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Publication Date
2021-04-01

DOI
10.1016/j.buildenv.2021.107590

Peer reviewed

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Lawrence Berkeley National Laboratory

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Energy Technologies Area
April 2021

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Abstract: Urban building energy modeling (UBEM) seeks to evaluate strategies to optimize building energy use at urban scale to support a city's building energy goals. Prototype building models are usually developed to represent typical urban building characteristics of a specific use type, construction year, and climate zone, as detailed characteristics of individual buildings at urban scale are difficult to obtain. This study investigated the Italian building stock, developing 46 building prototypes, based on construction year, for residential and office buildings. The study included 16 single-family buildings, 16 multi-family buildings, and 14 office buildings. Building envelope properties and heating, ventilation, and air conditioning system characteristics were defined according to existing building energy codes and standards for climatic zone E, which covers about half the Italian municipalities. Novel contributions of this study include (1) detailed specifications of prototype building energy models for Italian residential and office buildings that can be adopted by UBEM tools, and (2) a dataset in GeoJSON format of Italian urban buildings compiled from diverse data sources and national standards. The developed prototype building specifications, the building dataset, and the workflow can be applied to create other building prototypes and to support Italian national building energy efficiency and environmental goals.

Keywords: Urban Building Energy Model (UBEM); Building Prototypes; Building Typology; Residential Sector; Building Stock Modelling; Italy

1. Introduction

The human population in cities is constantly growing, together with urban energy usage and greenhouse gas emissions [1]. This poses great challenges for decision-makers (e.g., policymakers, distribution and transmission system operators, district heating and cooling managers, urban designers, and researchers) who aim to decrease energy consumption while improving living conditions in cities [2]. However, the lack of information about the energy use and energy savings potential of building stocks in cities is widespread [3]. One option for obtaining this information is to collect high granularity measured data through monitoring campaigns, but these methods are expensive and highly time-consuming, thus (yet) unsuitable [4]. In this context, the need to model all or part of a city's building stock and to simulate various energy scenarios has grown. Thus, different urban building energy modeling (UBEM) tools have been developed. UBEM differs from building energy modeling (BEM) of individual buildings, achieved through traditional building performance simulation (BPS) software, mainly in the size of the stock modeled and usually on the descriptive data availability. BEM is primarily focused on single buildings or small blocks, usually with detailed information of individual buildings (i.e., detailed description of layers of the envelope constructions [5]; geometry, heating, ventilation and air conditioning (HVAC) systems; occupants' behavior [6]), including highly detailed analyses [7]. Conversely, UBEM models at least a large block (i.e., dozens of buildings) and up to all buildings in a city (ranging from tens of thousands to millions of buildings). When dealing with such a large number of buildings, dataset development and computational efforts can be challenging, and thus, a few approaches emerged to better describe the buildings to ensure affordable labor and computational efforts [8].

UBEM is typically grouped into top-down and bottom-up models [9]. Top-down models link the energy use of the building stock to socioeconometric, technical, or physical drivers. Conversely, bottom-up models compute single building energy consumptions and eventually combine the results at different scales. Specifically, the energy calculation method can be statistical or physics-based. These physics-based models are derived by BEM and exploit single time-step calculations, considering the energy balance of buildings [10]. These models simulate in detail the building and locate it in the urban environment, trying to include physics interactions among buildings, between buildings and microclimate or other entities (e.g., water bodies, trees, streets), and within time [11]. The bottom-up physics-based models are the ones that are gaining momentum in the last years. This is mainly due to the increase of the computational capacity of computers and to the need to design urban energy systems and to plan sustainable urban development. In fact, among the main strengths of these models is the ability to predict future scenarios and achieve a high spatial and temporal detail of the results [12]. For example, lumped-capacitance models can perform district simulations several times to evaluate the impact of energy efficiency measures, requiring low computational resources [13]. However, the amount of data required to model the buildings is not lower than it is when conducting BEM. Therefore, to manage time and computation efforts while reaching the desired output, both in terms of spatial and temporal resolution, building modeling becomes a challenge that must be addressed before running any simulation, as described in the following sections.

1.1. The building stock modeling challenge

The modeling of building stocks is composed of two main steps: geometry settings and characterization of this geometry with the necessary thermophysical properties [14]. Thus, to achieve the proper level of description of large districts or cities, detailed building prototypes are necessary to represent correctly the urban environment according to the typical technologies and constructions of a nation. Usually, details of large building stocks are collected through census data and/or surveys [15], because large datasets are not always available. Both types of data are usually anonymous and not linked to a specific geometry. Single-building billing or metering data and energy certificates may also be available, but sometimes just for a relatively small part of the input needed when using UBEM tools [15]. For building modeling at a large scale, a combination of different data collected from different sources must be exploited [16]. This raises issues related to the integration of data with different terminology, and/or time and spatial resolution.

In BEM, the geometry is usually well known, and its description can also reach the detail level of single rooms and furniture. Conversely, in UBEM, this level of detail is not achievable for large building stocks; therefore, buildings are usually simplified to simple boxes as extrusion of their footprint along their heights. This is due to the lack of detailed data for all buildings in the stock, but also to the necessity of decreasing the computational effort during the simulation process, maintaining a realistic geometrical description [17]. To simplify this step, UBEM tools usually allow integration with geographic information system (GIS) technologies and formats. Particularly, the CityGML format is under development to become a standardized method to describe and collect urban data [18]. It is a GIS format that allows the representation of the geometry at a different level of detail and includes some elements of the surroundings (e.g., terrain, vegetation, water bodies, transportations). However, these data formats are not always available, and this lack strongly hinders the usage of UBEM tools.

The second step involves associating the necessary characteristics with the geometry. The specific information related to the building fabric, systems, and usage schedules must be set for all the buildings included in the model. Usually, to simplify this step, modelers use archetypes - ideal buildings that include the whole set of characteristics needed to run an energy simulation. These characteristics are usually average values, proven to be representative of the specific building stock or a part of it. The association of the archetype to a specific building is usually done by exploiting variables such as main building function, distributive parameters defining a building typology (e.g., tower, detached), construction year, and others. A specific extension of the CityGML format, called Energy ADE [19], attaches to the building geometry a basic characterization, which greatly helps the modelers. Especially, for bottom-up physics-based UBEM tools, some characteristics of the archetype (e.g., window to wall ratio, floor-ceiling height) are left to be parametric values that are useful to customize the final geometrical characterization of every single building in the model.

To better address the topic, a literature review of papers regarding archetypes was conducted in June 2020. Particularly, Boolean operators (i.e., AND, OR, and NOT) and exclusion criteria were utilized to adjust the research query executed in Scopus. A total number of 262 publications resulted from the search, and a second screening on titles and abstracts helped to exclude other irrelevant publications, bringing the final set to 150 publications. Within this group, 34 publications with an available full text were selected. Only publications with the specific aim of presenting new archetypes or methodologies for their generation were included. The result of the review is presented in Table 1. For each publication, the main characteristics are highlighted (i.e., location and size of the case study, included building type that regards typology and/or function, generation method followed, final number of archetypes, type of archetype, and declared novelty).

Table 1: Main references available in the literature regarding archetypes and/or their generation methodology

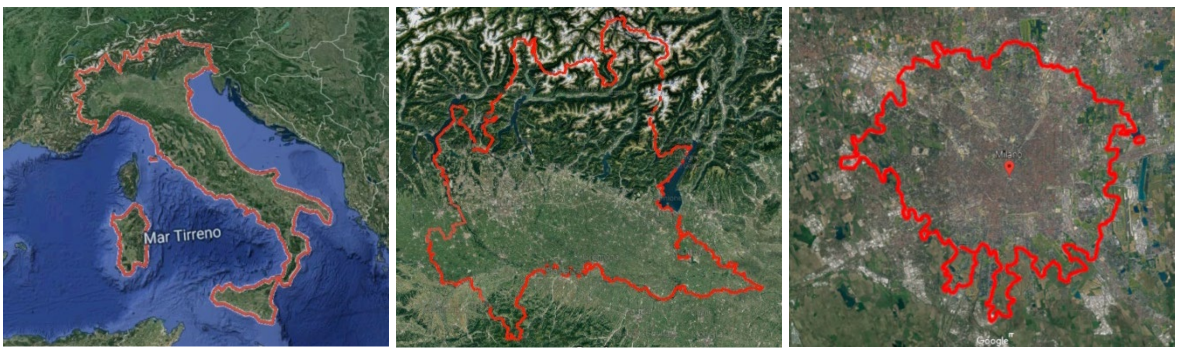
Authors	**Location of the case study**	**Size of the case study[1]**	**Building type[2]**	**Method[3]**	**Number of archetypes**	**Type of archetype**	**Novelty**	**Verification method**
Ahern and Norton, 2020 [20]	Ireland	406,918 (S)	RHS	Sg + An + Ca + Ag	35	Full	Use of large empirical databases	Goodness Of Fit on real annual data
De Jaeger et al., 2020 [21]	Genk, Belgium	847 (N)	SFD	Ag	Inferred	Full	Focus on occupant behavior	Percentage error on Annual Energy Use Intensity from statistical databases
De Jaeger et al., 2020 [22]	Belgium	1,230 (S)	SFD	Cu	Inferred	Full	Methodology	NRSME on specific KPI (e.g., peak demand), and on Annual Energy Use Intensity
Molina et al., 2020 [23]	Chile	6.5 million (S)	RHS	Cu	About 500	Full	Location	chi-square ($\chi2$) test of statistical significance
Beck et al., 2020 [24]	Nottingham, United Kingdom	D	SFD	Ca	5	Geometry	Focus on Geometry	Application on a similar case study
Ali et al., 2019 [25]	Ireland	S, R, U, D	RHS	Sg	Various	Full	Multi-scale methodology	Comparison against annual site energy from validated simulation results
Buttitta et al., 2019 [26]	United Kingdom	S	RHS	Sg	Inferred	Full	Focus on occupant behavior	Percentage difference and deviation against Annual metered Energy Use Intensity
Pasichnyi et al., 2019 [27]	Stockholm, Sweden	U	WBS	V	Various	Full	Multi-goal methodology	Comparison against annual energy declarations from the city of Stockholm
Yi and Peng, 2019 [28]	Seoul, South Korea	51,351 (D)	RHS	St	Inferred	Full	Focus on cooling loads	Comparison with records of 2014-17 period on the Cooling Degree Days

Streicher et al., 2019 [29]	Switzerland	25,000 (S)	RHS	St	54	Full	Whole nation	Comparison with other studies on Swiss registered and simulated Energy Use Intensity
Wang et al., 2018 [30]	Denmark	S	AB	Cu	Inferred	Full	Data-driven methodology	Calibration of models based on TABULA
Lavagna et al., 2018 [31]	Europe	S	RHS	St	24	Full	Whole EU	Results checked against average previous LCA assessments
Kristensen et al., 2018 [32]	Denmark	150 (S)	RHS	St (Bayesian inference)	Inferred	Full	Methodology coupled with calibration	The methodology includes a Bayesian calibration process + use in a case study
Nägeli et al., 2018 [33]	Switzerland	S	RHS	Ag	Inferred	Full	Methodology	Calibrated and validated on aggregate Annual Energy Use Intensity
Li et al., 2018 [34]	Yuzhong District in Chongqing, China	D	RHS	Cu + DI	Inferred	Heating/ Cooling energy	Methodology	The method is tested through a case study comparing the archetypes' Energy Use Intensity against detailed dynamic simulations.
Urquizo et al., 2018 [35]	Newcastle upon Tyne, United Kingdom	D, N, B	RHS	Cu	Various	Various	Multi-scale methodology	Cross-validation within the methodology and final comparison with Annual metered Energy Use Intensity
Cerezo et al., 2017 [36]	Kuwait City, Kuwait	336 (U)	RHS	V	Various	Full	Comparison of different methodologies	The methodology includes a Bayesian calibration + comparison with metered Annual Energy Use Intensity
Tornay et al., 2017 [37]	France	S	WBS	DI	About 12	Full	Urban canopy model	Information compared with other statistical databases
Pittam et al., 2017 [38]	Cork, Ireland	10,318 (U)	PHS	DI	18	Full	Case study	n.d.
Monteiro et al., 2017 [39]	Lisbon, Portugal	N	RHS	Various	Various	Full	Variation of the number of archetypes	Information compared with national statistical databases
Sokol et al., 2017 [40]	Cambridge, Massachusetts	2,263 (U)	RHS	St	Inferred	Full	Inclusion unknown parameters as probability distributions	Calibrated and validated with annual and monthly metered data of Energy Use Intensity
Loga et al., 2016 [41]	20 European Countries	S	RHS	DI + EA	Various	Full	Geographical extension	Annual Energy Use Intensity compared with national/local statistical databases
Berg et al., 2016 [42]	City centers of Palermo, Italy and Visby, Sweden	D	WBS	St	n.d.	Full	Case study	n.d.
Cerezo et al., 2015 [43]	Kuwait City, Kuwait	U	RHS	V	Various	Full	Comparison of different methodologies	Calibrated and validated with annual metered data of Energy Use Intensity
Ballarini et al., 2014 [44]	Middle Climatic Zone of Italy	S	RHS	DI + EA	32	Full	Location and extension	Annual Energy Use Intensity compared with local statistical databases
Pittam et al., 2014 [45]	Cork, Ireland	10,449 (U)	PHS	DI	20	Full	Case study	Annual Energy Use Intensity compared

								with local statistical databases
Mata et al., 2014 [15]	France, Germany, Spain and the United Kingdom	S	G: RHS; others: RHS + NR	Sg	F: 99; G: 122; S: 120; UK: 252	Full	Extension and NR	Annual Energy Use Intensity compared with local statistical databases
Kragh and Wittchen, 2014 [46]	Denmark	1,526,284 (S)	RHS	Cu	About 27	Full	Extension and methodology	Simulated energy results compared with local national databases
Vimmr et al., 2013 [47]	Chez Republic	S	RHS	Cu	n.d.	Full	Extension and methodology	Annual Energy Use Intensity compared with local national databases
Famuyibo et al., 2012 [48]	Ireland	S	RHS	St + Cu	13	Full	Methodology	n.d.
Ballarini et al., 2011 [49]	Piedmont, Italy	R	RHS	Cu	n.d.	Full	Extension and methodology	Annual Energy Use Intensity compared with local national databases
Dascalak et al., 2011 [50]	Greece	S	RHS (but extendable)	Cu	24	Full	Extension and methodology	Application on a case study
Fabrizio et al., 2011 [51]	Italy	S	OF	BM	1	Full	Focus on office and methodology	Comparison based on various research over Italian Office building stock
Tooke et al., 2011 [52]	Neighborhood in Vancouver, Canada	264 (N)	SFD	Cu	3	Geometry	Based on Lidar	n.d.

