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Modeling Boston: A workflow for the generation of complete urban building energy demand models from existing urban geospatial datasets

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Modeling Boston: A workflow for the generation of complete urban building energy demand models from existing urban geospatial datasets

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0 Abstract:

City governments and their partners are increasingly focusing on the development of urban energy efficiency strategies for buildings as a key component to meet policy-driven carbon reduction targets. Similarly, energy utilities and suppliers need to develop long term supply strategies that are cost efficient and resilient against natural and manmade interferences. To support these diverse needs, a new generation of urban building energy models (UBEM) is currently being developed for the estimation of citywide hourly energy demand loads down to the individual building level. However, for cities to apply them, effective modeling workflows adapted to their current urban data structures need to be provided. Within this context, the authors collaborated with the Boston Redevelopment Authority (BRA) and local building experts to develop a citywide UBEM based on the official GIS dataset of the city. The vision for this work was to produce a long term policy support tool that the city could regularly update going forward, and that provides actionable information for local communities to evaluate energy related decisions. The Boston model's scale (92,000 buildings), its integration with the city's actively maintained GIS datasets as well as the effort level required to maintain the model going forward demonstrate that the approach followed in this paper can be adopted across the US and worldwide wherever such data sets are available.

The geometric input for Boston's UBEM tool was extracted from GIS shapefiles, and a total of 76 different building archetypes were then assigned to individual buildings based on land use and building age. Most data manipulation and thermal model generation processes were conducted within the Rhinoceros 3D CAD environment. Individual building models were run using the US Department of Energy's EnergyPlus energy simulation program. Simulation results were cross checked against reported average energy use from the US Commercial Building Energy Consumption Survey 2003 (CBECS). Select citywide simulation results are presented, including a district intervention study for a combination of photovoltaics and demand side management technologies, demonstrating the ability of the UBEM to estimate the impact of such technologies on neighborhood hourly electricity loads. The manuscript closes with a discussion of a number of technical and logistical barriers that the authors encountered while building the UBEM as well as proposals of how to resolve these barriers going forward.

1 Introduction

In response to current global environmental challenges, city governments worldwide have developed ambitious long term greenhouse gas (GHG) emission reduction targets such as 40% and 60% by 2025 (San Francisco and London) or 80% by 2050 in New York City (NY 2014). The city of Boston is no exception and has set emission reduction goals of 25% by 2020 and 80% by 2050 as part of the Greenovate Climate Action Plan Update (Boston 2014). According to this plan, Boston's commercial, residential and transportation sectors account for approximately 50%, 25% and 25% of the city's GHG emissions, highlighting the need for Boston to focus on buildings and their energy supply infrastructure. Indeed, the plan mentions a plethora of building related measures from energy audits and retrofits to the accelerated deployment of renewable energy, district heating and cooling, as well as combined heat and power systems to be applied at the neighborhood and district scales. To initiate and coordinate such a wide range of measures not only requires substantial political consensus and innovative financing mechanisms, but also an intimate technical understanding of how the city's energy ecosystem may change over time as a result of these methods. For example, as solar photovoltaic gets increasingly deployed across the city, the electricity load curve of a typical summer day will change, and with it the economics of auxiliary power plants. To gain an understanding of such interrelated phenomena, the BRA and its stakeholders require planning tools that provide spatially and temporally resolved energy demands data for all buildings, and that facilitate the evaluation of "what if" scenarios to prioritize alternative interventions. Furthermore, such tools need to be based on actively maintained urban databases and practices so they can be effectively implemented. The Boston Community Energy Study (BCES) developed for the city of Boston by the MIT Sustainable Design Lab (SDL), MIT Lincoln Laboratory, and the Boston Redevelopment Authority (BRA), addresses these requirements by introducing a demand/supply model for the city.

This manuscript describes the process followed by the authors in the generation of the first citywide urban building energy model (UBEM) within a municipal department, comprising more than 85,000 buildings. An automated workflow for the generation and simulation of UBEM from a basic set of geospatial datasets used by US municipalities is proposed and applied, using the currently maintained GIS database from Boston as a case study. The specific goals of this work were to gage the effort level required to set up, run and analyze results from such a large urban model, as well as to translate simulation results into actionable information for city officials and their partners. In a complementary effort, energy demand results resulting from Boston's UBEM were then used by MIT Lincoln Laboratory to develop a series of micro-grid scenarios for various parts of the city (MIT Lincoln Lab 2015). Following a review of the evolving field of urban energy modeling in Section 2, a detailed description of the generation method for the Boston model is provided in Section 3 along with an example intervention study for an district in Boston. The study demonstrates the ability of the Boston model to estimate the impact of neighborhood-level hourly electricity loads if photovoltaics are combined with centrally controlled thermostats. Simulation results are analyzed in Section 4 and the manuscript closes with a discussion of a number of technical and logistical barriers found in the process as well as potential approaches of how to resolve these barriers going forward in Section 5.

2 Urban energy modeling

To meet the need of Boston and city governments worldwide to understand spatiotemporal energy demand patterns due to buildings, different types of urban models have been proposed over time, which fall in two main categories: "top-down" or "bottom-up" models. Traditional "top-down" building stock models link building energy use to macroeconomic variables such a population trends and economic activity, and mainly serve the purpose of predicting near future energy use extrapolating from the status quo (Howard et al 2012). They are therefore limited when exploring new technologies and they are not adequate for analyzing interventions where demands need to be characterized at the scale of the building. "Bottom up" models are based on individual building data processed statistically, analytically or both. Statistical methods link high level building descriptors such as vintage, usage type and occupancy to measured building energy use via linear regression models (Kolter and Ferreira 2011). Statistical models are "robust" since they are based on measured building data and thus able to accurately incorporate occupant behavior, which is notoriously difficult to accomplish in analytical models (Wilke et al 2013). On the flipside, statistical models are unable to predict energy use in hourly time steps or to simulate the combined impact of several energy efficiency measures in buildings. In order to address these two shortcomings of statistical models, a new type of bottom up models called Urban Building Energy Models (UBEM) has been recently introduced (Reinhart and Cerezo 2015). UBEMs apply simulation methods to represent individual buildings as dynamic thermal models, based on the same heat transfer equations and principles that govern individual building energy models (BEM). At the individual building level, the dynamic thermal simulation of BEM is already widely used for the design of high performance buildings (IBPSA 2011), code compliance, and certification for building rating systems such as LEED (USGBC 2015) in the US and BREEAM (BREEAM, 2015) in the UK. Being based on the same modeling of physical phenomena, an UBEM – calibrated against measured energy data – can support arbitrarily complex scenario development, including the combination of new technologies and modified occupant behavior. In order to further understand the impact of hourly load profiles on different energy supply systems, UBEMs can further be combined with dedicated energy supply simulation modules (Allegrini et al 2015, Fonseca and Schlueter 2015).

What are the steps required to build an UBEM model? In the process of building a BEM an energy modeler needs to use available design information to characterize both the envelope geometry and the non-geometric properties of a building (Constructions, systems, schedules, etc.), as well as the microclimatic conditions that surround it. This is typically a time consuming process with significant impact on the quality of the model. Based on these inputs an energy model is built and simulated. In the case of an UBEM model, this characterization becomes a significant challenge given the number and diversity of structures in the building stock and the impossibility of repeating the documentation process for every building in a city. In addition, the generation and simulation times for the resulting thousands of dynamic thermal models can become unacceptably high for its practical use. Therefore, in order to make UBEM a valid tool for real world application, a reconceptualization and automation of building energy model workflows is required. As documented in a recent review paper by the authors, a host of new workflows and methods had to be developed over the past decade to assemble and manage the enormous amount of data required to generate and ran an UBEM within a reasonable time frame (Reinhart and Cerezo 2015). Most of such methods share certain common traits, such as the modeling of individual building geometry, and the division of the building stock into "archetypes" (Sets of inputs representing a group of similar buildings) for the characterization of all non-geometric building properties. Within the process, buildings are modelled either as single (Nouvel et al 2013, Fonseca and Schlueter 2015) or multi zone (Robinson et al 2009, Reinhart et al 2013) dynamic thermal models.

More importantly however, all methods rely on the existence of complete data sources for geometrical and non-geometrical building information, which in reality are rarely available for large urban areas. In terms of building geometry data inputs, the most common data sources are Geographic Information Systems (GIS) databases or more complete 3D urban information models such as CityGML (OGC 2012). Regarding weather information, while most UBEM methods currently tend to base their analysis on citywide Typical Meteorological Years (TMY), several research groups have started to also model microclimatic phenomena around individual buildings such as local wind patterns or urban heat island effect. Finally, the systematic definition and calibration of building archetypes is the least well defined step within the process. Archetypes have been extensively used in top-down modeling of national stocks to classify building by use, age and shape (DallO, Galante, Torri 2012, Filogamo et al 2014), and characterizing them according to average properties of real buildings within that class (Ballarini, Corgnati, Corrado 2014). Similarly in UBEM workflows, once buildings have been classified, archetypes are typically applied as "templates" to the building geometry and stored in a library or a database (Cerezo, Dogan and Reinhart 2014). In a best case scenario, an archetype template library might already exist, based on a careful categorization and calibration against measured building energy data (TABULA 2012). However, in the absence of such currently rare studies, archetypes have to be classified and compiled in consultation with local experts, building codes and general building stock energy data.

