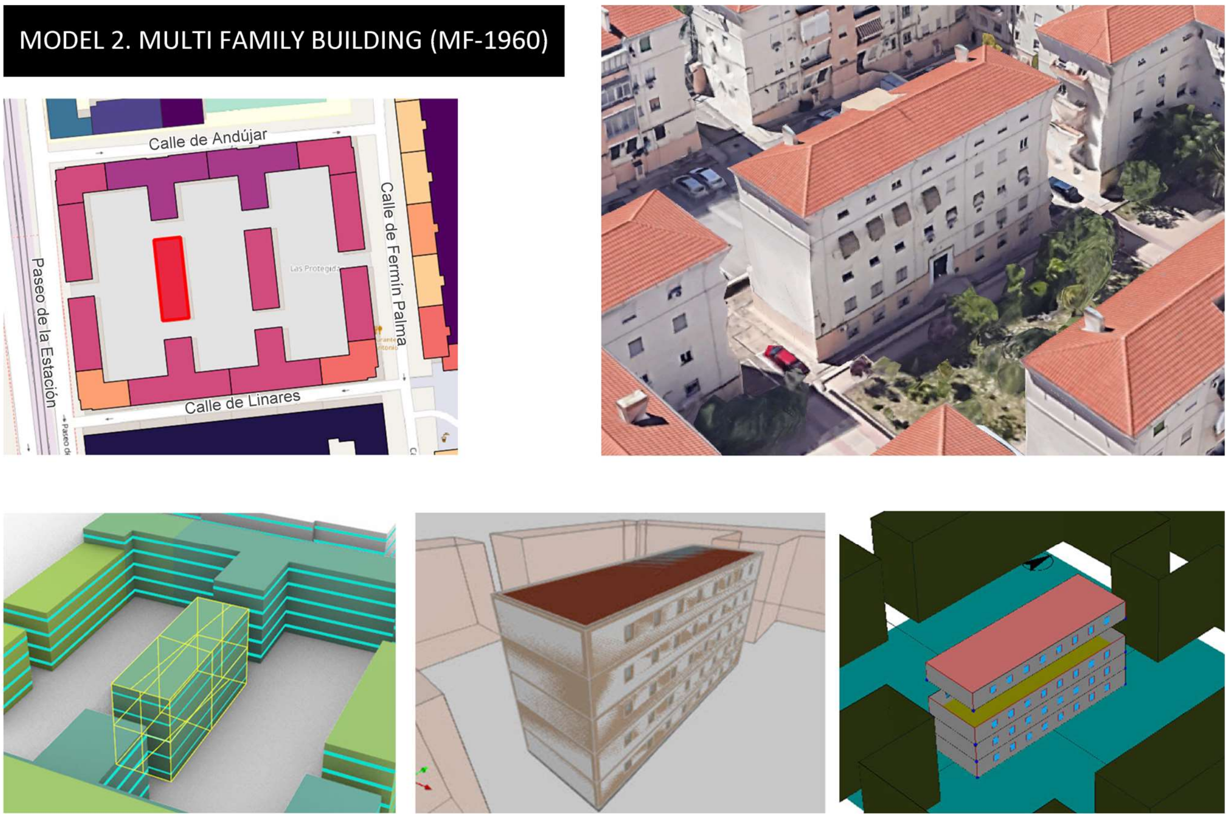

Figure A2. FREESTANDING MULTI-FAMILY BUILDING (MF-1960).

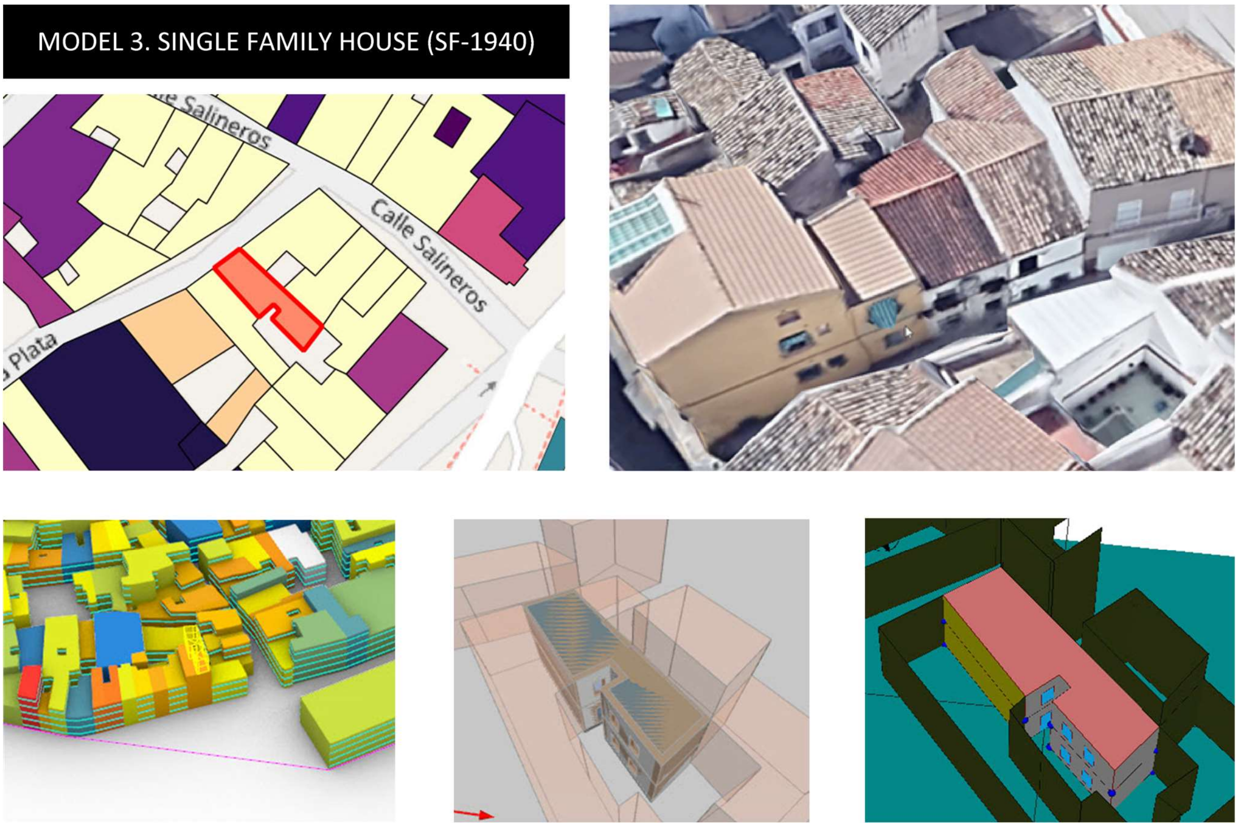

Figure A3. SEMIDETACHED SINGLE-FAMILY HOUSE (SF-1940).

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