[1] S = State/National, R = Regional/County/Zone, U = Urban, D = District, N = Neighborhood, C = Community/Block
[2] RHS = Residential Housing Stock, PHS = Public Housing Stock, SFD = Single-family dwellings, AB = Apartments buildings, NR = Non-residential, OF = Offices, WBS = Whole building stock
[3] Sg = Segmentation, Ca = Classification, Ag = Aggregation, Cu = Clustering, V = Various, St = Statistics, DI = Data Integration, EA = Expert Assumptions, BM = Benchmarking

Size refers to the dimension of the area or the number of buildings that are analyzed. However, the definition of the terms used in literature is not always explicitly defined. Thus, a differentiation to refer to the size of a case study is proposed in this study. The basic case is an entire state or nation (Figure 1A) (e.g., Italy). Then, each state can be divided into regions or zones (Figure 1B), (e.g., Lombardy). The case study can focus on a specific urban area or city (Figure 1C) (e.g., Milan) or a specific district (Figure 1D) (e.g., the central district in Milan, called Municipio 1), or a neighborhood (Figure 1E) (e.g., the Brera neighborhood in Milan). At last, when buildings are aggregated together and divided from other buildings by streets, they can be defined as a block (Figure 1F). The six different sizes emerged also in the literature review. In the publications, 50% dealt with archetypes developed for an entire state or nation, 18% with an urban area or a city, 16% with a district, 8% with a neighborhood, 5% with regional/zones, and 3% with block case studies.



A *B* *C*

Figure 1: Case study size: (A) state, (B) region, (C) city, (D) district, (E) neighborhood, (F) block.

Regarding building use typology, only 9% of the studies modeled the entire building stock. The majority of the case studies (65%) focused on the residential building stock in general, 12% on single-family dwellings, 6% on apartment buildings, and 6% of the publications dealt with public housing stock. Therefore, 94% of the publications focused on residential buildings. Only 3% of the studies addressed office buildings, and 3% addressed non-residential buildings in general.

As summarized in Figure 2, clustering was the primary method used to generate archetypes (30% of the publications), but also more general terms, such as segmentation (8%), classification (5%), and benchmarking (3%) were used. Of the studies, 8% used aggregation methods, and 16% were based on various types of statistics. Finally, 16% of the studies used data integration as one of the fundamental steps of the archetype generation, whereas 5% were based on some assumptions on experts' knowledge. 8% of the publications used a mix of more than one method. Depending on the used methodology, the number of archetypes can be declared to be fixed and derived by the analysis of the presented data, or it can be inferred by the methodology itself when applied to different case studies. The term "various," reported in Table 1, means that different case studies were analyzed in the same paper, bringing to different numbers of final archetypes.

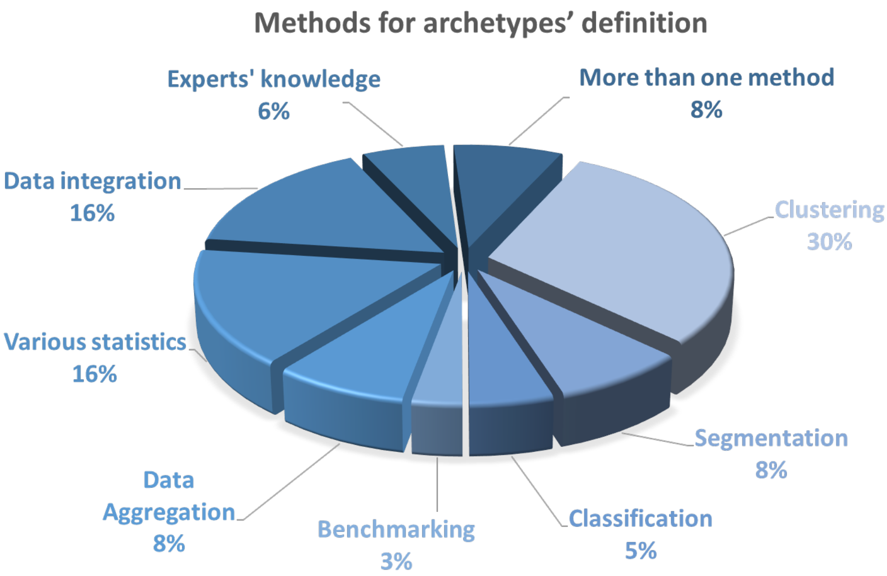


Figure 2 Summary of the methods to defined archetypes from the literature review

The majority of the studies focus on Europe, due to the Typology Approach for Building Stock Energy Assessment (TABULA) project and its follow-up Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks (EPISCOPE) [41,44,46,47,49,50]. These projects sought to establish a common classification approach for residential buildings at the national level for 21 European countries. They also make nations aware of the importance of archetypes models. As a matter of fact, archetypes are fundamental, not only so that UBEM can provide an overview of the building stock, but also for their explanatory potential, to provide a taxonomy of the stock. Moreover, they can be used directly to estimate different quantities (e.g., energy use, materials), to simplify the complexity of the building stock through different levels of detail, and to help frame and benchmark potentials [27]. Generally, and especially due to the TABULA/EPISCOPE projects, numerous archetypes are available for the Italian context (e.g., [31,41,47,51]). The developed archetypes are completed with simple models that are run to quantify the basic energy use of the represented buildings. However, this approach is not suitable for the use of bottom-up physics-based tools such as the City Building Energy Saver (CityBES). These tools require a certain amount of flexibility for application of the thermophysical characteristics to the specific geometry of each building in the model, based on its footprint and height. For this reason, archetypes flexible enough to be suitable for this new UBEM approach are needed, and these are usually called prototypes. Even though the terms *archetype* and *prototype* are often used interchangeably, here a differentiation is proposed. In this paper, an archetype is intended as an ideal example with an unchanging form that can never be modified, while a prototype is the first version of something that later updates can modify or improve [49] (i.e., a building energy model in this case) and is characterized by a parametric geometry (e.g., based on fixed parameters like window-to-wall ratio or percentage of the heated area).

Lastly, the methods used to verify the resulting archetypes are highlighted. In most cases, the energy results of the archetypes are directly compared with average annual energy data stored at local or national levels or metered for a specific case study. In some other cases, in the methodology itself, especially when it is based on clustering, a calibration step is included. For a few cases, a validation step is not mentioned because the archetypes are directly based on statistical analysis on the local or national databases. However, it must keep in mind, that for this new approach to UBEM, the validation and calibration processes are still considered a challenge [11], due to lack of available data, especially at high granularity, the limitations due to computation effort to run numerous simulations.

1.2. Aims and outline

This study arose from the intention to use one of the most advanced bottom-up physics-based UBEM tools for case studies on retrofitting the building stock in Northern Italy, to reduce energy use and carbon emissions in buildings to support local government and Italian national energy and environmental goals. Upon reviewing the available dataset and archetypes developed for the Italian context, it became clear that even if advanced and detailed projects like TABULA and EPISCOPE existed, prototypes suitable for this kind of large-scale analysis were missing. The United States Department of Energy (DOE) developed some guidelines for building models of the national building stock [53], explaining the workflow process and the reference input that was followed to characterize the American building stock. The same general idea was followed in this research, investigating two main urban building topologies (i.e., residential and office buildings) based on which prototypical energy models were developed with envelope and energy systems characterization.

This paper aims to characterize prototype buildings for Italian Climatic Zone E, which is suited for bottom-up physics-based UBEM tools that require geometry inputs given as a semantic geo-referenced dataset (e.g., CityGML or CityJSON). In particular, residential buildings (i.e., single-family dwellings, apartment buildings, public housing stock) and office buildings are included. This approach allows the application of an automated workflow for the simulation of larger city areas, while the existing archetypes representative of the Italian building stock are based on a fixed and defined geometry, thus hardly usable to investigate districts of real buildings with UBEM tools. The results from this study are: (i) a methodology that can be followed to expand and improve the prototype set for other climatic zones in Italy and European countries, (ii) the option to customize the presented characteristics of prototypes for other UBEM tools, in particular considering that the geometry is not fixed but depends on the input geometry, and (iii) an overview of the current urban data availability in the Italian context and the limitations and future perspectives to boost the usage and usability of UBEM tools.

This study is intended as the first phase effort of a larger project that aims to sensitize municipalities and researchers in a collection of new data and integration of existing datasets. Potentially, accurate prototype building models able to describe the whole Italian building stock, including all the building functions and climatic zones, could be developed through the coordinated actions of a larger number of stakeholders. Since the comparison with measured data is not easy to carry out when entire districts are considered due to both the lack of data and complexity of the comparison on aggregated values, the prototypes will be shared to use them on a large-scale in order to extend the network on this.

The remaining parts of the paper are organized as shown in Figure 3: Section 2 presents the current Italian data and archetype availability, along with their limitations and differences from prototypes; Sections 3 explains the process of collection, selection, and organization of data that led to the definition of prototypes described in Section 4; Section 5 describes the main applications of these resulting prototypes, and Section 6 concludes the paper with some final considerations and future outlooks.

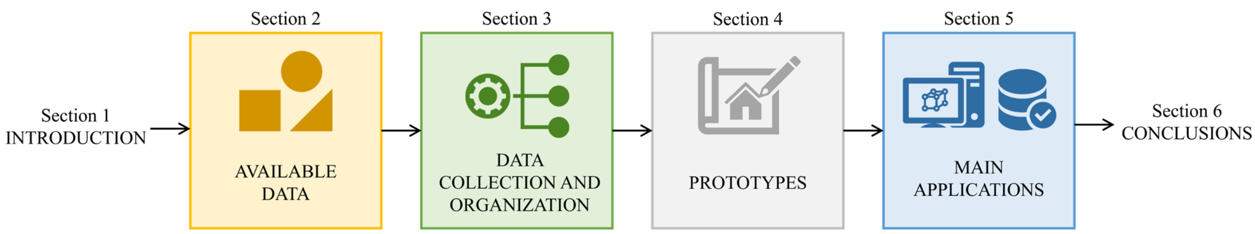


Figure 3: Schematic of the paper workflow

2. Review of existing Italian building data and archetypes

Buildings datasets exploitable for bottom-up physics-based UBEM need to include two groups of integrated information: geometrical data and thermophysical properties. Some particular features (e.g., window-to-wall ratio, thermal zoning, ceiling height, sill height) guarantee a certain level of flexibility to allow a proper adaptation of the characteristics to the geometry, enabling energy models with a relatively high level of detail for every building.

The first group of information (i.e., geometrical) is usually easy to gather thanks to the use of GIS software and map provider services. This is the main difference from using existing archetypes that usually have a fixed geometry; results may be influenced when comparing buildings in urban city centers with buildings that have layouts different than a rectangular geometry. The ability to use real geometry as an input allows archetypical models to be applied to real districts and cities, therefore developing a parametric model closer to reality. For the second set of information (envelope properties, internal loads, HVAC systems and related inputs), the data collection process is more challenging and time-consuming, especially when dealing with large datasets. The difficulties are related to the data collection, which is not done in an integrated and cohesive way. The absence of datasets that allow the characterization of large stocks of buildings (including both geometrical and thermophysical properties) and the lack of databases where data are integrated and harmonized have prohibited all but a few Italian city neighborhoods from being studied utilizing bottom-up physics-based UBEM tools. These tools, widely used in other countries interested in reducing energy use and carbon dioxide (CO_2) emissions of buildings, have the goal of obtaining an integrated and optimized design of retrofit interventions. Unfortunately, in the present state, only a few examples address the Italian context [16,44,54].

Currently, some Italian standards (summarized in Table 2) and the TABULA project [55] are the only databases available to characterize envelopes and systems of building stocks. However, the standards, although they collect a large amount of information, merely describe the geometrical and characteristics of the Italian building stock in a separate, non-integrated way. TABULA and EPISCOPE projects tried to fill that gap, but the developed energy models are not suitable for bottom-up physics-based UBEM tools like CityBES because they need single customized energy models for each building.

Table 2: Collection of the Italian standards describing the building stock

Title	**Year**	**Type**	**Main goal**	**Useful collected data**
Law 373	1976	National	First standard on building energy efficiency	Criteria for building insulation and heating systems
Law 10	1991	National	Energy efficiency in buildings and renewable energy sources	Envelope insulation and efficiency of the generation system
DPR 412/93	1993	National	Define climatic condition	Degree days of the climatic zone considered and heating setpoint
UNI 10339	1995	National	Air conditioning systems for thermal comfort in buildings	Ventilation rate for office buildings
EN 12464	2004	European	Lighting on working spaces	Lighting reference values for office buildings
Legislative Decree 192	*2005*	National	*Italian Transposition of the Directive 2002/91/EC*	Thermal transmittance of buildings and HVAC systems efficiency
EN 15251	2007	European	Input parameters for design and assessment of energy performance of buildings	Ventilation rate for office buildings
UNI/TS 11300	2008	National	General guidelines for building energy performance	Masonry building walls and systems spread based on regions and construction years
Law 90	2013	National	Transposition of Directive 2010/31/ EU of 19 May 2010, on energy performance in buildings	Criteria and methodologies to improve buildings' energy performance and to integrate renewable energy sources
UNI/TR 11552	2014	National	Extension of Appendix A of UNI/TS 11300	Main building constructions (walls, roofs, floors) spread based on regions and construction years
ISO 18523 - 1	2016	International	Energy performance of buildings — Schedule and condition of building, zone, and space usage for energy calculation	Reference schedules for internal loads
EN 15193	*2017*	European	Energy performance of buildings — Energy requirements for lighting	Reference lighting loads
EN 16798	2019	European	Energy performance of buildings — Input parameters for design and assessment of energy performance of buildings	Definition of internal loads

The following section presents the main Italian standards and the TABULA project in more detail.

2.1. Italian Standards

The main information required for a precise definition of Italian prototype buildings that will be presented in detail in the following sections are summarized in Table 3.