The good news for a municipality interested in working with UBEM over an extended period of time is that the task of gathering data inputs for an archetype template library is generally a onetime effort which requires a limited amount of maintenance. Depending on the city however, building stocks may evolve quite rapidly as new areas get developed, and it is hence important that datasets for UBEM stay in sync with reality. Unfortunately, most municipalities have neither the level of building documentation nor the resources to develop such initial effort from scratch. It is hence necessary to provide them with UBEM workflows which are built upon the datasets that they actively maintain, and to guarantee the compatibility of results with their existing databases. Geographic Information Systems (GIS) databases have become commonplace in planning departments all over the world. In the US, a technically sophisticated city the size of Boston with a building stock of over 100,000 and an area of 124 km2, typically has a dedicated GIS department that centrally maintains a rich digital dataset of the city assets. Because of this institutional presence, city employees are familiar with GIS related tools and new plans for urban development tend to be designed in compatible environments. Typical entry fields in such databases are parcel and building footprint, as well as building height, age and use. In most jurisdictions a complementary tax assessment database further supplies building floor area, number of bedrooms, assessment value and the dates of major renovations. Given their flexibility for storing geometry and data, and the effort level that goes into maintaining these datasets (Property taxes constitute a vital revenue stream for cities) they are a natural data source for citywide UBEMs .

Given their ensuing appeal, several previous research projects have adopted GIS or extended geospatial databases as a base for UBEM modeling tools for developing neighborhood scale case studies. All of these studies were developed in somewhat exceptional situations in which complete building archetype data was either already available or was specifically developed for the project. Sehwarat and Kensek simulated a block of 27 documented office buildings in Los Angeles proposing GIS as an "Urban BIM" (Sehwarat and Kensek 2014). Fonseca and Schlueter tested a fully integrated GIS/UBEM tool in a 1392 buildings district in Zug, Switzerland, obtaining spatially and temporally specific results based on a custom heat balance model (Fonseca and Schlueter 2015). The Swiss model was linked to existing detailed databases including the demands of manufacturing processes. Based on the paper it remains in how far the authors had engaged in a formal relationship with the city of Zug for its application. Using an available, more advanced geospatial database system, Nouvel et al combined a CityGML dataset with a single zone heat balance model to predict heating energy use in buildings across neighborhoods in Germany and The Netherlands, using the SIMSTADT tool (Nouvel et al 2015). CityGML is a semantic data format that has been implemented for jurisdictions across Germany, where a fully documented national archetype library exists.

Although the use of a GIS base format is a common UBEM approach, no previous work has shown the effective implementation of a citywide UBEM modeling tool within the current practices of an active planning department for which previous archetype documentation did not exist. To achieve this, modelling workflows have to be adapted on top of the actively maintained GIS datasets of the city, and the level of detail in the model has to be adjusted to available entry fields. While working through this adoption process, the authors worked closely with the BRA, in order to not only create a complete UBEM of the city but also to identify and discuss specific challenges of its application in practice. The methodology developed in the generation of the modeling workflow for Boston is described in the following section.

3 Methodology

In order to address the goal of the BRA to generate hourly energy demand data at a building scale for the complete city of Boston, a full UBEM was developed as part of the CWES project. The methodology distinguished between three steps necessary for the construction of the model: *Model characterization, model generation and model simulation*. While common to any building energy modeling (BEM) effort, these activities become increasingly complex in the case of an urban model and the number of sources to be managed becomes larger. The following sections describe this process in detail as applied to the model of the city of Boston.

3.1 Model Characterization

The generation of a city wide UBEM requires extensive documentation of the built environment down to the scale of the individual building. This task includes the characterization of three main datasets required for the generation of dynamic thermal models: Weather information, building and context geometry, and building construction and usage data. Although in an ideal complete bottom-up UBEM each of those datasets would be defined for each building, in practice the level of definition is determined by the available data sources. In the case of the weather for example, hourly climate datasets for building performance simulation have been available for a number of years for all major cities in the US, usually in the form of the established Typical Meteorological Year (TMY) data format (Crawley, Hard, Lawry 1999). Within the urban environment however, local microclimatic phenomena such as the urban heat island effect (Bueno et al 2012) result in different conditions for each location considered. Since most municipalities are unable to maintain a network of weather stations to individually characterize TMY data by block, local microclimatic effort either have to be ignored or simulated. In the case of Boston, it has previously been shown that the variations in energy use caused by modelling the Urban Heat Island across different parts of the larger metropolitan area leads to variations in predicted energy use around 8-10% when compared with TMY3 file from Boston Logan Airport (Street et al 2013). To reduce model complexity for the citywide energy study, the authors therefore used the TMY3 file for Boston for all buildings in the city.

Building related data inputs (Geometry, constructions and usage) introduce a larger modelling challenge. The extent to which they can be defined depends on the information currently stored by municipal departments and the accessibility of their urban information systems. Traditionally, many of the building and property related datasets in a city have existed only in document format, not associated with any geographic information. However, over the past decades Geographic Information Systems (GIS) databases have become commonplace in many regions of the world, turning into the de-facto standard for urban data management, especially in the US. However, cities are less standardized in terms of the exact data that they centrally collect on all of their buildings. The workflow presented below details how variables in Boston's GIS model were mapped to the UBEM model, starting with the current database system structured around the parcels layer. For this work the 2014 version of the city's GIS dataset served as the basis for the model generation.

Data Collection and Management

As a first step, all urban datasets available digitally and related with building and property information were collected. These initial sources were obtained either in the form of GIS shapefiles, with associated attribute tables, or as simple database tables. Table 1 lists all major entry fields that were used in the project, including the exact field name and the database key field available in each case. For a definition of selected fields is provided in Appendix 1. Typical urban sources can be grouped into geographic information, including geometric features, and non-geographic information such as databases and individual tables. For Boston, geographic data included polygon type shapefiles for parcels (PRC) and building footprints (BLD), as well a point type shapefile for "lite" tax assessment records (TXP). In addition, a "full" dataset of tax records for each property for the 2014 fiscal year (TXR) was provided as a text file to complement the lite dataset. As part of TXR, look-up tables were provided associating property type use codes (PTYPE) with the use name. Other TRX entries were the associated land use code (LU) (See Appendix 2) as well as definitions for all Boston assessment codes. These datasets had to be connected so that available information could be attributed to individual buildings throughout the city. Unfortunately, no datasets for measured electricity or fuel consumption for individual buildings or urban samples were available to calibrate the model. For that reason, assumptions in terms of building geometry, constructions, and usage patterns were made according to general building stock information previously collected by the city of Boston.

Dataset (CODE)	Data Type	Unique Key	Selected Data Field	Original Field Name
Tax Parcels FY14 (PRC)	GIS Shapefile	PID_PARCEL	-	-
Building Footprints (BLD)	GIS Shapefile	None	Roof Elevation Ground Elevation Structure Type Building Land Use Code	ROOF_ELEV GRND_ELEV IEL_TYPE BRA_LAND_U
Property Tax Record Lite (TXP)	GIS Shapefile	PID	Condominium Id Parcel Id Land Use Code Property Type Code Max Number of Floors	CM_ID PID_PARCEL LU PTYPE NUM_FLOORS
Property Tax Record Full (TXR)	Database Table	PID	Year Built Year Remodeled Structure Type Residential Info Condominium Info Condo Unit Info	YEAR_BUILT YEAR_REMOD STRUCTURE (See Appendix 1) (See Appendix 1) (See Appendix 1)

In the existing Boston GIS database system the most detailed property data is defined at the scale of the parcel. Existing information is associated with a tax identification number (PID) corresponding to a point within the TXP dataset and a record in the TXR. In addition, each point is also associated with a parcel identification number (PID_PARCEL) which refers to the specific parcel and address it belongs to within PRC (Figure 1). In most cases, when there is a single property owner within the parcel, both PID and PID_PARCEL codes will match. However in the case of condominiums where multiple owners exist in a parcel, a third id number (CM_ID) is defined that matches the id of the parcel. Besides, most geometric information including building elevation, ground elevation and footprint is associated with the BLD dataset which has no common unique id with the PRC dataset. In BLD one or more polygons will be defined within each parcel each one representing either a full building or a section of a building with a single value for elevation. The lack of a unique building id in the dataset adds a level of complexity to the data management process.