Table 3: Summary of the main sources of information for the development of Italian prototypes

	Retrieved Information	Geographical Level	Integration and Consistency	Coverage	Level of detail
UNI/TS 11300	Masonry building walls and systems spread based on regions and construction years.	National; Regional	Data scattered throughout the standard and not uniformly presented. Lack in consistently presenting the geographical and historical distribution of the structures in the country.	Geographical coverage focuses mostly on northern Italy. Time coverage only partially represents reality.	Lack of description for new surfacing technologies.
UNI/TR 11552	Main building constructions (walls, roofs, floors) spread based on regions and construction years.	National; Regional	Lack of detailed data for some geographical areas. Incomplete data on the historical succession of the construction methods.	Geographical coverage focuses mostly on northern Italy. Time coverage only partially represents reality.	Discrepancies in the degree of detail for envelope elements.
TABULA	database of the main types of residential buildings for pre-defined geometries contains the construction and installation characteristics of residential buildings.	National	Focused specifically on residential buildings, even though representative of an entire region, simulated with climatic data of a single city.	Focus on the building stock of a single region of northern Italy.	Lack of details for buildings that are not used as households.
ISTAT	Statistical data recovered from past censuses regarding geometric and thermophysical features of buildings.	National; Regional	Data divided into various databases, at large scale integration of data can be time-consuming.	Geographical coverage at the national level.	Lack of detailed data at lower-scale levels.
Agenzia delle Entrate	Data on energy consumption of buildings.	National; Municipal	Missing a platform where all data are collected and harmonized.	Data collected on the whole country	Specific data for every municipality.
Cadastral Data	Topographic database with geometrical and geo-referenced buildings' characteristics.	Municipal	Data collected by the municipality, but a platform with collected and harmonized data is missing.	Coverage on a national scale.	Data are specific for every municipality.

2.1.1. UNI/TS 11300

In 2002, the European Commission issued the Directive 2002/91/EC on the energy performance of buildings [56]. This directive introduced general guidelines for various European countries for the adoption of a methodology of calculation for building energy performance, the definition of minimum energy requirements, the inspection of heat generators and systems, and the definition of energy classes for buildings. This directive was transposed into the Italian legislation after the intervention of a technical committee and applied through the adoption of national Technical Standard UNI/TS 11300, which was issued in 2008 [57] and modified in 2014.

The UNI/TS 11300 Technical Standard was created to define a unique calculation methodology for determining building energy performance. It is divided into four parts. The first gives guidance for the determination of the building's energy requirements for summer and winter air conditioning. The second is more specific and focuses on primary energy requirements and efficiencies for winter air conditioning and domestic hot water (DHW) production. The third part provides information on determining the primary energy demand and efficiency for summer air conditioning, and the fourth guides the use of renewable energy and other methods of energy generation for space heating and hot water production [57]. In particular, the first and second parts of the standard provide useful information exploitable for the definition of archetypes.

The first part, "Determination of the thermal energy needs of the building for summer and winter air conditioning, defines the monthly methods for the calculation of thermal energy needs for heating and cooling. The technical specification is addressed to all possible applications provided by UNI EN ISO 13790:2008 - design calculation, energy assessment of buildings through the calculation in standard conditions, or in particular, climatic and operating conditions. To simplify the methodology for the calculation of energy needs and consumption relating to existing buildings whose envelope's thermophysical characteristics are unknown, the standard provides appendixes containing details of the most widespread opaque and transparent structures in Italy [58].

The standard's first appendix shows the thermal transmittance of the opaque components of existing buildings. A table is dedicated to each element of the envelope in which a transmittance value is assigned according to the thickness of the element and the main construction technologies with which it is made. To complete this first appendix, a summary table categorizes every possible component of the envelope, namely vertical opaque closures to the outside and the inside, flat and pitched roof, the floor under any non-conditioned environment, and basement on cellar, pilotis, and ground. These are categorized according to three conditions: climate zone (C or D, and E or F, according to Presidential Decree 412/1993 [59], which divides the peninsula into six climatic zones from "A" to "F" (Figure 4), based on heating degree days (HDD), year of construction (from 1976 to 1985 or from 1986 to 1991), and an element's thickness (variable from 0.20 to 0.40 m). Knowing these three conditions, it is possible to obtain the thermal transmittance value of a particular element built in a given period in a given climate zone and having a given thickness [60].

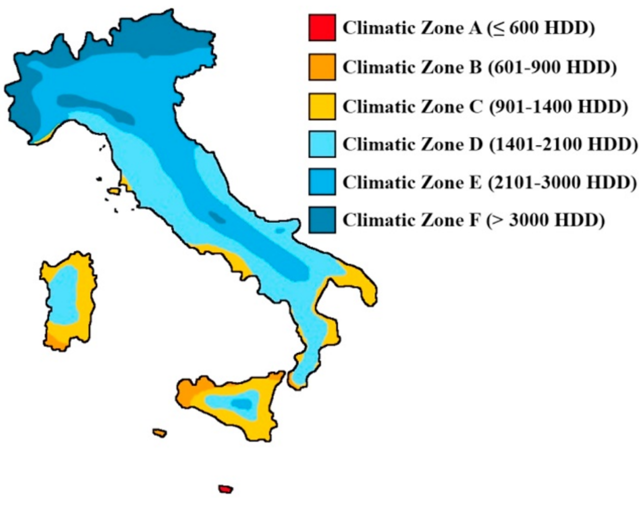


Figure 4: Italian climatic zone distribution [59]

The standard's second appendix is organized as an abacus of the wall structures used in Italy. The abacus aims to provide information on the main masonry structures used in the building industry and their spread throughout the country. The first half of the appendix is a list that concerns only the description of certain types of opaque vertical walls, describing their composition in terms of materials and indicating for each material the density and conductivity. The second half deals with the geographical spread of the elements described in the previous part. For some Italian regions, mainly in the north, tables are proposed according to the time of construction, and the most widespread type of wall among those described above is suggested. A third column contains additional information on the type of structure that is suggested for particular areas (e.g., historical centers) or particular building use (e.g., social housing) [60].

The second part, "Determination of primary energy needs and yields for the winter air conditioning and domestic hot water production" defines the efficiency of heating and DHW production systems, and the overall primary energy needs of such systems. In this case, there are no appendices from which it is possible to obtain detailed data, but a series of tables containing pre-calculated values are provided. These tables present different data for each type of heat generator and distribution system, which are characterized according to their insulation, which is derived from the installation date: before 1961, between 1961 and 1976, between 1977 and 1993, and after 1993. Through this series of tables, it is also possible to characterize the buildings for technological systems [61].

2.1.2. UNI/TR 11552

In 2014, Standard 11300 was updated in all its parts in the light of new regulations on the containment of energy use by the European Commission [60–63]. This revision took place following the conclusion of the TABULA project, which started in 2009 and concluded in 2012. For the project, fifteen European states worked on the creation of a database for each country with residential reference buildings capable of representing the entire stock of that state [64,65], as further discussed in Section 3.2. Following that project's conclusion, and thanks to the new data and knowledge obtained, the Italian Thermotechnical Committee (CTI) decided to extend the appendix (Appendix A) that in the UNI/TS 11300 of 2008 contained the abacus of opaque structures composing residential buildings, and make it an independent technical report called Technical Report UNI/TR 11552.

The first half of the report presents the main construction types used in Italy in three parts. Each part describes a different envelope element: perimeter walls in the first part, floors in the second, and roofs in the last part. Each of the three parts reports the main technologies that are usually used in the construction of the elements of the envelope. For each technology, there is a description of the layers for which the thermophysical characteristics are indicated. Thermal transmittance and other characteristics are calculated for different combinations of layer thicknesses. The second half shows the geographical spread of the structures described above. As for the Appendix of Standard 11300, tables are proposed concerning some Italian regions, mainly northern ones, where the main construction techniques are suggested according to the period of construction. The main novelty that can be found in this second version concerns a considerable increase in the degree of detail as regards the data for the Piedmont region. This is because the work developed during the TABULA project was based mainly on buildings built in that region [66].

2.1.3. Observations on Italian standards

The analysis of the standards for determining the thermal energy needs of the building, and the subsequent technical standard containing the abacus of the structures, reported in the previous paragraphs, highlight some problems that must be addressed.

Integration and consistency: UNI/TS 11300 is the first standard that provides data for the characterization of existing buildings from a thermophysical point of view in case of impossibility to carry out more in-depth analysis. However, these data are scattered in the first two parts of the standard and are not presented uniformly. Regarding the constructions, only the vertical walls are included, and they are presented in the first half of Annex A in UNI/TS 11300 part 1. The data concerning the geographical distribution of the constructions are covered in the second half of Annex A. Finally, the data concerning heating and DHW systems are contained in UNI/TS 11300 part 2. This situation was not resolved by the evolution of the legislation. With the revision of 2014, the part concerning the structures and their geographical location, expanded and adapted according to the new data, became the Technical Standard UNI/TR 11552, while the data concerning building systems remained as it was in UNI/TS 11300 part 2, also revised in 2014. Thus, no integration between the data is guaranteed, and they remain divided between various standards and their versions. Moreover, there is a lack of a single integrated database that is easy to access and complete.

Level of detail: In the first version of Standard 11300, when the abacus of existing structures was drawn, the focus was only on the vertical opaque elements. This lack is also addressed by the authors of the standard, who in the introductory chapter emphasize how incomplete and constantly updated the list is. This update took place with the 2014 revision of the standard. In the new version, this deficiency has been partly resolved. With the extension of the abacus, more elements have been added to describe the main technologies that make up the building envelope, but the vertical opaque structures still are treated in greater detail than the roofs and floors: for the perimeter walls, numerous examples deal with the different types of construction, from the most traditional (such as stone walls or masonry) to the more modern ones (such as prefabricated walls). This degree of detail is not reached by the other categories, which are treated in less detail. Only a few examples are presented for horizontal structures that are defined as representative of more than one hundred years of construction techniques. In this way, the typical variety of the different areas of Italy is reduced to a few examples that only partially reflect reality.

Geographical coverage: When analyzing the part of the abacus of the structures that tries to define the geographical spread of construction technologies, it is clear the attention is mainly focused on Northern Italy. In the first version of the abacus contained in Appendix A of the UNI/TS 11300 standard, the northern regions considered were Liguria, Lombardy, Veneto, and Emilia. The rest of the Italian peninsula was characterized by Tuscany, Abruzzo, and Campania. With the revision in 2014, only one region was added—Piedmont—again, located in Northern Italy. This particular focus on Northern Italy shows the lack of continuous geographical coverage. Large portions of the Italian territory with specific climates and conditions are not included, making the abacus usable only in cases where the structures are located in the indicated or neighboring areas, or where the climatic and context conditions of the areas not included are similar to those that are included.

Time coverage: Regarding time coverage, the situation is also similar to the geographical spread. The tables that show the coverage of the structures' territory show periods during which certain construction technologies were in use. Except for what is described for the Piedmont region, which presents a good level of detail, the time is usually divided into two classes—from 1900 to 1950 and from 1950 onwards—with some exceptions in 1970. This time division only partially represents reality. In particular, after 1950, the prefabrication of buildings and the introduction of energy-saving laws [67] were brought to the development of new building techniques, creating greater variability that is not reflected in the suggested time classes.

2.2. The TABULA project

Between 2006 and 2016, the Intelligent Energy Europe Program (IEE) launched three consecutive projects to make retrofitting residential stock simpler and more efficient. The first DATAMINE project, which started in 2006 and ended in 2008, had the task of improving knowledge about the energy performance of building stock through the use of energy performance certificates (EPC) [68]. The data collected and analyzed represent the basis from which the TABULA project started in 2009. The aim was to classify the building stock according to the energy properties of the buildings and to define for each category representative archetypes of all the buildings that are part of it [64,69]. Starting from the results obtained with this second project, between 2013 and 2016, the EPISCOPE project used the archetypes defined during TABULA to monitor the renewal activities of the European building stock through the calculation of building renovation scenarios at different scaling levels. The results of the assumed scenarios and monitoring procedures aim to track progress in terms of building energy performance and help stakeholders ensure adequate levels of refurbishment to achieve the European targets for 2020, 2030, and 2050 [70–72].

The objective of TABULA, the second project started by IEE, was the creation of a database of the main types of residential buildings in Europe for pre-defined geometries. The database, divided by member states, contains the construction and installation characteristics of residential buildings in the 13 European states that participated in the project. The stock of residential buildings that the project aims to study has been divided according to the size of the buildings and the period in which they were built. The results obtained from this classification are presented, employing tables in which the main data concerning the characteristics of the geometry, envelope, and the distribution systems for domestic hot water, heat, and cooling, if present, are presented for each time class and building typology. These building typologies have been used for the definition of energy consumption in the business as usual scenario and the definition of two categories of retrofit interventions: light renovation and deep renovation. These renovation scenarios are designed to support policymakers at various levels in the definition of energy improvement interventions in residential buildings [73,74]. Italy also participated in this project, but given the difficulty in finding consistent data at the national level for the characterization of the residential building stock, the analysis was carried out only for one Italian region where the availability of information was adequate: Piedmont [44].

For the construction of the Italian building typology, the analysis presented started from the identification of 10 classes that determine the period of construction of the building, defining dimensional, construction, and energy characteristics; each one typical of that historical period. Each period of construction is characterized by buildings with different dimensions that meet the different construction needs typical of that period. Four classes with specific extensions and geometry have been identified: single-family house, terraced house, multi-family house, and apartment block. These two groups of characteristics (i.e., construction year and building typology) contribute to creating the building typology matrix [44]. The matrix is made up of cells of rows that determine the time classes and columns that define the geometry of the building according to the four classes previously indicated. The buildings that are represented in the cells are defined as model buildings, and these are assigned with geometric construction and system characteristics partly derived from archetypes (i.e., buildings whose characteristics are defined following statistical analysis and partly derived from real buildings, representative of that building category in that period when there is a lack of statistical data) [75]. The data used for the description of buildings from the point of view of building systems are derived from the experience of the study's authors and the advice of experts in the field, as well as from the support of scientific literature. The technical systems have been defined mainly through the use of the UNI/TS 11300 standards, and partly through the experience of the authors together with the scientific literature [76]. The buildings obtained and characterized for technological systems and construction features have been simulated to define performance in both the business as usual and retrofit scenarios. A quasi-steady state monthly model was used to calculate the final and primary energy requirements for space heating and DHW, and for CO_2 emissions. The climatic data of the city of Turin have been assigned as a necessary input for the climate characterization of buildings. The results obtained with simulations of the business as usual scenario represent the typical archetypes of residential buildings located in climate zone E, which according to Italian legislation is characteristic of municipalities between 2,100 and 3,000 heating degree-days [76].

2.2.1. Observations on TABULA project

After analyzing how TABULA was developed, some considerations must be addressed to understand its suitability for UBEM tools.

Integration: The TABULA project was born from the will of the European Commission to create a method to define entire stocks of buildings, whether national or regional, through the use of archetypes that describe the main characteristics of the entire stock by summarizing those buildings in a single typical construction. Given the nature of the project, the attention is rightly placed on those buildings used only as housing units, leaving aside all those buildings that, although partly having spaces used as dwellings, also use spaces for the commercial, receptive, or tertiary sector. The TABULA project represents a good percentage of the buildings that make up the building stock of the Piedmont region but still lacks integration with other building typologies (i.e., no buildings that have functions other than purely residential are included).

Consistency: A second issue that emerges from the data analysis for the definition of building needs is the use of a single file for climate data. Although defined as representative of the whole Piedmont region, the stock of buildings is simulated using only the typical climate data of the city of Turin [76]. This inconsistency can cause problems when buildings simulated with the climatic characteristics of a city placed in zone E are located in a mountain environment, and therefore in climate zone F, or areas belonging to climate zone E are in more rural conditions.

Geographical coverage: As in the previous example, from the analysis of the TABULA project it is possible to see how the simulations on the archetypes defined in the first phase were carried out using Turin's climate data. The results obtained were used to define the characteristics of the entire stock of buildings in the Piedmont region. Since it is defined as one of the most representative building stocks in climate zone E, the archetypes obtained from the previous simulations are defined as representative of all the buildings located in municipalities belonging to zone E. Given the lack of exhaustive and detailed data on the types of residential buildings characteristic of the other climatic zones that characterize the Italian peninsula (namely, A, B, C, D, and F) there is a lack of complete geographical coverage for the entire Italian peninsula, making this study usable only for stocks of buildings that are located in geographical areas corresponding to that of Piedmont. The TABULA project represents 944,690 buildings, 18.2% of total residential buildings in climate zone E (5,191,960) and 7.7% of all Italian residential buildings (12,187,698) [77–79].

2.3. Other building databases

There are also cases where the previous resources were not used to define the thermophysical characteristics of buildings, so different methodologies and resources were used. They are mostly studies conducted at two different spatial levels—regional and municipal—and for each a different database was used.

Studies that focus on the characterization of residential buildings at the municipal level deal with several buildings that are usually not too tall, either because of the study's narrow focus or because the authors chose to focus only on a part of the entire residential stock. In these cases, the definition of the buildings' characteristics is usually very detailed because more specific and communal level resources are used for small datasets. The geometrical and geo-referenced characteristics of the buildings are deduced from the municipal topographic database, and through these characteristics, it is possible to model the buildings under study three-dimensionally. By consulting the cadastral data, it is possible to find not only finer-grained information. To define typical equipment and systems, statistical data recovered from the census and made available by Istituto Nazionale di Statistica (ISTAT) are used. Finally, data on energy consumption are obtained from Agenzia Delle Entrate [80], which periodically communicates them to the relevant municipal offices. These databases, which are characterized by a uniform structure throughout the national territory, do not have a platform where all data are collected and harmonized, so time-consuming data linking work is necessary [16,54,81].

Despite the high level of detail that can be achieved with this methodology, it is not recommended for studies at national or regional levels because there is no database that collects all the necessary data at the national level. This methodology is therefore mainly suitable for municipalities or districts, since the main databases used are at the municipal level, and the work of linking and harmonizing the data obtained from different sources is time-consuming.

As for studies carried out at the regional level, the procedure is different. Due to the large number of buildings in the building stock, it is not possible to conduct a detailed analysis as can be done with smaller datasets. It is also not possible to simply add up the consumption for each building because of the high number of buildings and the lack of knowledge of the energy consumption of the buildings in the stock. Therefore, a statistical approach is used for analysis at the regional or national level, through the definition of model buildings characterized by geometric and thermophysical features that are considered representative of certain categories and are defined as archetypes. Statistical data collected, organized, and published by ISTAT is used to define the necessary characteristics. The archetypes were determined according to the building's age, and each period was characterized by a typical construction technology that defined the envelope from a geometric and thermophysical point of view. These are then assigned (again, on a statistical basis) to the systems for heating, cooling, and domestic hot water, thus obtaining a series of archetypes representative of the different categories that make up the entire building stock [82–84].

The use of this type of database is suitable in cases where the number of buildings making up the stock is too high to proceed with the methodology described above. Although the results are not as detailed as would be in an analysis of a set of buildings at the municipal level, the results obtained in some applications of this methodology show a good correspondence between the consumption data obtained in reality and the consumption data obtained as a result of simulations in steady-state, with deviation values about 10% [82].

3. Prototype building model development

According to the annual report of the Energy Conservation in Buildings and Community Systems (ECBCS), archetypes and prototypes can be created from expert opinion, top-down statistics on characteristics of the stock, an empirical database of the entire stock of buildings, or an empirical database of well-classified reference buildings [85].

3.1. Selected building typologies

The analysis done by ISTAT regarding the building typology at the national level shows that 84% are residential buildings and among them, about 52% corresponds to single-family houses. In 2017 the energy consumption related to residential housing was about 33 million tonnes of oil equivalent (Mtoe), of which 70% was related to heating and cooling, 3,8% less than 2016 [77]. These data show the importance of the new policies developed at national and regional levels to decrease energy need in residential buildings and thus their energy use. In particular, this work focused mostly on Italian climatic zone E (2101<HDD<3000), which is the most common in Northern and Central Italy representing about 4,250 municipalities out of 8,100 (Figure 3 [59]). Thus, reducing the focus to the North Italy, about 48% of the buildings are single-family houses, 24% are terrace houses, 25% are multi-family buildings, and only 3% corresponds to large apartment blocks.

Based on these data, this work focused on the development of prototype models of single-family and multi-family buildings whose geometry can be modified according to the input data given by geo-referenced tools (i.e., GIS), thus working with parametric models rather than static hypotheses. In fact, the possibility to use real geometry rather than simplified, will improve the final results, associating the input data to several buildings at the same time and reducing the uncertainties to the accuracy of the software used for urban modelling, as shown by Zarrella et al. [13]. Considering that in the city center of most Italian cities multi-family buildings and apartment blocks have often been used for offices, both residential and non-residential end uses have been investigated. Office prototypes have been defined using the same envelope used for residential applications for the period before 2005, changing internal loads according to standards that regulate thermal comfort and indoor environmental quality (IEQ) for office buildings.

Italian residential building typologies were already well described by the IEE-TABULA project [76], which aimed to define a shared classification of common "building typology" for each European country into archetypes. However, when modeling buildings at the urban scale, geometry and footprint of the building are usually given as input developing shapefiles or other similar formats for 3D modeling. The specific geometry of each individual building and the number of stories can be attached to the input GeoJSON file and modified by users. Single-family buildings can be a single story or more and are divided into living zone, garage, and attic. Multi-family buildings are divided by apartment units, where each unit is a thermal zone to simplify the model of the whole building.

Therefore, American prototypes developed by DOE have been used as guidelines to establish the main layout of the required inputs, but buildings footprint and dimensions have not been precisely defined since they will be taken as input using the geo-referenced tools. The study focused on single-family housing (SFH) (Figure 5A and 5B) and multi-family housing (MFH) (Figure 5C), which are the most prevalent in Northern Italy, defining both the residential and the office end use due to the change of use of many buildings in urban city centers. MFHs include a small number of apartments, generally about 20, divided into two to five floors. The same definition was used to partly fulfill the problem of coherent data collection. Since prototypes must be representative of the building typology in terms of its geometrical features, thermal properties, and HVAC technology within the climatic zone considered, available information was collected from different European and national standards and that information will be presented in the next sections.

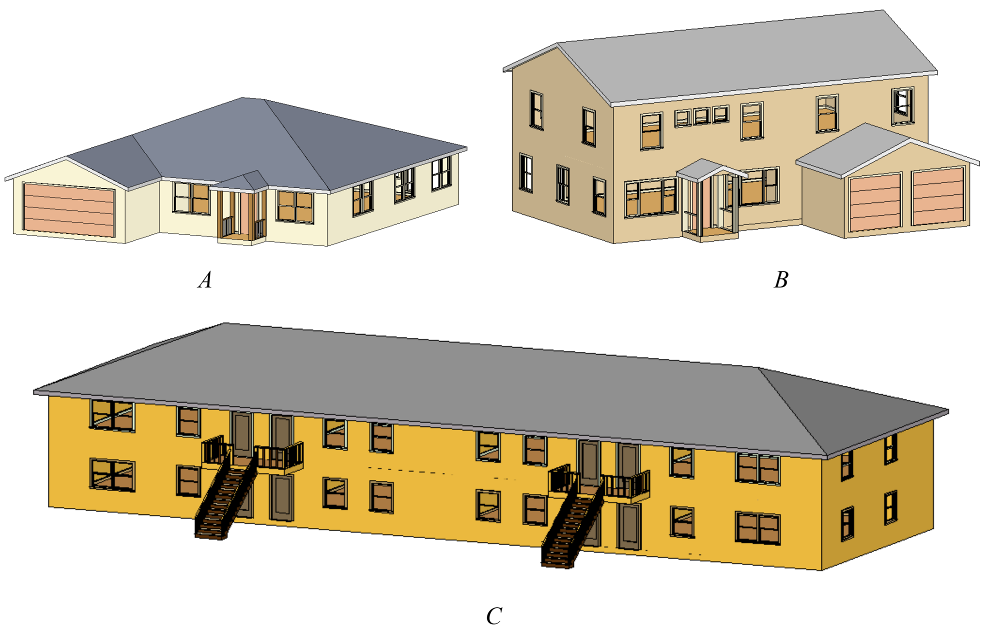


Figure 5: Example of residential building layout: (A) One-story single-family, front view, (B) Two-story single-family, front view, (C)Multi-family, front view

3.2. Construction years

Ten different periods of construction were considered. For the years before 1930 to 1960 a time step of 15 years was used, since it was not meaningful to use a smaller time step due to the two World Wars and the poor technologies available. During the industrial development after the 1960s and up to 2000, a great number of construction technologies were applied from Northern to Southern Italy, varying from different types of brick walls to concrete or prefabricated walls; therefore, a 10-year time step was more appropriate. After 2000, the time step was further reduced to 5 years, because the technological development rapidly changed the construction and retrofit strategies, in particular, due to the new European and Italian directives related to building performance that require a higher insulation level.

3.3. Building construction elements

According to the National Institute of Statistics, the most common types of residential construction in North Italy are made of bricks (e.g., solid, hollow) or concrete, which correspond respectively to the 57% and 27% of the building types (Figure 6). Considering that in urban city centers many multi-family buildings have become office buildings, the same envelope properties have been used for the analysis.

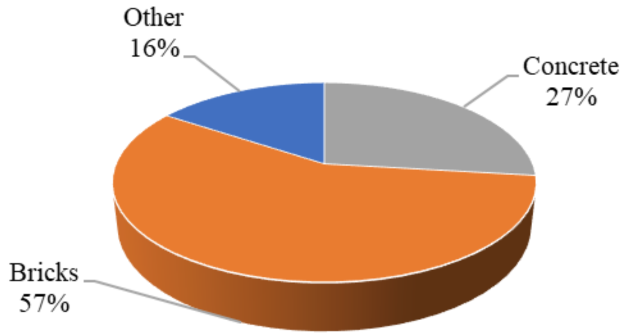


Figure 6: Typical materials used for construction in Northern Italy

Before the Second World War in Northern Italy, most of the buildings were made of wood and solid bricks, which were the materials that were available and reliable . The results presented in Figure 7 can be used as representative percentages to apply prototype buildings at urban scale, defining the construction materials based on real statistical data belonging to the National census. Even though few data regarding previous construction are available, stones and wood can be considered common materials used for buildings' external walls and roofs before 1945. Reinforced concrete became common between 1960 and 1980 for residential and office buildings. Before the '60s it was used only in big cities like Milan (since 1950), where industrial development was bringing more and more people from the countryside who required low-income housing units. In previous years, reinforced concrete was used mostly for big industrial buildings, to allow the construction of slab covering considerably long spans able to withstand heavy loads, and to offer good fire resistance. Moreover, this fluid material was suitable for multiple geometries and later for prefabricated structures. While the TABULA dataset includes the use of prefabricated concrete panels only from about 2000, in this work this material and technology were present from the early 1950s to today, in parallel with brick walls.

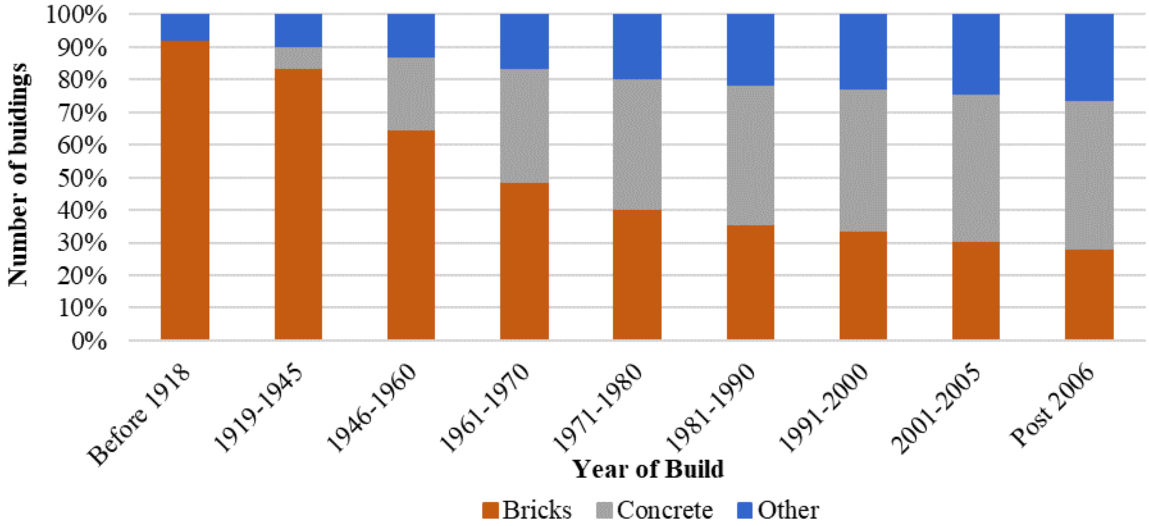


Figure 7: External wall envelope according to the year of construction

Building construction elements were defined according to national standards requirements for the most recent construction, whereas buildings older than 1976 were characterized according to the literature. In fact, Law 373 of 1976 was the first standard regarding building energy efficiency [86], and it defined some general criteria for building insulation and the installation of heating systems (e.g., oil and gas boilers for space heating and domestic hot water).