Figure 1 Available Boston GIS datasets
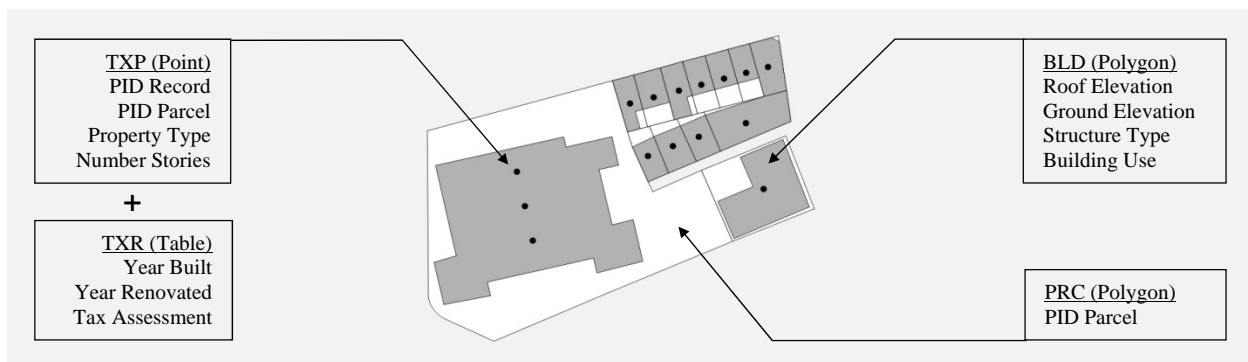
An exhaustive analysis was developed to identify missing or incomplete entries within the datasets listed in Table 1as well as to find building/parcel combinations which can sufficiently characterize individual buildings. This process required the creation of a SQL database for the management of parcel and tax information, and the association of building footprint geometries in BLD with the appropriate parcel using a spatial join between tables within the GIS tool ArcMap. The following points describe in detail all data manipulations developed as part of this analysis:

- Table data fields from TXP and TXR were joined in a common database table. Based on the established relations between PTYPE and LU codes, queries were developed by code to check for mismatches between the two fields. Wrong associations between property ids were queried and corrected for condominiums.

- All property entries were classified in three tables: Individual owner ids, unit owner ids, and main condo ids. Based on this classification all unit owner type entries were aggregated to the corresponding main condo id (CM_ID). Individual unit info fields (Unit usage, heat/cool system, number of rooms, etc.) were simplified in the aggregated entry to the most common value in the set, e.g. if 80% of registered units in a condominium had central air conditioning, the same condition was assumed for all of them. Finally, individual owner and condo main entries were combined in a refined table.
- Parcel polygons in PRC were joined with the resulting property tax records information using the PID_PARCEL. Parcels with no corresponding record were discarded. Parcels with more specialized property types such as infrastructure buildings, substations, underwater structures, etc. were also eliminated from the data set.
- Resulting parcel tax records information were joined to polygons in BLD. In order to link them, a spatial join was created using the centroid of each building polygon as a reference i.e. all centroids falling into a parcel were assigned the attributes of that parcel's record. Building polygons without a viable join were discarded.
- Once all polygons in the BLD dataset were connected with an entry of parcel tax records final queries were processed. All buildings with especial IEL_TYPE codes (Foundation, ruin, etc.) were discarded. Finally those with neither ROOF_ELEVATION data nor NUM_FLOORS data were also excluded from the set.

As a result of this process, a clean dataset of building footprints with all available parcel data was generated. The numbers of discarded records as well as the causes for their removal are presented in the results section. In the following section, the methodology for characterizing building data requirements from this dataset is presented.

Geometry Characterization

Building and context 3D geometry are required to calculate volumes, surfaces and orientations in an UBEM. At a minimum the combination of building footprints in GIS shapefiles with roof heights can be used to automatically generate 2.5D massing flat roof models suitable for energy simulation. At the time this study was developed the city of Boston had produced for representational purposes detailed boundary 3D urban models and had access to LiDAR data. However, the excess of detail of their representation and their extent limited only to certain areas rendered them inappropriate for an UBEM. For that reason a 2.5D extrusion model was chosen as the best geometry characterization strategy, based on the BLD footprint polygons. Within the available dataset two fields are related to the required extrusion height and need to be defined and consistent in each building model: Roof elevation (ROOF_ELEV) and maximum number of floors in the parcel (NUM_FLOORS). The building elevation was calculated as the difference between the roof elevation and the average ground elevation for all polygons in that parcel. Three different situations were found in the dataset: Both elevation and floor count available, or only one of the two available. In the first case an average floor height was calculated based on both data points, and checked against an acceptable of range of 2.5 to 4.5 m. For the second and third cases the missing value was estimated based on an average floor height obtained from all first case buildings.

Archetype Characterization and Validation

As mentioned above, an UBEM requires the use of "building archetypes" i.e. sets of inputs representing a group of buildings with similar properties. Archetypes generation requires two steps: In *segmentation*, the investigated building stock is divided into groups according to building age, use, shape, climate, etc. (Filogamo et al 2014) In *characterization*, a complete set of thermal properties have to be defined for the archetypes representing the previously defined groups, either by using a real sample building or an "average" virtual building based on statistical building data and/or expert opinions (Ballarini, Corgnati, Corrado 2014). The level of accuracy and flexibility of the model largely depends on this process, which itself is limited by the amount of available information for the building stock in terms both of structures data and usage data.

For the Boston model, the segmentation into archetypes was done in collaboration with Greenwich Solutions, a local building consulting group with experience in energy audit and that had previously done related work for the BRA. Working of their classification system, buildings were grouped by property use type and year of construction. The first was used to distinguish between different usage patterns, while the second was be used as a proxy to set envelope construction and systems properties. Typical form parameters such as size (Low rise, midrise, high rise) were ignored since actual building geometry was assigned based on the GIS shapefile as explained above. Additional parameters in the dataset referring to structure, material, roof shape, or type of heating fuel were only available for residential properties and could therefore not be applied for segmentation. Four construction periods were considered: Built before 1950, 1950 to 1980, 1980 to 2000, and after 2000 (Table 2A).

Table 2A Segmentation categories by period

Category code	Category name	BRA categories
1	Pre1950	YEAR_BUILT < 1950
2	1950to1980	1950 <= YEAR_BUILT < 1980
3	1980to2000	1980 <= YEAR_BUILT < 2000
4	Post2000	YEAR_BUILT >= 2000

Although a "year of renovation" entry field was available, the data was incomplete for many properties and the definition itself was ambiguous, lacking information regarding the extent of a renovation. As a consequence, only the year of construction field was considered during the assignment of archetypes which means none of the buildings underwent any specific energy retrofits since construction. This certainly far-reaching assumption will be revisited below. Regarding use types, the existing 271 codes in the datasets were grouped into 19 usage classes following recommendations from Greenwich Energy and the BRA. Tables 2A and 2B summarize the categories chosen, resulting in a total of 76 archetype definitions (See Appendix 2 for a description of BRA property types).

Table 2B Segmentation categories by use compared to CBECS categories

Category code	Category name	CBECS category	Simplified code	Simplified name
1	Residential	Residential	1	Residential
2	Retail	Retail	2	Retail
3	Office	Office	3	Office
4	School/Daycare	Education	4	School/Daycare
5	Medical/Lab	Health Care	5	Medical/Lab/Production
6	Fire/Police	Public Order Safety	6	Fire/Police
7	Convention/Assembly	Public Assembly	7	Convention/Assembly
8	Supermarket	Food Sales	8	Supermarket
9	Hotel	Lodging	9	Hotel
10	Restaurant	Food Service	10	Restaurant
11	AthleticFacility	Public Assembly	7	Convention/Assembly
12	Museum	Public Assembly	7	Convention/Assembly
13	Worship	Religious Worship	13	Worship
14	Garage	-	14	Garage
15	Warehouse/Storage	Warehouse Storage	15	Warehouse/Storage
16	Library	Public Assembly	7	Convention/Assembly
17	College/Academic	Public Assembly	7	Convention/Assembly
18	Transport	Public Assembly	7	Convention/Assembly
19	Industrial	-	5	Medical/Lab/Production

Following the definition of archetypes, non-geometric building energy modeling parameters had to be assigned for each archetype. These parameters include thermal properties of all envelope surfaces and glazing, internal peak loads for equipment and lighting use, HVAC systems settings and schedules of usage (See Table 3 for a complete list of the considered inputs). An ideal approach to set all of these parameters would be the use statistical data from the investigated building stock. In absence of such data the authors decided in correspondence with the BRA to set envelope, systems, loads and schedule properties according to Greenwich Solutions previous experience and existing energy codes (Greenwich Solutions 2015, ASHRAE 2013). Amongst those variables, those related with user behavior such as peak occupancy, equipment and lighting loads are particularly difficult to estimate especially in large commercial buildings such as laboratories or convention centers where the impact of internal loads on building energy use dominates of envelope properties. In order to verify that the resulting simulation results were

plausible, each use type was compared against measure building energy uses for that building type from the Commercial and Residential Buildings Energy Consumption Surveys (CBECS/RBECS) published by the US Energy Information Administration (USEIA 2012, USEIA 2009). The average Energy Use Intensity (EUI) by end use from these surveys was used to estimate peak values through iterative simulation of an average sized building for each archetype. This average building was modeled in isolation assuming standard core and perimeter thermal zoning per floor and simulated using EnergyPlus In the cases where the Boston archetype did not find a match in the survey, the use type was simplified by assimilating it to the closest existing one, resulting in a reduction of the final archetype count from 76 to 52 (See Table 2B for final use types in the model). For the complete characterization of parameters in each archetype please see Appendix 3.