Later, in 1991, a new standard regarding the efficient use of energy in buildings was released [67]. The law provided precise indications on the parameters that must be respected in terms of envelope insulation and efficiency of the generation systems, extending the limitations both to private and public buildings. It includes a mandatory technical report that must be delivered to the municipality together with the project, which certifies the correspondence of the building characteristics with the limits required by the standard.

The Italian transposition of the Directive 2002/91/EC [56] took place with Legislative Decree n.192 on August 19, 2005 [87]. In addition to precise requirements related to the thermal transmittance for building elements and HVAC systems, it provided a methodology for calculating building energy performance and for promoting the rational use of energy through information and awareness of end users and training and updating of workers in the building sector.

Finally, the most important Directive on Buildings' Energy Performance (Directive 2010/31/UE) [88] was transposed with the Law n.90/2013 and with the related legislative decree of June 2015 [89–91]. The thermal transmittance of the building envelope was significantly reduced with 5 centimeters (cm) to 15 cm of insulation for opaque structures, while those of windows were reduced to 1.8–2 [W/(m^2 K)]

3.4. Heating and cooling systems

The heating systems were characterized based on the register of the thermal plant of Lombardy, which is the most complete dataset available regarding heating and DHW systems in Italy [92]. The data collected are considered to represent all of Northern Italy, since Lombardy hosts 16% of the total Italian population and 35% of both the municipalities and the population living in climatic zone E.

The first investigation addressed the fuel type of the installed systems. As shown in Figure 8, 91% of the installed systems are supplied by natural gas, whereas oil-fired boilers have been almost completely replaced by other systems thanks to many incentivization policies for the replacement of these polluting and inefficient systems [92].

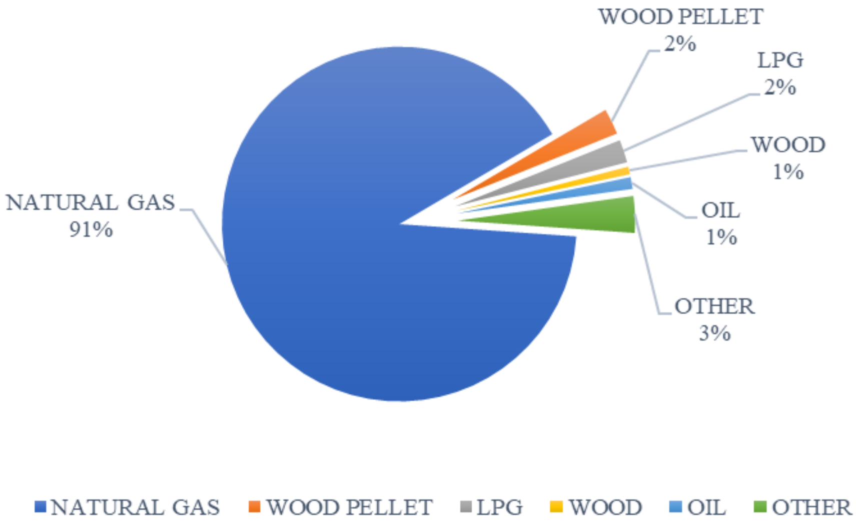


Figure 8: Type of fuel used for heat generation in Lombardy [92]

Figure 9 shows the percentage of traditional and condensing gas boilers installed. Before 2005, traditional gas boilers were the most common heat generator for space heating and domestic hot water, while the more efficient condensing systems became more popular from 2005.

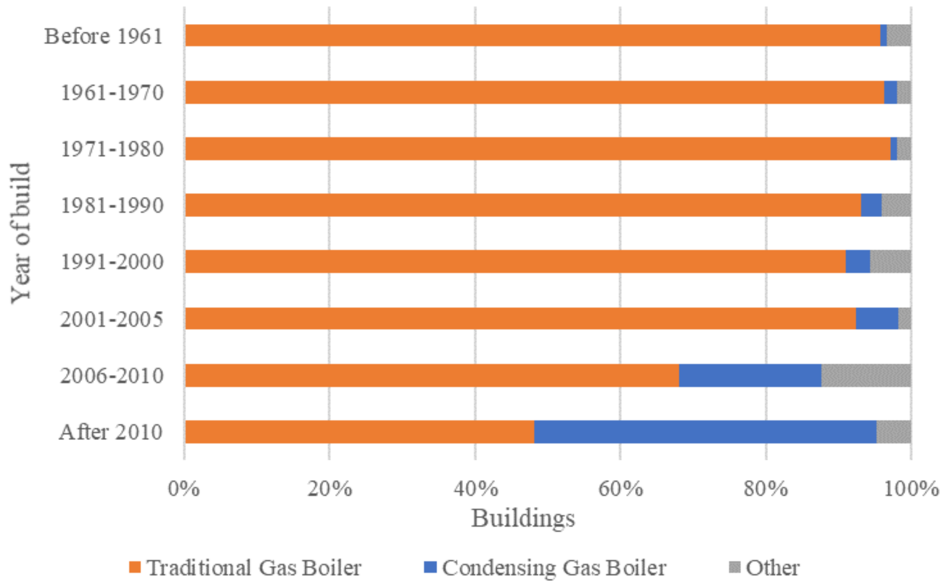


Figure 9: Types of generation systems supplied by natural gas [92]

Generation efficiencies were considered according to the statistics analyzed for Lombardy as a representative region of northern Italy, according to the year of installation, the average peak power installed for each unit (about 24 kilowatts) and based on both legislative decree n. 192/2005 [87] and UNI TS 11300-2 [61].

Systems installed before 1960 in MFH, thus in office buildings, were considered as a traditional gas boiler with a generation efficiency of 84.8%, independently on the presence or absence of storage tanks. These systems were installed mainly for each unit, serving to supply heat for space heating and DHW. According to the standards, the efficiency assigned to centralized heating systems for class V and VI is about 86%, due to the higher installed power. Class VII still includes a centralized non-condensing gas boiler, with a minimum efficiency of 86%, but DHW is supplied by single unit electric boilers. The same system has been applied for class VIII, upgrading it to a condensing gas boiler with 88% of minimum efficiency. Class IX and X present a single unit condensing gas boiler both for space heating and DHW, with efficiency equal to 92%. SFHs have independent systems for both space heating and domestic hot water, and the corresponding generation efficiencies range between 85% and 95% according to the year of installation and the typology (non-condensing or condensing gas boiler).

Heating setpoint temperature in indoor environments is fixed by the Italian legislative decree DPR 412/93 [59] at 20°C with a dead band of 2°C to satisfy the user's thermal comfort. The heating system can work up to 14 hours per day, according to the specific directives for Italian climatic zone E, on average from 6 am to 11 am and from 3 pm to 10 pm. The setpoint temperature for cooling is set equal to 26°C, based on the requirements to satisfy thermal comfort. The working hours were mostly set in the afternoon, from 12 pm to 10 pm, when the influence of solar radiation and outdoor air temperature is more significant. However, since cooling is not ruled by national standards and its installation is strictly dependent on the users' choice, the cooling systems have been assigned only for classes VIII to X when split systems became less expensive, and thus more frequently installed. The energy efficiency ratio (EER) in cooling is between 2.5 and 3, according to the class.

3.5. Internal Loads

3.5.1. Residential buildings

Internal loads were defined according to Italian standards related to residential use. Due to the extremely variable behavior of residential users, there are not many precise parameters that can be defined as representative of the Italian building stock. However, EN 16798-1:2019 introduced some applicable values for internal loads; in particular, occupancy has been set as 28.3 m^2/person and DHW use was 100 L/(m^2 y).

Infiltration rates are related to the permeability of the envelope, the climatic conditions (wind speed and direction and the temperature difference between external and internal environment), and user behavior. Therefore, the values of the air exchange rates defined can change significantly considering residential users and envelopes. Standard UNI TS 11300 [57] provides an average value of 0.3 h^{-1} as an average infiltration rate. Older buildings with extremely air permeable enclosures have been characterized with 0.5 h^{-1}, while recent construction with the greater airtightness granted by higher performing opaque and glazed solutions, and helped by controlled mechanical ventilation (CMV), is considered to have an infiltration rate of 0.1 h^{-1}.

The design lighting power required for a residential building is usually calculated by the sum of the power rating of each lamp installed in a room or area. However, it is variable information based on the subjective need or preference of the people living in the house. Reference values were taken from EN 15193-2 [93], calculated as the average value of the typical specific loads defined for kitchens, living rooms, bathrooms, and bedrooms. In particular, the highest internal load related to the lighting system, corresponding to the use of old incandescent lamps still in use in some private units, is 11.5 W/m^2. Considering the overall luminous efficiency of real lamps available from technical reports [94,95], the same load was converted with an average efficiency for halogen lamps and LED lamps, obtaining 6.6 W/m^2 and 1.6 W/m^2, respectively. Electric loads different from the lighting system are also extremely variable according to user behavior and depending on their needs. Therefore, 3 W/m^2 has been taken as the average value given by standard EN 16798-1 [96].

3.5.2. Office buildings

Internal loads for non-residential applications have been widely defined by European and Italian standards, obtaining multiple and different values for the same application. Standards applied in this work have been considered the most significant and widely used in the reference periods. For example, standards suggest multiple values of occupancy density in the past years. However, the range is between 0.08 and 0.1 person/m^2, and according to standard EN 16798 [96], the value of 0.1 person/m^2 has been used.

Standard UNI 10380:1994 [97], substituted by UNI EN 12464-1:2004 [98], suggests a reference luminance value of 500 lux to guarantee the proper comfort in office spaces, which corresponds to 5 to 15 W/m^2 according to the efficiency of the lighting system used (e.g., 5 W/m^2 for LED lamps, 10 W/m^2 for halogen lamps, and 15 W/m^2 for incandescent lamps).

As defined for residential prototypes, the infiltration rate is between 0.1 and 0.5 air changes per hour (h^{-1}) based on the year of build, since it is mainly related to envelope properties. Office buildings are also supplied by mechanical ventilation systems, with different airflow rates depending on the building class. When standard EN 15251 [99] was in effect from 2007 to 2019, 10 liters per second (l/s) per person was the ventilation rate suggested for the highest comfort category, until it was replaced by EN 16798-1 [96]. In the most recent buildings, ventilation rates range from 8 l/s to 20 l/s per person, depending on the difference between open-space and single office and according to the adaptability of the person. Therefore, an average value of 16 l/s per person has been chosen. For buildings belonging to class VII and lower, Italian standard UNI 10339, with a reference value of 11 l/s per person, is used [100].

4. Prototype building model specifications

The result of the previous analysis of national and international standards, other than existing datasets, is the definition of 16 prototypes for residential single-family and multi-family buildings and 14 prototypes for multi-family buildings (considering both traditional and pre-fabricated construction technology) now used as offices, maintaining the same shape and characteristics, but changing internal loads. The dataset of collected information can be used for multiple research and applications that will be described in Section 5, partly overcoming the lack of coherent information available in Italy. Figure 10 presents the workflow used to define the buildings' prototypes that can be applied to replicate the study increasing the dataset with new building types.

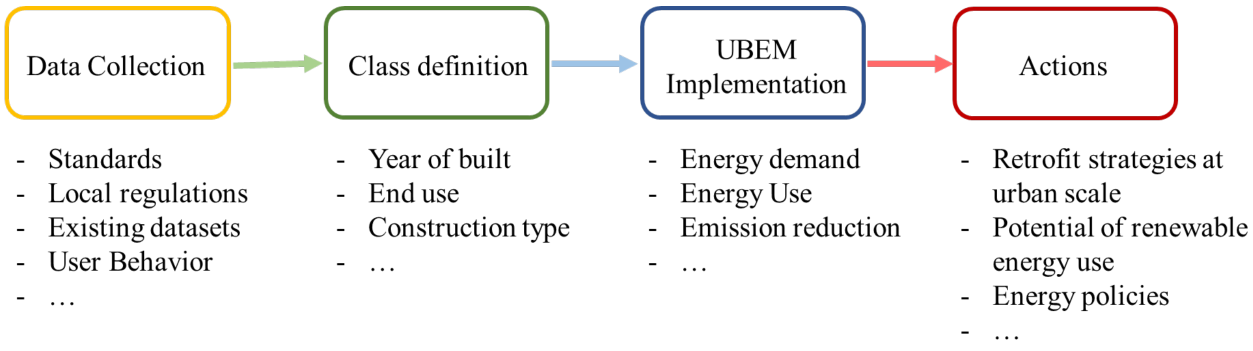


Figure 10: Workflow summary for the development of buildings' prototypes

Office buildings were represented by eight classes from before 1930 to 2005, when the change of use became reasonable considering the evolution of the city centers from residential to buildings mainly related to services. Buildings built after 2005 were excluded because they were built specifically for office or residential purposes, thus no change of use was needed. The characteristics analyzed can be grouped into two main categories: envelope and HVAC system. The building elements considered to characterize the envelope of prototype buildings are roofs, ceilings, floors, external walls, and windows. Considering that the first end use of the building was supposed to be residential, the typical glazed area corresponds to one-eighth of the footprint area as required from the national standard [101] for each building typology.

The envelope layers and their characteristics have been defined based on the standard UNI/TR 11552 [66], and 10 construction age classes were defined (Figure 11).

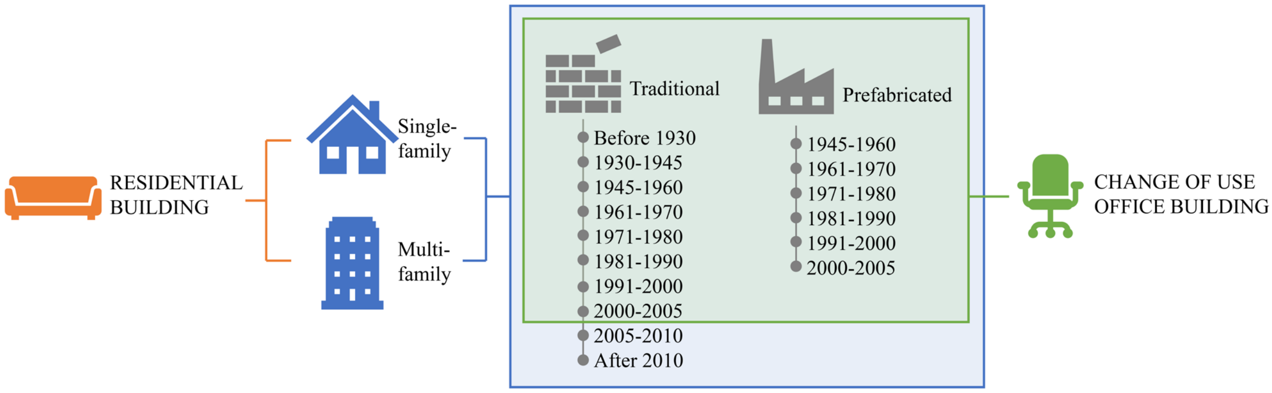


Figure 11: Development of the buildings' prototypes

Some input parameters for the UBEM simulations can be defined according to the specific case study if known: the number of stories, the building height, the end use, the construction year, the footprint, and the building shape. The overall thermal transmittance of the envelope, as well as setpoint temperature for heating and cooling, also can be modified during the simulation setup. Other parameters such as the window-to-wall ratio are pre-defined for the specific prototype typology, which is also a source of information when there is not sufficient data availability.

An accurate definition of the building envelopes is presented in Table 4, which includes a brief description of the construction element and the related thermal transmittance. The characterization was decided according to the most frequent typology described in standard UNI 11552. Windows properties have been defined according to TABULA and verified with national limitations related to standards (Table 5).

A great part of the building stock of residential buildings was mainly built with traditional materials such as solid and hollow bricks, as described by TABULA. However, the census made by ISTAT reports a significant percentage of buildings made of concrete belonging to the period immediately after the Second World War.

Table 4: Description of the envelope according to the period of construction

Class	Year of Build	Construction Element	Envelope Description	Thermal Transmittance [W/(m^2 K)]
Class I	Before 1930	Roof	Wooden roof/No insulation	2.50
		External wall	Stone masonry	2.58
		External floor	Concrete ground slab	1.88
		Internal floor/Ceiling	Beams-wooden slab	1.22
Class II	1930–1945	Roof	Wooden roof/No insulation	2.50
		External wall	Solid bricks	1.35
		External floor	Concrete ground slab	1.88
		Internal floor/Ceiling	Steel beams and hollow bricks	2.14
Class III	1945–1960	Roof	Reinforced brick-concrete slab	1.47
		External wall (traditional)	Hollow wall brick masonry	1.05
		External wall (prefabricated)	Cinder blocks	1.22
		External floor	Reinforced concrete slab, traditional screed	1.88
		Internal floor/Ceiling	Brick-concrete slab - traditional screed	1.62
Class IV	1961–1970	Roof	Reinforced brick-concrete slab, traditional screed	1.45
		External wall	Hollow wall brick masonry	0.98

		(traditional)		
		External wall (prefabricated)	Cinder blocks with cavity	1.14
		External floor	Floor with reinforced concrete slab, traditional screed	1.88
		Internal floor/ceiling	Brick-concrete slab - lightweight screed	1.51
Class V	1971-1980	Roof	Ceiling with reinforced brick-concrete slab	1.45
		External wall (traditional)	Hollow/solid bricks with cavity	0.98
		External wall (prefabricated)	Precast Reinforced concrete wall, slightly insulated	0.70
		External floor	Reinforced concrete slab, traditional screed	1.88
		Internal floor/Ceiling	Brick-concrete slab - traditional screed	1.52
Class VI	1981–1990	Roof	Reinforced brick-concrete slab	0.84
		External wall (traditional)	Hollow bricks with cavity	0.67
		External wall (prefabricated)	Precast Reinforced concrete wall, low insulation	0.70
		External floor	Reinforced concrete slab, lightweight screed	1.88
		Internal floor/Ceiling	Brick-concrete slab - lightweight screed	1.54
Class VII	1991–2000	Roof	Reinforced brick-concrete slab	0.81
		External wall (traditional)	Hollow/solid bricks with insulated cavity	0.60
		External wall (prefabricated)	Precast Reinforced concrete wall, low insulation	0.81
		External floor	Reinforced concrete slab, lightweight screed	1.23
		Internal floor/Ceiling	Reinforced brick-concrete slab, traditional screed, insulated	1.36
Class VIII	2000–2005	Roof	Reinforced brick-concrete slab, insulated	0.52
		External wall (traditional)	Hollow/solid bricks with cavity	0.54
		External wall (prefabricated)	Precast reinforced-concrete wall, low insulation	0.47
		External floor	Reinforced concrete slab, lightweight screed, insulated	0.85
		Internal floor/Ceiling	Brick-concrete slab, lightweight screed, insulated	0.85
Class IX	2005–2010	Roof	Reinforced brick-concrete slab, insulated	0.33
		External wall (traditional)	Perforated bricks and medium insulated	0.30
		External floor	Reinforced concrete slab, lightweight screed, insulated	0.33
		Internal floor/Ceiling	Brick-concrete slab, lightweight screed, insulated	0.54
Class X	After 2010	Roof	Reinforced brick-concrete slab, insulated	0.33
		External wall (traditional)	Brick blocks and external high insulated	0.23
		External floor	Reinforced concrete slab, lightweight screed, insulated	0.33
		Internal floor/Ceiling	Brick-concrete slab, lightweight screed, insulated	0.34

Table 5: Description of the windows according to the period of construction

Class	Year of Build	Description	Window Thermal Transmittance [W/(m^2 K)]
Class I	Before 1930	Single glass, metal frame without thermal break	5.70
Class II	1931–1945		

Class III	1946–1960	Single glass, wood frame	4.90
Class IV	1961–1970		
Class V	1971–1980	Double glass, air-filled, metal frame without thermal break	3.70
Class VI	1981–1990		
Class VII	1991–2000	Double glass, air-filled, metal frame with thermal break	3.40
Class VIII	2001–2005		
Class IX	2006–2010	Low-e double glass, air or other gas-filled, wood frame	2.20
Class X	After 2010	Low-e double glass, air or other gas-filled, wood frame	1.8

Finally, the analysis of the data concerning the heating and cooling systems is summarized in Table 6. Heating systems are either centralized or independent, and their efficiency may vary according to the class and its type (condensing or non-condensing). DHW is supplied accordingly, using an electric boiler when the heating system is not independent for each unit. The cooling system has been applied for the last three cases (i.e., from 2000), when cooling traditional split became less expensive, thus more interesting for users. Centralized cooling systems were not considered because they are usually installed for new buildings, while this work focused on the buildings that changed their use during the years; since these systems would have required major actions, they are not commonly applied.

Table 6: Summary of the heating and cooling systems

Class	**End use**	**System**	**Cooling**	**Centralized/Independent**
Before 1930	Residential	Traditional gas boiler for SH and DHW	No	Independent for each unit
1930–1945	Residential	Traditional gas boiler for SH and DHW	No	Independent for each unit
1945–1960	Residential/Office	Traditional gas boiler for SH and DHW	No	Independent for each unit
1961–1970	Residential/Office	Traditional gas boiler for SH and DHW	No	Independent for each unit
1971–1980	Residential/Office	Traditional gas boiler for SH and DHW	No	Centralized for the whole apartment block
1981–1990	Residential/Office	Traditional gas boiler for SH and DHW	No	Centralized for the whole apartment block
1991–2000	Residential/Office	Traditional gas boiler for SH/DHW with an electric boiler	No	Centralized SH/ Independent DHW
2000–2005	Residential/Office	Traditional gas boiler for SH/DHW with an electric boiler	Yes	Centralized SH/ Independent DHW
2005–2010	Residential	Condensing gas boiler for SH and DHW	Yes	Independent for each unit
After 2010	Residential	Condensing gas boiler for SH and DHW	Yes	Independent for each unit

Since the information used is mostly based on national and international standards, other than existing databases, the prototype models are significant, representing not only a great part of the national building stock but also a methodology that can be followed and replicated for other Italian case studies and climatic zones adapting the information needed.

For these reasons, load fractions have been defined for occupancy, lighting, and appliances both for office use (Figure 12*),* according to the guidelines of standard BS ISO 18523-1 [102], and residential use (Figure 13). The schedules are derived by the calculation of average values to represent both retired and common residential users based on EN 16798-1 [96]. Each fractional schedule will be then multiplied by the reference values defined in *Section 3.5.1* and *Section 3.5.2*.

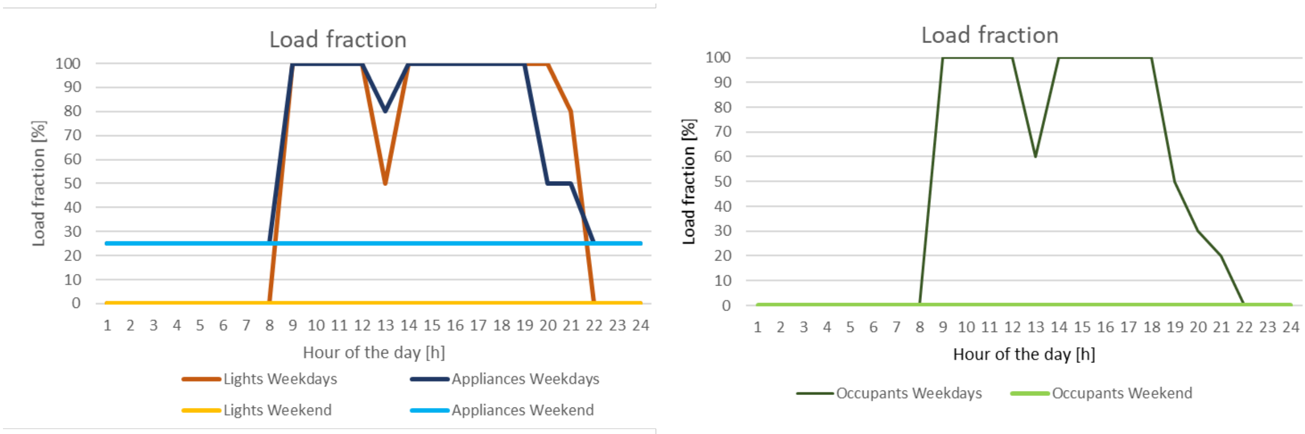


Figure 12: Load fraction for occupants, lighting, and electric appliances according to EN 18523-1 [102] *for office use*

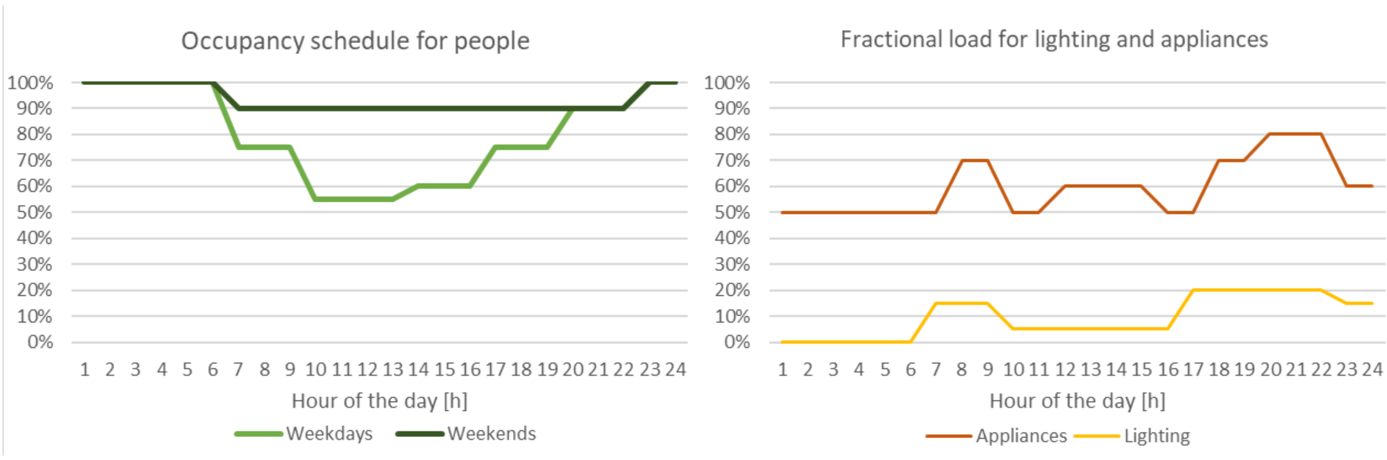


Figure 13: Fractional load schedule for occupants, lighting, and appliances for residential use

5. Possible applications

The prototypes can be used in detailed large-scale energy models, easing the simulations of groups of buildings. Among numerous purposes, these models help in the evaluation of the effectiveness of energy conservation measures, energy policies and incentives, the definition of priority lists of intervention on the building stock on a technical base, scenarios assessment for district plants (e.g., district heating, district cooling, storage), building operational management, assessment of solar photovoltaic potential, and analysis of urban microclimate.

In particular, several bottom-up physics-based UBEM tools were developed in recent years [8]. Among the main ones, CityBES [103], umi [104], and URBANopt [105] make use of EnergyPlus [106] and/or OpenStudio [107], and they can simulate the energy performance of building stocks [10]. The tools usually provide a manual upload of the geometry that is combined with default prototypes for its characterization. This task remains a challenge for most case studies. Then, thanks to the developed building typology, through attributes (e.g., construction year, building typology), a full set of building characteristics is assigned to the specific geometry. These prototype buildings, created from the information presented in the previous paragraphs, are fully characterized EnergyPlus models that include internal zoning, window-to-wall ratio, loads and occupancy schedules, and all the other necessary characteristics except the constructions and systems. In particular, construction is intended as roofs, external walls, external floors, internal ceilings, internal horizontal and vertical partitions, interior furnishings, and windows. Each material is characterized by its thickness, thermal conductivity, density, specific heat, thermal absorptance, solar absorptance, and visible absorptance. Then the materials are combined in constructions, finally organized in technologies. The systems settings include the setpoint temperature and humidity, internal loads (e.g., gas and electric equipment, internal lightings, water use, occupancy, infiltration, air changes), external lightings, elevators, daylight controls, energy costs, and type and efficiency of the hot water systems and HVAC systems. Once all the buildings are fully characterized, the simulation can run. At the current state, the three tools' prototypes are developed based on the DOE commercial reference buildings [53,108]. These default characterizations are helpful for U.S. case studies. Moreover, when no data are available, they are a resourceful option to assess preliminary results for cities in other contexts. However, for urban areas with a historical and technical history different from that of the United States (e.g., Italy), the default characterization could result in large mismatches between the modeled and the real buildings, particularly for envelope and systems technologies. Thus, the developed prototypes are suitable for the application of CityBES to Italian case studies representing the characteristics of Italian construction technologies and typical HVAC applications.