Table 3 Characterized archetype data inputs

Thermal data type	Included data inputs
Envelope construction	Façade material layers and U value Roof material layers and U value Ground floor material layers and U value Interior floor material layers and U value Partition material layers and U value Glazing type and U value Window to wall ratio Average infiltration rate
Thermal loads	Peak hourly occupancy Peak hourly equipment/plug load Peak hourly lighting load Peak hourly hot water consumption
Building systems	Heating system set point temperatures and COP Cooling system set point temperatures and COP Ventilation peak airflow rate Hot water system supply temperatures and COP
Operations schedules	Occupancy schedule (Week/Weekend) Equipment/plug schedule (Week/Weekend) Lighting schedule (Week/Weekend) Hot water use schedule (Week/Weekend) Ventilation schedule (Week/Weekend) Heating availability schedule (Week/Weekend/Season) Cooling availability schedule (Week/Weekend/Season)

3.2 Model Generation

Once climate data, building massing models and archetype data were available, they needed to be combined in a thermal simulation model, single or multi zone, appropriate for the purposes of the study. In this case an automated workflow was implemented to generate multi zone thermal models for each building. The workflow needed to be able to create and analyze building volumes, divide them into zones, solve adjacencies between them and finally assign archetype information to the resulting zones. Each building was represented by a dynamic EnergyPlus multi-zone model with one zone per floor with one window per façade polygon, in order to capture the effects of solar shading in different heights of the building. Given the large number of buildings in the model (Close to 100,000) no further zoning detail was introduced by floor since such subdivision would have generated unacceptably high simulation times without meaningfully increasing the accuracy of the model. However, in order to increase the scalability of the proposed system, zone geometries were generated so that they could be further subdivided within the proposed workflow.

The workflow consisted of a multicomponent toolset within the CAD environment Rhino 3D (McNeel 2015a), using municipal GIS datasets as a base input for building geometry, ground elevation and context (Figure 2). Custom C# applications were built for the automated generation of 2.5D models, their division in floor zones, the generation of windows and shading calculations, within the parametric Rhino plugin Grasshopper. Computationally costly operations, such as shading calculations and window generation, were programmed in parallel. In the case of shading, conventional raytracing search techniques were combined with a distance search algorithm, in order to identify potential neighboring structures before choosing the shading surfaces to be used in simulation. The process of geometry manipulation is depicted in Figure 3.
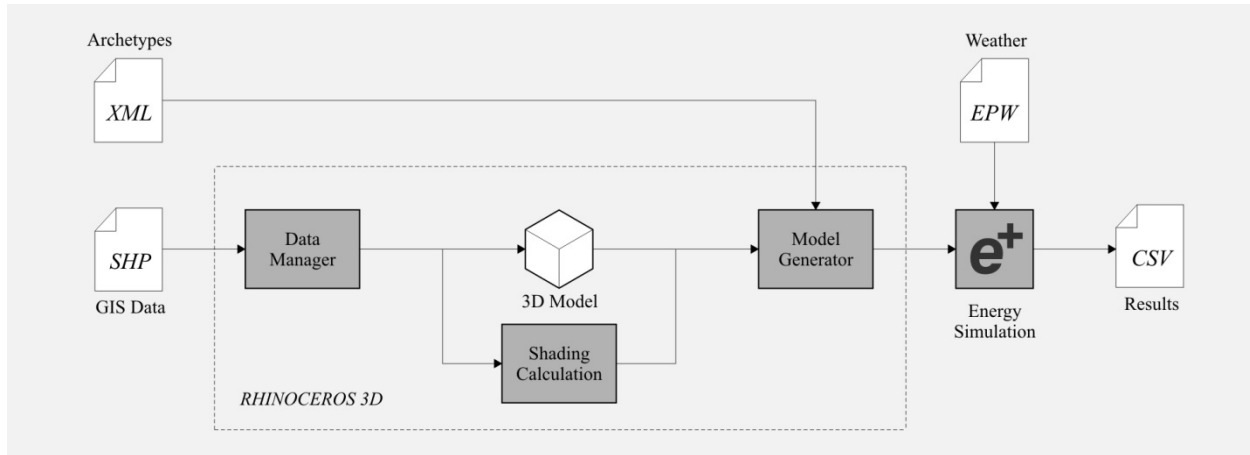
Figure 2 UBEM developed modelling tool workflow

A key issue in the creation of the 2.5D model for UBEM purposes is the level of detail of the building footprint polygon used as a base for the extrusion. Usually 2D footprints maintained by municipalities are automatically generated from imagery, and include a large variety of kinks, curves and details. While correct in the representation of the building these features are unnecessary for the simulation of a thermal zone, introducing a large number of additional surfaces to be processed which in turn leads to increased simulation times. To simplify model geometry polygon simplification techniques can be applied to GIS datasets which reduce the number of points or segments in the original shape according to more or less advanced rules. However these techniques present two main difficulties for their use in UBEM: They may change the built area of a building and perturb actual adjacencies between neighboring structures. In this work a standard polygon simplification method available in the GIS ArcMap software was applied (ESRI 2015) to recognize those adjacencies.
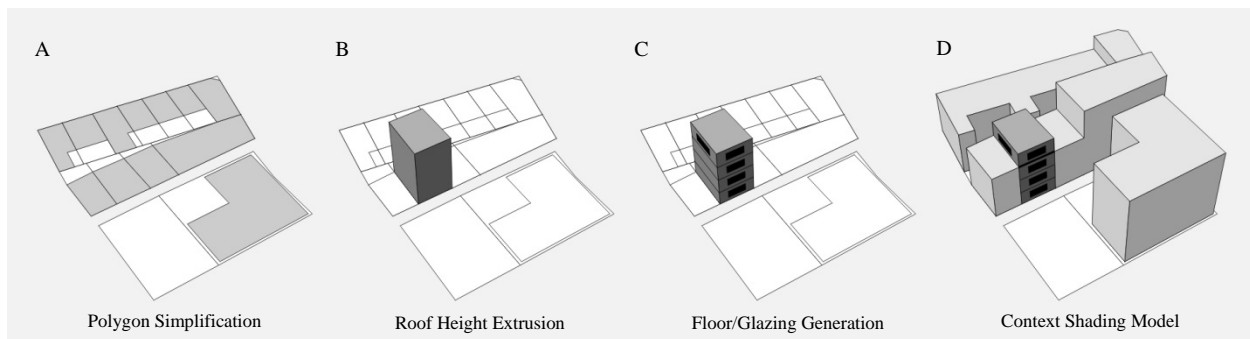

Figure 3 Building geometry modeling process

Within the workflow the previously developed simulation parameters for each archetype were stored and implemented in an XML template file format developed by the authors as a standard for urban energy modeling (Cerezo, Dogan, Reinhart 2014), and automatically assigned to each building model according to the GIS dataset information. In this format all simulation parameters are stored as a library of space types with data dependencies for materials, constructions and schedules. Finally, in the chosen dynamic energy simulation engine (EnergyPlus) each building energy model is stored in an IDF text file, packaged and ready-to-run. Once all modeling steps were completed, IDF files for all parcels in the model were generated using the Archsim plugin tool (Archsim 2015) for Rhino Grasshopper (McNeel 2015b) which combined XML parameters with Rhino3d geometry for thermal zones and shading surfaces.

3.3 Model Simulation

Building thermal models for building in a UBEM represents the most complicated and time consuming aspect of the process. However once the model is available, its dynamic simulation process can also represent a logistical challenge: While simple steady state simulation models for several thousand buildings can be executed in a matter of an hour on a standard laptop, the simulation time for thousands of dynamic multi-zone models may take days. This

time can be significantly reduced by parallelizing both the IDF generation and simulation using multicore computer clusters or cloud services. Less computationally intensive processes have been previously proposed for the simplification of envelope and thermal mass (Kim et al 2014) or clustering large models through single space models (Dogan and Reinhart 2014). A parallel computing approach was chosen for the Boston project and IDF simulations were distributed through two 16 core dedicated desktops. Given the limitations for Rhino 3D in processing large numbers of surfaces, as well as the impracticality of running the total number of simulation in one batch, the Boston dataset was divided in 14 neighborhoods with similar numbers of thermal zones, which were built and simulated separately. The complete simulation was performed in 55 - 60 hours.

3.4 Scenario Analysis

Finally, in order to demonstrate the range of decision making applications of a full city UBEM, a potential future energy scenario was simulated and analyzed for a section of Boston. The area including the neighborhoods of Back Bay, South End and Columbus was chosen as a case study due to the diversity of building uses including a majority of nonresidential building floor area (75%) concentrated in 15% of the land area. The scenario chosen for the analysis focuses on the current interest of the City of Boston in distributed generation systems for electricity, in particular urban solar photovoltaic (PV) (City of Boston 2015). A hypothetical future scenario is considered for the area in which a 50% of all roofs are covered in PV panels in order to reduce the electricity demand to be covered by conventional fossil fuel plants within the grid. In order to calculate the potential solar electricity production of the complete area the 3D model generated for energy simulation in Rhino3d was used as a starting point. Roof surfaces were extracted using a custom C# component within the Grasshopper plugin, and simulated under the Boston Logan TMY3 weather file using EnergyPlus. An average efficiency of 15% was assumed for all PV models. Lastly the hourly production results were subtracted from the electricity demand curve from the neighborhood.

Although the potential generation from PV can be calculated straightforwardly, it has been shown that the implementation of large PV systems in urban areas might not be positive for the electricity grid and significantly decreases its theoretical benefits (MITEI 2015). In addition to required investments for the upgrade of the supply infrastructure, a fundamental challenge for their effectiveness is the temporal shift between the electricity consumption peak (in the evening) and the production peak (at noon). This creates a very large difference between the general base load and the maximum, which requires additional energy production plants to run for short periods of time reducing their efficiency and increasing the price of electricity. This difference can be reduced by improving the efficiency of buildings in operation through retrofit or demand response strategies. An UBEM such as Boston's allows for the analysis of the hourly impact of such improvements. In this case the resulting demand curve for electricity was modelled under two scenarios for the hottest day of the year, the 7th of July. In the first, scenario A, buildings perform in their current state. In the second, scenario B, a theoretical demand response strategy is assumed in which all commercial buildings increase their cooling thermostat temperatures for 2 hours in the evening (5-6 PM) a value between 2 and 4 degrees C. Such technique, which would require the implementation of some smart control system for the buildings, would produce a small reduction in thermal comfort but could also reduce the peak in demand making PV feasible.

4 Results

In the following, different aspects of the Boston UBEM are presented. First, results regarding data management and archetype generation are analyzed in detail, presenting the percentage of the documented city structures which could were modelled and characterized. Next, annual and hourly whole city energy demand results are analyzed for peak summer and winter consumption days. Energy use intensity (EUI) distributions for each archetype use are then compared to national averages from CBECS. Finally, hourly results for the proposed urban solar PV generation and demand response scenario from section 3.4 are analyzed, showing the capability of the model to assess spatially and temporally specific interventions.

4.1 Dataset Processing Results

The data collection and management steps presented in section 3.1 were applied to the Boston datasets in order to generate a complete building dataset for simulation. As part of this process, a portion of the initially available records for taxes (TXR), parcels (PRC) and building footprints (BLD) had to be discarded due ot missing or inconsistent data entries. The initial total of 163,499 tax records in TXR was aggregated by parcel ID into 99,803 parcel records. After joining with the GIS parcel geometry in PRC, 581 records did not produce a match. In addition, 5,805 parcels were found to have a property type not fit for being modelled such as underwater structures, storage silos or substation (See Annex 2) resulting in a further sample reduction of 6.4%.

The BLD footprint dataset originally included a total of 128,593 polygons representing different building volumes. From that set, 552 polygons representing buildings under construction, in ruin or mobile structures were eliminated. Another 25,602 outside structures, such as garden sheds, kiosks, etc. were discarded as well, leaving 102,091 from the initial polygon count. The remaining buildings represent 98% of Boston's built floor area. All of those structures were discarded because their use type makes them unsuitable for energy modelling. During the ensuing data manipulation steps, more structures had to be discarded as follows. The joining of the BLD footprints with their pertaining parcels resulted in 549 mismatches. Another 386 polygons were discarded for lack of height information and 5,302 polygons were eliminated for representing very small building features. The final modeled set consisted of 92,397 polygons, representing a 95% of the total Boston parcels and 97% of the building floor area suitable for modelling i.e. only 3% of the floor area could not be modelled due to data issues.

Within the remaining dataset, 3,439 building footprints were defined as "Tax Exempt" in the Boston property type database and could therefore not be assigned to any of the archetypes. Similarly, 1,561 footprints did not have a year of construction. The archetype characterization process required to manually revisit such entries and choose an appropriate use code. For those without year of construction, generic "after 1950s" conditions were assigned. The resulting archetype use segmentation showed residential and office as the two main categories with floor areas of 52% and 24%, respectively. 53% of the floor area was built before 1950 (Figure 4A and B).
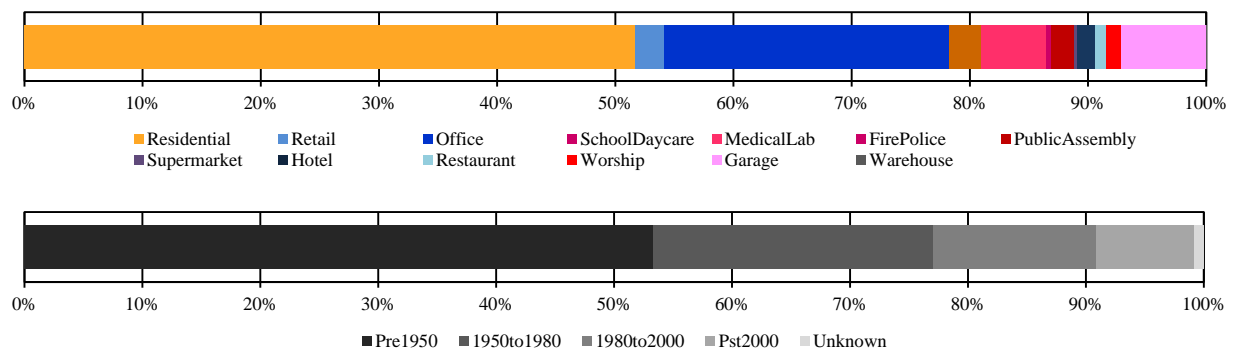

Figure 4A-B Building floor area by archetype use and period

4.2 Energy Demand Results

Following the above describe thermal model generation process, annual and hourly simulations were generated by building and aggregated by parcel ID, for five end uses: Space heating, space cooling, plug loads, lighting loads, and domestic how water heating. Hourly demand values were calculated for the four end uses and grouped between electricity demand (Including cooling, plug and lighting loads) and heat fuel demand (Including heating and hot water). General results are presented here both in terms of annual EUI and total hourly energy demands for the complete built stock. Figure 5 A to L shows the distribution and average of simulated EUI values for each archetype use. In each case the simulated average (SimA) is compared with the CBECS national average (NatA) used in section 3.2 for the characterization of archetypes. The Average EUIs ranged from a minimum 87 kWh/m2 for garages to a maximum of 679 kWh/m2 in the case of medical and lab buildings. The error of the average EUI compared to the calibration CBECS national average is in most cases within an acceptable error range of 5% to 20% with the simulated value always being higher than the CBECS reference.