Finally, the development of building prototypes for Italy can provide reference building models able to describe the majority of the building stock. This supports the development of building energy codes and standards by providing an energy benchmarking of the stock and a standardized detailed inventory of the urban, regional, and national stock.

6. Conclusions and future outlook

Archetypes and prototypes are a useful medium to characterize UBEM. They are exploited to apply some features to similar buildings, without prior specific knowledge about the properties of each building included in the energy model. For the Italian context, some archetypes already exist. However, their characterization may not be thorough enough to describe the building stock for detailed UBEM.

A final number of 10 classes, according to the period of construction, have been developed for the prototypes of residential buildings located within Italian climatic zone E (which counts for 52% of the Italian municipalities), and 8 corresponding classes were defined for office buildings. Considering both single-family and multi-family buildings, traditional and prefabricated structures, 32 prototypes are related to residential use and 14 are related to offices.

The work to create these prototypes highlighted some strong limitations of the data available in the Italian context. In particular, very few data are available for other climatic zones and other building typologies (e.g., malls, hospitals). Moreover, the developed prototypes are still limited in number and typology, thus, the differences that are present in a real city are lost. In UBEM, this is not an issue when the results are aggregated spatially and temporally. On the contrary, for applications in which the spatial/temporal description should be considered, more detailed prototypes, regarding the building fabric and technical systems, could be integrated with more spatial diversities within the subareas of the city. The dynamic analysis developed for multiple years, which considers the time passing and its influence on the buildings' performance (such as the efficiency decrease of the systems and the building fabric) requires a parametric prototype that could be implemented when the time span of the simulation is long. Moreover, the diversity in terms of occupant behavior among buildings of the same occupancy type should be taken into account to obtain realistic energy demand patterns and the impacts of behavioral changes over time on building energy demand.

The development of these prototypes will be useful for multiple applications. They can be directly used as a baseline to develop Italian case studies with various UBEM tools, since they provide reference information when specific data are not available. The prototypes can also be used as a reference database for research investigations on the Italian building stock, as they are representative of single-family and multi-family buildings for residential applications, and office buildings for those residential units that were converted in urban city centers. The application of the models developed and the collected data will be fundamental to support energy efficiency policies and strategies at a wider level, meeting the strict requirements of European directives.

This future achievement will be possible only with a more integrated and collaborative approach to data gathering and integration. In response to the current situation of dispersing and separated databases, an integrated approach could be managed by the municipalities, in which geometry, cadastral data, technological characteristics, and eventual smart meter readings are integrated into a single database. In addition, for future projects, Building Information Modeling (BIM) could be added, as this approach is mandatory in Italy since 2019 for projects with a budget over 100 million euros.

The gathering of such data could be helpful to create a full set of prototype reference buildings, similar to that developed for the DOE commercial reference buildings [108]. This study could be extended to the whole Italian context, including all the climatic zones and all the main building typologies, being widely replicable and accessible, considering that the information sources are national and international standards and existing databases. The parametric input of geometry is an innovative solution to develop more flexible prototypes and archetypes.

Acknowledgments

The authors would like to thank their universities, namely the University of Padova, Polytechnic University of Milan, Free University of Bozen-Bolzano, and Università IUAV di Venezia for the opportunity granted by making this collaboration possible. This study is possible from a collaboration between these institutions and Lawrence Berkeley National Laboratory and shows the far-reaching results coming from teamwork and international collaborations.

References

[1] United Nations, World Urbanization Prospects - Population Division - United Nations, (2018).
[2] D. Reckien, M. Salvia, O. Heidrich, J.M. Church, F. Pietrapertosa, S. De Gregorio-Hurtado, V. D'Alonzo, A. Foley, S.G. Simoes, E. Krkoška Lorencová, H. Orru, K. Orru, A. Wejs, J. Flacke, M. Olazabal, D. Geneletti, E. Feliu, S. Vasilie, C. Nador, A. Krook-Riekkola, M. Matosović, P.A. Fokaides, B.I. Ioannou, A. Flamos, N.A. Spyridaki, M. V. Balzan, O. Fülöp, I. Paspaldzhiev, S. Grafakos, R. Dawson, How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28, J. Clean. Prod. 191 (2018) 207–219. https://doi.org/10.1016/j.jclepro.2018.03.220.
[3] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: Approaches, challenges and opportunities, Renew. Sustain. Energy Rev. 16 (2012) 3847–3866. https://doi.org/10.1016/j.rser.2012.02.047.
[4] F. Causone, A. Sangalli, L. Pagliano, S. Carlucci, Assessing energy performance of smart cities, Build. Serv. Eng. Res. Technol. 39 (2018) 99–116. https://doi.org/10.1177/0143624417725220.
[5] F. Causone, S. Carlucci, M. Ferrando, A. Marchenko, S. Erba, A data-driven procedure to model occupancy and occupant-related electric load profiles in residential buildings for energy simulation, Energy Build. 202 (2019) 109342. https://doi.org/10.1016/J.ENBUILD.2019.109342.
[6] S. Carlucci, M. De Simone, S.K. Firth, M.B. Kjærgaard, R. Markovic, M.S. Rahaman, M.K. Annaqeeb, S. Biandrate, A. Das, J.W. Dziedzic, G. Fajilla, M. Favero, M. Ferrando, J. Hahn, M. Han, Y. Peng, F. Salim, A. Schlüter, C. van Treeck, Modeling occupant behavior in buildings, Build. Environ. 174 (2020) 106768. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.106768.
[7] T. Hong, M. Ferrando, X. Luo, F. Causone, Modeling and Analysis of Heat Emissions from Buildings to Ambient Air, Appl. Energy. (2020).
[8] M. Ferrando, F. Causone, An overview of urban building energy modelling (UBEM) tools, in: Proc. BS2019, Rome, 2019.
[9] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: A review of modeling techniques, Renew. Sustain. Energy Rev. 13 (2009) 1819–1835. https://doi.org/10.1016/j.rser.2008.09.033.
[10] T. Hong, Y. Chen, S.H. Lee, M.A. Piette, CityBES : A Web-based Platform to Support City-Scale Building Energy Efficiency, Urban Comput. (2016). https://doi.org/http://dx.doi.org/10.1145/12345.67890.
[11] M. Ferrando, F. Causone, T. Hong, Y. Chen, Urban building energy modeling (UBEM) tools: A state-of-the-art review of bottom-up physics-based approaches, Sustain. Cities Soc. 62 (2020) 102408. https://doi.org/10.1016/j.scs.2020.102408.
[12] J.A. Fonseca, A. Schlueter, Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts, Appl. Energy. 142 (2015) 247–265.

https://doi.org/10.1016/j.apenergy.2014.12.068.
[13] A. Zarrella, E. Prataviera, P. Romano, L. Carnieletto, J. Vivian, Analysis and application of a lumped-capacitance model for urban building energy modelling, Sustain. Cities Soc. In Press (2020). https://doi.org/http://dx.doi.org/10.1016/j.scs.2020.102450.
[14] C.F. Reinhart, C. Cerezo Davila, Urban building energy modeling - A review of a nascent field, Build. Environ. 97 (2016) 196–202. https://doi.org/10.1016/j.buildenv.2015.12.001.
[15] É. Mata, A. Sasic Kalagasidis, F. Johnsson, Building-stock aggregation through archetype buildings: France, Germany, Spain and the UK, Build. Environ. 81 (2014) 270–282. https://doi.org/10.1016/j.buildenv.2014.06.013.
[16] A. Pasquinelli, G. Agugiaro, Gavardo 3D: un esempio di modellazione integrata di dati secondo CityGML (e la sua estensione Energy ADE), in: ASITA, Salerno, 2017: pp. 837–844.
[17] T. Dogan, C. Reinhart, Shoeboxer: An algorithm for abstracted rapid multi-zone urban building energy model generation and simulation, Energy Build. 140 (2017) 140–153. https://doi.org/10.1016/j.enbuild.2017.01.030.
[18] A. Koukofikis, An Integration of Urban Spatial Data with Energy Simulation to Produce X3D City Models : The case of Landkreis Ludwigsburg, Web3D '15 Proc. 20th Int. Conf. 3D Web Technol. (2015) 101–105. https://doi.org/10.1145/2775292.2775325.
[19] G. Agugiaro, J. Benner, P. Cipriano, R. Nouvel, The Energy Application Domain Extension for CityGML: enhancing interoperability for urban energy simulations, Open Geospatial Data, Softw. Stand. 3 (2018) 2. https://doi.org/10.1186/s40965-018-0042-y.
[20] C. Ahern, B. Norton, A generalisable bottom-up methodology for deriving a residential stock model from large empirical databases, Energy Build. 215 (2020) 109886. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.109886.
[21] I. De Jaeger, A. Vandermeulen, B. van der Heijde, L. Helsen, D. Saelens, Aggregating set-point temperature profiles for archetype-based: simulations of the space heat demand within residential districts, J. Build. Perform. Simul. 13 (2020) 285–300. https://doi.org/10.1080/19401493.2020.1727567.
[22] I. De Jaeger, G. Reynders, C. Callebaut, D. Saelens, A building clustering approach for urban energy simulations, Energy Build. 208 (2020) 109671. https://doi.org/https://doi.org/10.1016/j.enbuild.2019.109671.
[23] C. Molina, M. Kent, I. Hall, B. Jones, A data analysis of the Chilean housing stock and the development of modelling archetypes, Energy Build. 206 (2020) 109568. https://doi.org/https://doi.org/10.1016/j.enbuild.2019.109568.
[24] A. Beck, G. Long, D.S. Boyd, J.F. Rosser, J. Morley, R. Duffield, M. Sanderson, D. Robinson, Automated classification metrics for energy modelling of residential buildings in the UK with open algorithms, Environ. Plan. B Urban Anal. City Sci. 47 (2020) 45–64. https://doi.org/10.1177/2399808318762436.
[25] U. Ali, M.H. Shamsi, C. Hoare, E. Mangina, J. O'Donnell, A data-driven approach for multi-scale building archetypes development, Energy Build. 202 (2019) 109364. https://doi.org/https://doi.org/10.1016/j.enbuild.2019.109364.
[26] G. Buttitta, W.J.N. Turner, O. Neu, D.P. Finn, Development of occupancy-integrated archetypes: Use of data mining clustering techniques to embed occupant behaviour profiles in archetypes, Energy Build. 198 (2019) 84–99. https://doi.org/https://doi.org/10.1016/j.enbuild.2019.05.056.
[27] O. Pasichnyi, J. Wallin, O. Kordas, Data-driven building archetypes for urban building energy modelling, Energy. 181 (2019) 360–377. https://doi.org/https://doi.org/10.1016/j.energy.2019.04.197.
[28] C.Y. Yi, C. Peng, An archetype-in-neighbourhood framework for modelling cooling energy demand of a city's housing stock, Energy Build. 196 (2019) 30–45. https://doi.org/https://doi.org/10.1016/j.enbuild.2019.05.015.
[29] K.N. Streicher, P. Padey, D. Parra, M.C. Bürer, S. Schneider, M.K. Patel, Analysis of space heating demand in the Swiss residential building stock: Element-based bottom-up model of archetype buildings, Energy Build. 184 (2019) 300–322. https://doi.org/https://doi.org/10.1016/j.enbuild.2018.12.011.
[30] A. Wang, R. Li, S. You, Development of a data driven approach to explore the energy flexibility potential of building clusters, Appl. Energy. 232 (2018) 89–100. https://doi.org/https://doi.org/10.1016/j.apenergy.2018.09.187.
[31] M. Lavagna, C. Baldassarri, A. Campioli, S. Giorgi, A. Dalla Valle, V. Castellani, S. Sala, Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock, Build. Environ. 145 (2018) 260–275. https://doi.org/https://doi.org/10.1016/j.buildenv.2018.09.008.
[32] M.H. Kristensen, R.E. Hedegaard, S. Petersen, Hierarchical calibration of archetypes for urban building energy modeling, Energy Build. 175 (2018) 219–234. https://doi.org/https://doi.org/10.1016/j.enbuild.2018.07.030.
[33] C. Nägeli, C. Camarasa, M. Jakob, G. Catenazzi, Y. Ostermeyer, Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks, Energy Build. 173 (2018) 443–460. https://doi.org/https://doi.org/10.1016/j.enbuild.2018.05.055.
[34] X. Li, R. Yao, M. Liu, V. Costanzo, W. Yu, W. Wang, A. Short, B. Li, Developing urban residential reference buildings using clustering analysis of satellite images, Energy Build. 169 (2018) 417–429. https://doi.org/https://doi.org/10.1016/j.enbuild.2018.03.064.
[35] J. Urquizo, C. Calderón, P. James, Understanding the complexities of domestic energy reductions in cities: Integrating data sets generally available in the United Kingdom's local authorities, Cities. 74 (2018) 292–309. https://doi.org/https://doi.org/10.1016/j.cities.2017.12.019.