This bias in the simulations might have been caused by the assumption that buildings built before 1950 in Boston had not been renovated. While clearly not reflecting reality, this assumption had to be adopted since the state of energy refurbishment of individual buildings is unknown to the city. Another contributing simplification was that model considered a single usage description for all spaces in the building as well as one thermal zone per floor. A more detailed zoning of building floorplans could have addressed these limitations and be implemented going forward. In the case of Fire/ Police and Worship facilities discrepancies between UBEM predictions and CBCS are 122% and 167%, respectively, and may have been caused by the uncommon programmatic uses of such buildings, which cannot easily be reproduced by automatically generate energy models with standard floor heights.
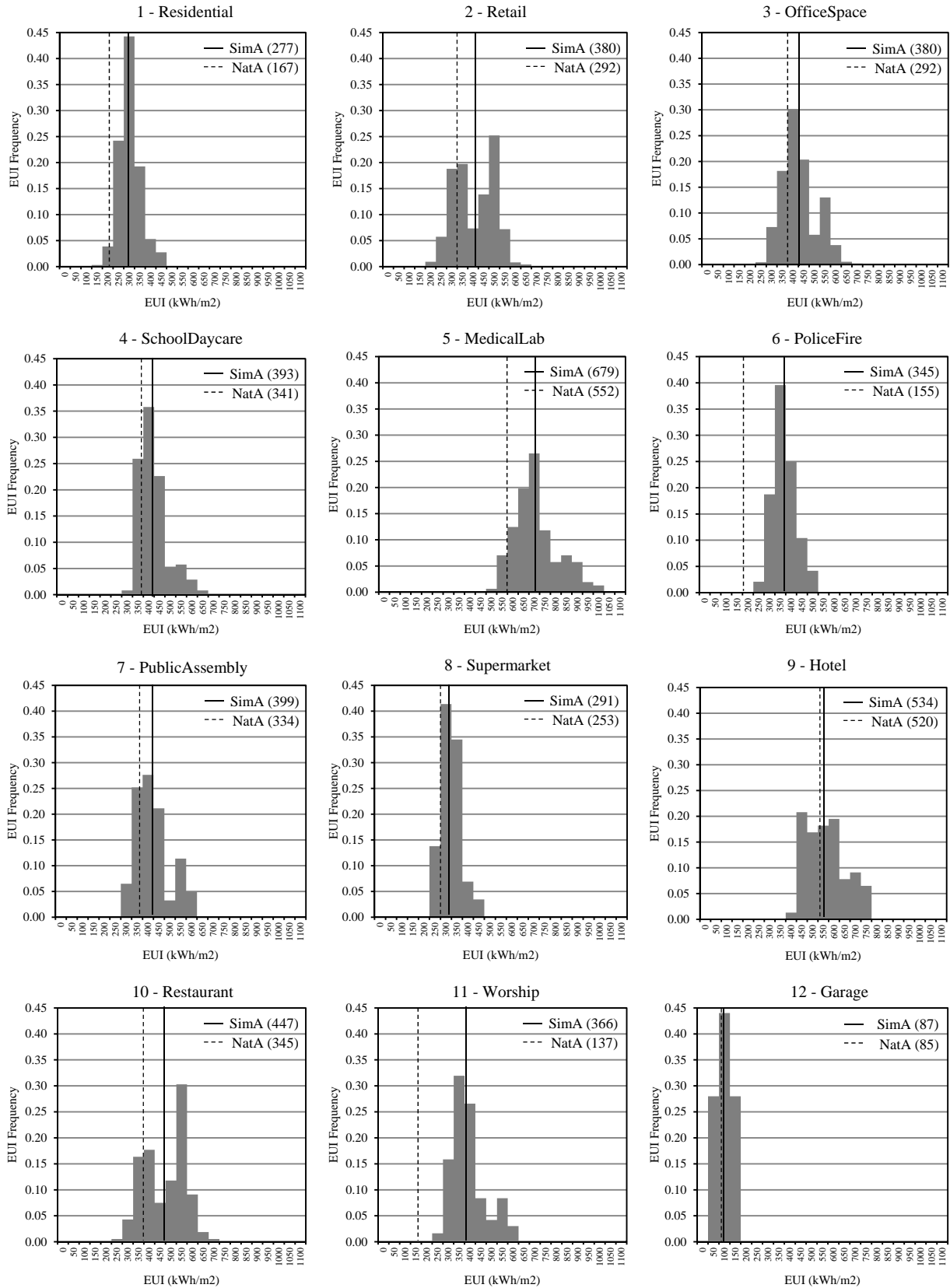
Figure 5 A-L EUI distributions with simulated (SimA) and CBECS (NatA) averages for 12 use types

The hourly energy demand was calculated as well by building and aggregated by parcel ID for booth fuel types, producing one terabyte of data for the complete model of the city of Boston. In order to analyze the results of the simulation peak days were chosen for the summer and winter seasons. In the case of summer the 6th of July was chosen as the analysis day, since it presented the highest average dry bulb temperature according to the EPW dataset used for simulation. Figure 6 shows the hourly total demand for all buildings in the city, classified by general use type (6A) and fuel type (6B). For the sake of this analysis all non-residential uses were grouped in two general categories: Commercial (Including archetypes 2, 3, 8, 9, 10, 12) and Public/Civic (Including 4, 5, 6, 7, 11). The results present a load profile with two peaks concentrated in the morning (2,221 MWh) and the late afternoon (3,173 MWh). The latter is mainly caused by the concentration of cooling loads for both residential and non-residential buildings. The figure reveals that the majority of loads on a summer day are electric whereas heating fuel is mainly required for hot water use and concentrated on residential buildings in the morning and evening. Throughout most of working hours commercial buildings are responsible for about half of the load. Only in the late afternoon residential cooling temporarily becomes responsible for 37% of the load.
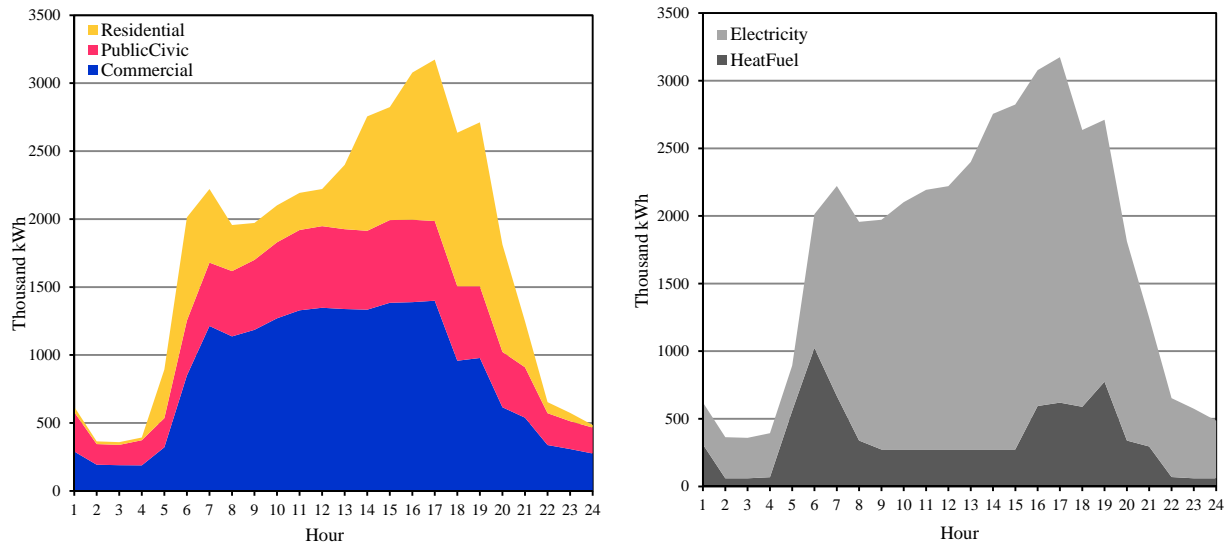

Figure 6A-B Simulated hourly energy demand by use group and fuel type for summer peak day
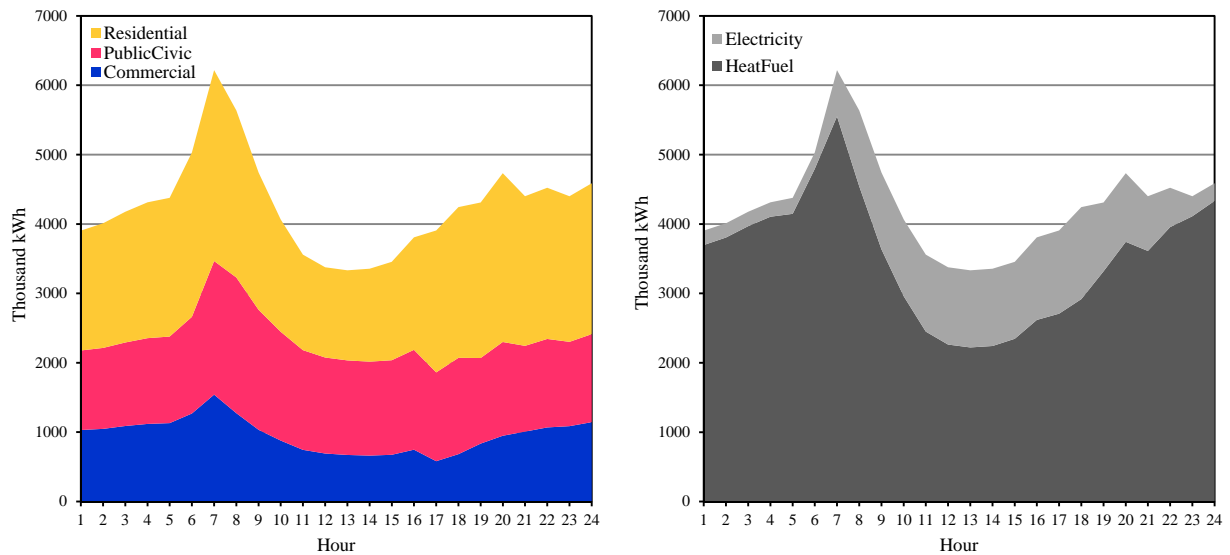

Figure 7A-B Simulated hourly energy demand by use group and fuel type for peak winter day

The 30th of January was chosen as the winter analysis day, and Figure 7 shows again hourly demand results for all buildings classified by use (7A) and fuel (7B). During winter energy loads are higher at night, with a significant peak in the early morning (6,217 MWh) caused by an increasing in heating needs when night setback temperatures are substituted by occupied hour's set points. The reader should note that this peak is probably exaggerated as the model simply assumes that a large number of buildings change from nighttime setback to daytime temperatures between 6am and 7am. Throughout the day, over 80% of the loads correspond to heating fuel. (In this study and based on the limited heating type data for Boston, most of buildings are assumed not to have electric heating). Figure 7A suggests that during winter residential buildings make up the largest portion of energy use (45%) with commercial buildings contributing another 33%.

4.3 Scenario Results

The hourly resolution in the model as well as its capability to analyze any specific location of the city allows for the study and consideration of multiple advanced decision scenarios at the level of the parcel. According to the test scenarios proposed in section 3.4, the solar PV potential production for all roofs in the case study area was simulated as presented in the methodology section, assuming that 50% of the roof areas are covered with PV modules with 15% efficiency. The hourly results for the day of analysis (6th of July) (See Figure 9) show a peak production at noon of 106 MWh and a daily total of 831 MWh. Electricity demand by hour for the same day was obtained for both scenarios A and B showing a nighttime minimum load of 40 MWh as well as a daytime peak at 5 PM of 341 MWh. The resulting distribution of "Base Demand" for scenario A in the study area for the peak hour is represented geographically in Figure 8 in a 200 x 200 m analysis grid, showing a clear distinction between commercial and residential areas and a peak around the Prudential Center commercial core.
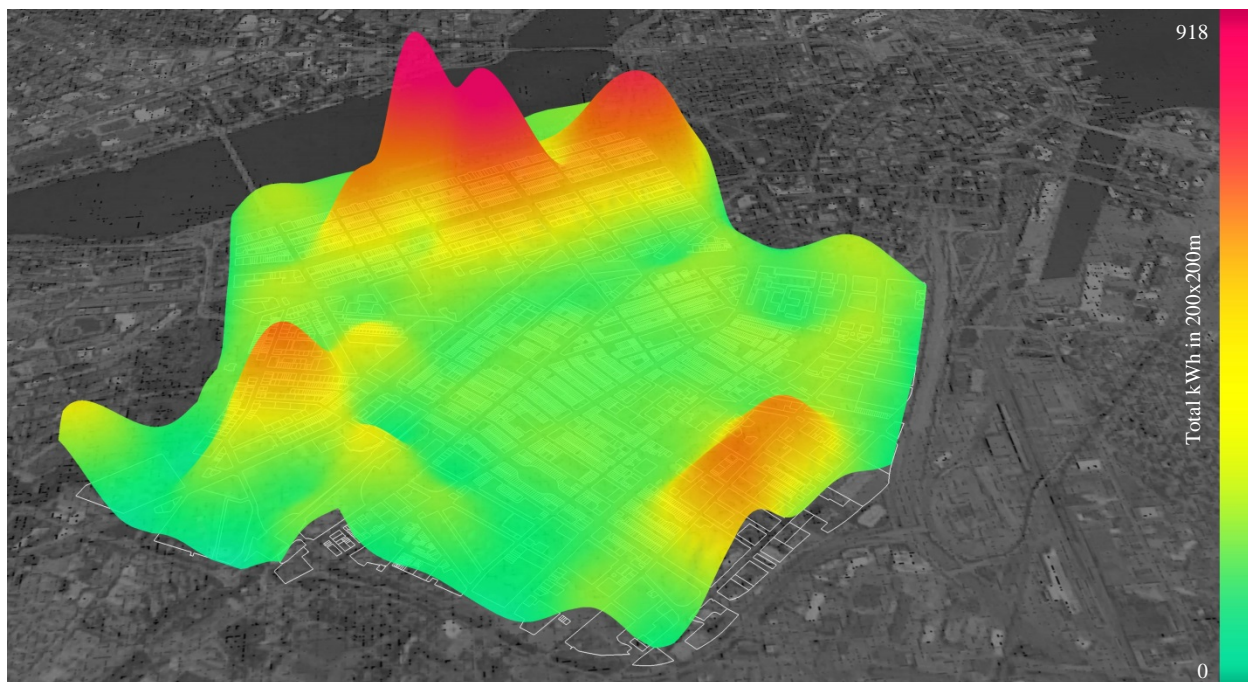
Figure 8 Study area 5 PM electricity demand for scenario A (200m grid)

In scenario B "Base Demand" the implementation of the demand response controls for commercial buildings after 5 PM resulted in a reduction of hourly demand of 8 to16% between 5 and 7 PM. The final load curve for "Reduced Demand" after the PV implementation is presented for both scenarios in dark grey in Figure 9. In scenario A, a large and fast increase in consumption is created between 2 and 5 pm as a result of the PV implementation, which would require the operation of less efficient and more costly power plants. Scenario B presents a significant reduction of the peak at 5 PM of 50MWh, which closes the gap between day base load and maximum load for the case study. This new load gap stays similar to the original one existing in scenario A "Base Demand", allowing for extensive PV generation without increasing the strain on the grid. Such load manipulation at the scale of the specific building is only possible through the use of an UBEM model as the one presented here.
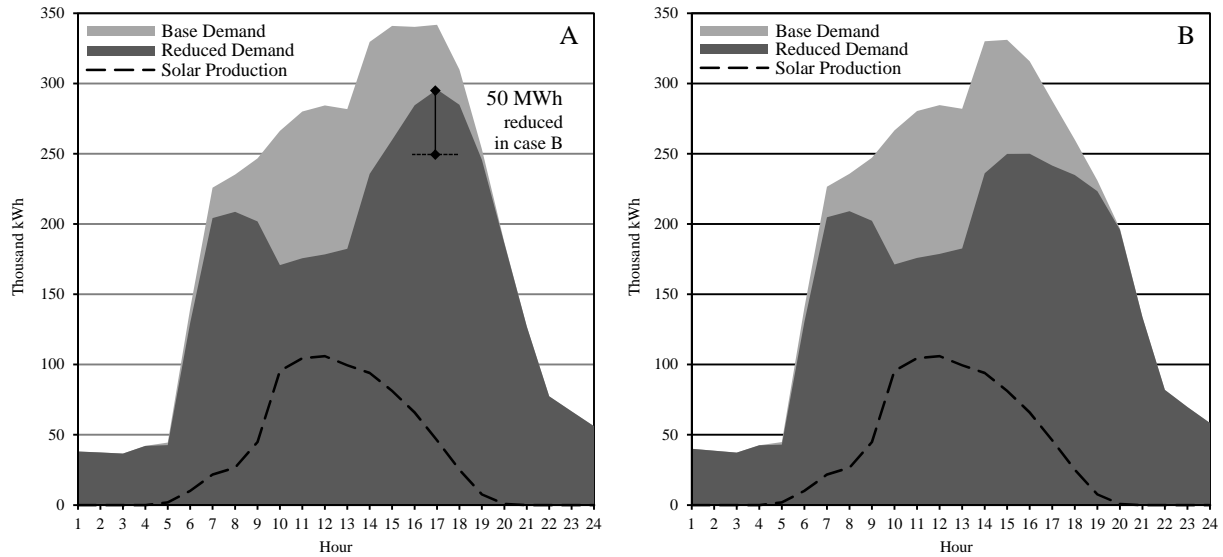
Figure 8 Study area simulated hourly electricity demand for scenarios A and B

5 Discussion and recommendations

Sections 2 and 3 of this document have presented in detail the application of an automated workflow for the generation of UBEM, capable of producing hourly and building specific energy demands for a complete city. The complexity of the modeling effort using basic urban GIS datasets as actively maintained by the city of Boston helped identifying limitations on the data sources, structure and application. The following points focus on the main challenges faced by the authors, and provide general recommendations about how to move forward in the application UBEM for Boston or elsewhere.