[36] C. Cerezo Davila, J. Sokol, S. AlKhaled, C.F. Reinhart, A. Al-Mumin, A. Hajiah, C. Cerezo, J. Sokol, S. AlKhaled, C.F. Reinhart, A. Al-Mumin, A. Hajiah, Comparison of four building archetype characterization methods in urban building energy modeling (UBEM): A residential case study in Kuwait City, Energy Build. 154 (2017) 321–334. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.08.029.
[37] N. Tornay, R. Schoetter, M. Bonhomme, S. Faraut, V. Masson, GENIUS: A methodology to define a detailed description of buildings for urban climate and building energy consumption simulations, Urban Clim. 20 (2017) 75–93. https://doi.org/https://doi.org/10.1016/j.uclim.2017.03.002.
[38] J. Pittam, P.D. O'Sullivan, G. O'Sullivan, An Archetype Based Building Stock Aggregation Methodology Using a Remote Survey Technique BT - Smart Energy Control Systems for Sustainable Buildings, in: J. Littlewood, C. Spataru, R.J. Howlett, L.C. Jain (Eds.), Springer International Publishing, Cham, 2017: pp. 89–115.
[39] C.S. Monteiro, A. Pina, C. Cerezo, C. Reinhart, P. Ferrão, The Use of Multi-detail Building Archetypes in Urban Energy Modelling, Energy Procedia. 111 (2017) 817–825. https://doi.org/https://doi.org/10.1016/j.egypro.2017.03.244.
[40] J. Sokol, C. Cerezo Davila, C.F. Reinhart, Validation of a Bayesian-based method for defining residential archetypes in urban building energy models, Energy Build. 134 (2017) 11–24. https://doi.org/https://doi.org/10.1016/j.enbuild.2016.10.050.
[41] T. Loga, B. Stein, N. Diefenbach, TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable, Energy Build. 132 (2016) 4–12. https://doi.org/https://doi.org/10.1016/j.enbuild.2016.06.094.
[42] F. Berg, E. Genova, T. Rroström, Interdisciplinary building categorization - A method to support sustainable energy efficiency strategies in historic districts, in: CESB 2016 - Cent. Eur. Towar. Sustain. Build. 2016 Innov. Sustain. Futur., 2016: pp. 41–48.
[43] C. Cerezo, J. Sokol, C. Reinhart, A. Al-Mumin, Three methods for characterizing building archetypes in urban energy simulation. A case study in Kuwait City, in: 14th Int. Conf. IBPSA - Build. Simul. 2015, BS 2015, Conf. Proc., 2015: pp. 2873–2880.
[44] I. Ballarini, S.P. Corgnati, V. Corrado, Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project, Energy Policy. 68 (2014) 273–284. https://doi.org/10.1016/j.enpol.2014.01.027.
[45] J. Pittam, P.D. O'Sullivan, G. O'Sullivan, Stock aggregation model and virtual archetype for large scale retrofit modelling of local authority housing in Ireland, in: Energy Procedia, Elsevier B.V., 2014: pp. 704–713. https://doi.org/10.1016/j.egypro.2014.12.434.
[46] J. Kragh, K.B. Wittchen, Development of two Danish building typologies for residential buildings, Energy Build. 68 (2014) 79–86. https://doi.org/https://doi.org/10.1016/j.enbuild.2013.04.028.
[47] T. Vimmr, T. Loga, N. Diefenbach, B. Stein, L. Bachová, Tabula-residential building typologies in 12 European countries-good practice example from the Czech Republic, in: CESB 2013 PRAGUE - Cent. Eur. Towar. Sustain. Build. 2013 Sustain. Build. Refurb. Next Gener., 2013: pp. 813–816.
[48] A.A. Famuyibo, A. Duffy, P. Strachan, Developing archetypes for domestic dwellings—An Irish case study, Energy Build. 50 (2012) 150–157. https://doi.org/https://doi.org/10.1016/j.enbuild.2012.03.033.
[49] I. Ballarini, S.P. Corgnati, V. Corrado, N. Talà, Improving energy modeling of large building stock through the development of archetype buildings, in: Proc. Build. Simul. 2011 12th Conf. Int. Build. Perform. Simul. Assoc., 2011: pp. 2874–2881.
[50] E.G. Dascalaki, K.G. Droutsa, C.A. Balaras, S. Kontoyiannidis, Building typologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock, Energy Build. 43 (2011) 3400–3409. https://doi.org/https://doi.org/10.1016/j.enbuild.2011.09.002.
[51] E. Fabrizio, D. Guglielmino, V. Monetti, Italian benchmark building models: The office building, in: Proc. Build. Simul. 2011 12th Conf. Int. Build. Perform. Simul. Assoc., 2011: pp. 1981–1988.
[52] T.R. Tooke, M. vanderLaan, N. Coops, A. Christen, R. Kellett, Classification of residential building architectural typologies using LiDAR, in: 2011 Jt. Urban Remote Sens. Event, 2011: pp. 221–224. https://doi.org/10.1109/JURSE.2011.5764760.
[53] M. Deru, K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, R. Michael, M. Yazdanian, J. Huang, D. Crawley, U. S. Department of Energy - Commercial Reference Building Models of the National Building Stock, Golden, Colorado, 2011.
[54] G. Agugiaro, Energy planning tools and CityGML-based 3D virtual city models: experiences from Trento (Italy), Appl. Geomatics. 8 (2016) 41–56. https://doi.org/10.1007/s12518-015-0163-2.
[55] V. Corrado, Welcome at TABULA, (2010). https://episcope.eu/iee-project/tabula/ (accessed June 17, 2020).
[56] The European Parliament and the Council of the European Union, Directive 2002/91/EC on the energy performance of buildings of the 16 December 2005, Brussels, Belgium, 2005.
[57] UNI Ente Nazionale Italiano di Unificazione, UNI/TS 11300, Milano, Italy, 2008.
[58] UNI Ente Nazionale Italiano di Unificazione, UNI/TS 11300 - Part 1: Evaluation of energy need for space heating and cooling, (2014).
[59] Il Presidente della Repubblica, Italian legislative decree n.412/1993, Gazz. Uff. 26 Agosto 1993. (1993).
[60] UNI Ente Nazionale Italiano di Unificazione, UNI/TS 11300-1 Part 1: Evaluation of energy need for space heating

and cooling, (2008).
[61] UNI Ente Nazionale Italiano di Unificazione, UNI/TS 11300 - Part 2: Evaluation of primary energy need and of system efficiencies for space heating and domestic hot water production, (2008).
[62] UNI Ente Nazionale Italiano di Unificazione, UNI/TS 11300 - Part 3: Evaluation of primary energy and system efficiencies for space cooling, 2010.
[63] UNI Ente Nazionale Italiano di Unificazione, UNI/TS 11300 - Part 4: Renewable energy and other generation systems for space heating and domestic hot water production, 2014.
[64] IEE Project TABULA, (n.d.). https://episcope.eu/iee-project/tabula/ (accessed June 17, 2020).
[65] Typology Approach for Building Stock Energy Assessment - Intelligent Energy Europe - European Commission, (n.d.). https://ec.europa.eu/energy/intelligent/projects/en/projects/tabula (accessed June 15, 2020).
[66] UNI Ente Nazionale Italiano di Unificazione, UNI/TR 11552: Abaco delle strutture costituenti l'involucro opaco degli edifici - Parametri termofisici, Milano, Italy, 2014.
[67] Presidente della Repubblica Italiana, LEGGE 9 gennaio 1991, n. 10: Norme per l'attuazione del Piano energetico nazionale in materia di uso razionale dell'energia, di risparmio energetico e di sviluppo delle fonti rinnovabili di energia, Rome, Italy, 1991.
[68] Intelligent Energy Europe, Collecting DATA from Energy Certification to Monitor Performance Indicators Basics of the DATAMINE Project, (2009).
[69] Intelligent Energy Europe, Typology Approach for Building Stock Energy, (2012).
[70] Intelligent Energy Europe, Monitor Progress Towards Climate Targets in European Housing Stocks Main Results of the EPISCOPE Project - Final Project Report, 2016. http://episcope.eu/monitoring/overview/.
[71] Overview, (n.d.). https://episcope.eu/monitoring/overview/ (accessed June 23, 2020).
[72] IEE Project EPISCOPE, (n.d.). https://episcope.eu/iee-project/episcope/ (accessed June 23, 2020).
[73] European Commission, Typology Approach for Building Stock Energy, (2012).
[74] Typology Approach for Building Stock Energy Assessment - Intelligent Energy Europe - European Commission, (n.d.).
[75] V. Corrado, I. Ballarini, S.P. Corgnati, Building Typology Brochure – Italy. Fascicolo sulla Tipologia Edilizia Italiana., 2016.
[76] V. Corrado, I. Ballarini, S.P. Corgnati, Typology Approach for Building Stock: National scientific report on the TABULA activities in Italy, 2012.
[77] ENEA, Piano d'Azione Italiano per l'Efficienza Energetica - ALLEGATO 1 - Riqualificazione energetica del parco edilizio nazionale, (2017) 1–21. https://ec.europa.eu/energy/sites/ener/files/documents/it_building_renov_2017_annex_1_neeap_it.pdf.
[78] V. Corrado, I. Ballarini, Processes in European Housing Stocks - L ' avanzamento della riqualificazione energetica del patrimonio edilizio residenziale regionale (Regione Piemonte , IT) Report nazionale / Versione finale, 2016.
[79] IT Italy - Scenario Results and Monitoring Approaches, (n.d.). https://episcope.eu/monitoring/case-studies/it-italy/ (accessed June 17, 2020).
[80] Agenzia delle Entrate, (n.d.). https://www.agenziaentrate.gov.it/portale/servizi (accessed June 23, 2020).
[81] G. Dall'o', A. Galante, M. Torri, A methodology for the energy performance classification of residential building stock on an urban scale, Energy Build. 48 (2012) 211–219. https://doi.org/10.1016/j.enbuild.2012.01.034.
[82] L. Filogamo, G. Peri, G. Rizzo, A. Giaccone, On the classification of large residential buildings stocks by sample typologies for energy planning purposes, Appl. Energy. 135 (2014) 825–835. https://doi.org/10.1016/j.apenergy.2014.04.002.
[83] M. Caldera, S.P. Corgnati, M. Filippi, Energy demand for space heating through a statistical approach: application to residential buildings, Energy Build. 40 (2008) 1972–1983. https://doi.org/10.1016/j.enbuild.2008.05.005.
[84] G.V. Fracastoro, M. Serraino, A methodology for assessing the energy performance of large scale building stocks and possible applications, Energy Build. 43 (2011) 844–852. https://doi.org/10.1016/j.enbuild.2010.12.004.
[85] Energy Conservation in Buildings and Community Systems, EBC Annex 31 Stock Aggregation Background Report: Stock Aggregation - Methods for Evaluation the Environmental Performance of Building Stocks, 2004.
[86] Presidente della Repubblica Italiana, Legge dello Stato 30/04/1976 n. 373: Norme per il contenimento del consumo energetico per usi termici negli edifici, Rome, Italy, 1976.
[87] Decreto Legislativo 19 agosto 2005, n. 192 - Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia, 2005.
[88] The European Parliament and the Council of the European Union, Directive 2010/31/EU of 19 May 2010 on the energy performance of buildings, Brussels, Belgium, 2010.
[89] Presidente della Repubblica Italiana, Legge 90/2013: Disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazione energetica nell'edilizia per la definizione delle procedure d'infrazione avviate dalla Commissio, Rome, Italy, 2013.
[90] Presidente della Repubblica Italiana, Decreto interministeriale 26 giugno 2015 - Adeguamento linee guida nazionali per la certificazione energetica degli edifici, Rome, Italy, 2015.
[91] Presidente della Repubblica Italiana, Decreto interministeriale 26 giugno 2015 - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici, Rome,

Italy, 2015.
[92] Regione Lombardia - Infrastrutture Lombarde S.p.A., CURIT - Catasto Impianti Termici Lombardia, (n.d.). http://www.curit.it/ (accessed May 15, 2020).
[93] European Committee for Standardization-CEN, BS EN 15193: Energy performance of buildings — Energy requirements for lighting - Part 2: Explanation and justification of EN 15193-1, Module M9, Brussels, Belgium, 2017.
[94] General Electric, GE Halogen Lamps, (n.d.). https://products.gecurrent.com/document-library (accessed June 15, 2020).
[95] Philips, LED Bulbs, (n.d.). https://www.lighting.philips.com/main/prof/led-lamps-and-tubes/led-bulbs#pfpath=0-LED_GR (accessed June 15, 2020).
[96] European Committee for Standardization-CEN, BS EN 16798 - Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acousti, Brussels, Belgium, 2019.
[97] U. Ente di Normazione Italiano, UNI 10380: Illuminotecnica. Illuminazione di interni con luce artificiale., Rome, Italy, 1994.
[98] European Committee for Standardization - CEN, EN 12464 - Light and lighting - Lighting of work places - Part 1: Indoor work places, Brussels, Belgium, 2004.
[99] European Committee for Standardization-CEN, BS EN 15251 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, Brussels, Belgium, 2007.
[100] Comitato Termotecnico Italiano - CTI, UNI 10339 - Air conditioning systems for thermal comfort in buildings - General, classification and requirements - Offer, order and supply specifications, Rome, Italy, 1995.
[101] Ministero della Sanità, Decreto ministeriale Sanità 5 luglio 1975 - Modificazioni alle istruzioni ministeriali 20 giugno 1896, relativamente all'altezza minima ed ai requisiti igienico-sanitari principali dei locali di abitazione, Rome, Italy, 1975.
[102] International Standard Organisation - ISO, ISO 18523-1:2016 Energy performance of buildings — Schedule and condition of building, zone and space usage for energy calculation, 2016.
[103] T. Hong, Y. Chen, M.A. Piette, X. Luo, CityBES, (2017). https://citybes.lbl.gov/ (accessed June 20, 2020).
[104] C.F. Reinhart, T. Dogan, A.J. Jakubiec, T. Rakha, A. Sang, Umi - an Urban Simulation Environment for Building Energy Use , Daylighting and Walkability, Proc. BS2013. (2013) 476–483. https://doi.org/10.1016/bs.pbr.2015.01.004.
[105] B. Polly, C. Kutscher, D. Macumber, M. Schott, From Zero Energy Buildings to Zero Energy Districts, in: 2016 ACEEE Summer Study Energy Effic. Build., 2016: pp. 1–16.
[106] U.S. Department of Energy's, EnergyPlus, (2018). https://energyplus.net/ (accessed June 20, 2020).
[107] O. of E.E. and R.E. National Laboratory of the U.S. Department of Energy, OpenStudio | OpenStudio, (2018). https://www.openstudio.net/ (accessed June 20, 2020).
[108] U.S. Department of Energy, Commercial Reference Buildings, (n.d.). https://www.energy.gov/eere/buildings/commercial-reference-buildings (accessed June 17, 2020).