5.1 Available Urban Building Data

As it has been shown in the previous sections of this work, the current state of the art urban building energy modeling techniques allow for the creation and simulation of fairly detailed urban building energy models (UBEM). Available geometry formats in CAD, LIDAR or GIS, used in most cities, can be used to generate thermal multi zone models, and weather data can be obtained in simulation file formats for almost any urban location with a sufficient level of detail, even taking into account micro climatic effects. In addition, there is no lack of sophisticated modeling tools for UBEM capable of producing models, given that their required data inputs are available, and there is enough computational power through parallel or cloud computing run whole city simulations in a manageable amount of time. In this case, almost 100,000 buildings were simulated is less than 3 days using 2 multicore computers.

However, and regardless of the modeling technique, the characterization of building geometry, properties and usage patterns remains a challenge for the effective application of UBEM at such a large scale. The modeling work presented in in this document has shown that it is possible to build a citywide model solely based on currently available urban GIS datasets. But it has also revealed the extensive data processing required to manage those datasets and the limitations they impose. Currently, the full potential of UBEM tools cannot be exploited without heavy refinements of the urban datasets used in the classification and characterization of archetypes. Focusing first on the limitations of available data for the classification of building into archetypes, the main identified issues are summarized below (See Table 4). Beside these obstacles, the characterization of archetypes presents an even larger challenge. Virtually no city maintains constructions and usage patterns information for buildings which can be used for simulation. Therefore the only available sources are previous regional studies about typical constructions, systems and usage patterns, or local experts or consultants who might be able to give a judgement about those parameters. In the case of Boston the latter option was pursued, revealing the need of a better understanding of the built stock in the city. Finally, in terms of the geometry of building envelopes, the available footprints and heights required an excessive amount processing time, in which polygons were simplified according the specific needs of energy modeling. This excess of detail in urban 3D models is consistent through municipalities in the US, and more advanced computational methods need to be developed for the adaptation of existing datasets.

Table 4 Data issues for archetype classification

Data limitation	General description	Recommendation
Spatial data resolution	Most digitally available information about buildings exists only at the scale of the parcel but is not defined by building. This is result of most of such data being part of property tax assessments, where information is gathered by owner ID. At the same time no unique building ID exist, making it impossible to link each parcel with the structures it contains and each data point with the right structure and/or floor.	Introduction of a building ID with a floor identifier, related with the existing parcel and owner IDs, so that tax assessment and other data can be specifically assigned.
Tax data limitations	Property tax assessments represent almost the only building information source ubiquitously available in US cities, but miss many fundamental basic inputs necessary for archetype classification. Particularly important is the lack of window to wall ratios, glazing type, façade and roof type and insulation or number of occupants.	Investigate potential secondary datasets available within the city, such as building construction permits. Develop a local database for number of building occupants.
Building age/retrofit	Year of construction and renovation fields, best available proxy for insulation level and systems efficiency, are incomplete or incorrect for many parcels. In addition, no definition of the level of renovation is provided.	Complete the existing fields for all parcels. Document not only the last but also intermediate renovations, and define if they affect the envelope, the systems, etc.
Single vs mixed use	Property types, main identifier for the activities within a building, are defined by tax assessment parcel only. In the case of mixed use parcels or buildings, labelled as such in the tax database, it is impossible to know which buildings or floors correspond with which use.	Provide in mixed use cases a description of the combination of property types by building and the percentage of the floor are dedicated to each one of them.
Tax exempt properties	Tax exempt parcels in Boston are characterized as such, instead of according to their actual use property type.	Correctly document them, storing the tax exempt status in a spate field.

A critical reader may wonder whether the uncertainties introduced in the model by this long list of data limitations make UBEM results unfit for practical usage. However, any urban energy model is built on the assumption that the specific conditions of each building cannot be reproduced perfectly, and its purpose is to answer questions about the comparative urban level impact of potential interventions. For many of such considerations common practice average archetypes, such as the ones developed for the Boston model, have proven enough to obtain meaningful results (Reinhart and Cerezo 2015). The Boston UBEM which, as presented in section 4, has shown average demands within an acceptable error from those of the national averages in CBECS and RBECS, fulfills that requirement. This encouraging result now withstanding, there is an unquestionable need for the generation by the city of Boston of more detailed and consistent data about the building stock in all categories mention below. This would require in the opinion of the authors two main efforts to be developed:

- The *revision of the current city databases*, so that the process of creation and simulation of this citywide model can be repeated, and the model regularly updated, without the intervention of expert consultants. This refinement and update work can only be developed by the municipality itself. The introduction of building IDs with use and age information defined at that scale, as well as complete and consistent building heights, would facilitate this effort. The characterized archetype set developed in this project and stored in a standardized open XML library will allow for the update of the model in the future.
- The *development of a documentation program*, in which the data inputs of building archetypes are improved through building audit or visit in order to produce a complete catalogue for a climatic region. The process of selecting a representative sample of buildings from a particular archetype and obtaining detailed descriptions of constructions, systems, and occupancy have proven to significantly increase the quality of urban models (Cerezo et al 2015), and in general improve the currently very limited information that municipalities about their built assets. This detailed documentation of building stocks is in fact not a new idea, and the European Union has been developing building archetypes by country since 2010 as part of the TABULA project (TABULA 2012), combined with archetype specific retrofit packages and building energy certificates. This second effort requires a larger investment of resources and time to produce, maintain and update a building stock catalogue, but also has additional benefits since the resulting baseline models can be used by designers, contractors or utilities when working with the municipalities in the region of study. For that reason the authors believe that the initial stages of such documentation initiative should be developed by state research institutions and governments, while their specific city update should be a responsibility of the municipality.

5.2 Model Quality and Measured Energy Data for Validation

Although the work previously presented has shown the feasibility of a citywide UBEM built on the available data sources, there has been nothing said about its level of accuracy compared to the specific performance of individual buildings in Boston. Unfortunately, even when average EUI values fall into a reasonable range, the lack of individual building measured energy use data at a monthly or hourly scale made it impossible to go further in the calibration of the CWES model. As referred before, this issue does not invalidate the model, since it has been shown by previous research that when results are aggregated at the scale of the neighborhood the error compared to real energy use stays below unacceptable 5 to 10% (Reinhart and Cerezo 2015). The use of single building hourly results however, might lead to wrong assumptions and has to be taken with caution. For that reason the importance of a more flexible access to detailed measured energy use data cannot be overstated, and in the opinion of the authors it has to become a priority for municipalities and utility companies. The availability of building measured data allows for the probabilistic analysis of archetype parameters and the generation of experimental distributions for them, resulting in significantly more accurate demand distribution predictions (Cerezo et al 2015). Furthermore, it helps identifying wrong assumptions in the characterization of archetypes as shown by Aksoezen et al. who observed the unexpected relationship between heating consumption and age of the building for a sample of the Swiss built stock (Aksoezen et al 2015). The city of Boston and several other US municipalities have given steps in this direction with the introduction of energy reporting and disclosure programs (BERDO in Boston) which require buildings over a certain size to make public their consumption at a yearly level (City of Boston 2015). However there are still numerous legal obstacles related with privacy concerns which require to be addressed. For models like the CWES in Boston or similar initiatives to help policy makers and urban planners to make informed decision a new data sharing framework is necessary.

5.3 UBEM as an Urban Planning Tool

The value in any simulation model, and particularly in such a complex one, resides in its capacity to correctly inform and influence a decision about design or policy. As presented in Section 2 a series of previous top down and bottom up energy modeling approaches have been developed for that purpose. As urban energy policy decisions require more detailed information to address future planning interventions new forms of modeling need to be developed. Citywide UBEM as the one created for the City of Boston and described in this document allow comparing different intervention strategies at a scale never achieved before with three new distinguishing characteristics:

- Energy measures can be applied to specific selected buildings.
- Energy demands can be analyzed at the hourly scale.
- Energy supply can be considered for specific local systems.

These characteristics give UBEM a significant flexibility, providing municipalities and stakeholders with the option to not only compare potential interventions, and also detailed implementation strategies. In a combination of solar generation and demand response, such as the one presented in the results section of this work, an UBEM allows to test multiple combinations of targeted buildings for achieving a single objective: Emission reduction, cost reduction, etc. Following the same approach, the city of Boston has devoted further work in collaboration with MIT Lincoln Labs to study potential locations for urban micro grids according to multiple cost metrics (MIT Lincoln Lab 2015). In these examples or any similar complex scenario interventions, Boston is now able to identify many paths to achieve its long term emission reduction goals, and negotiate with city stakeholders the most promising ones. For this reason the authors believe that citywide UBEM models provide decision makers with a high level of agency the planning of urban energy systems, which justifies the effort of their development.

After reading this work however, a reader interested in the application UBEM to urban planning might think that the effort of processing data, creating archetypes and running simulations is too high, and that it requires a very specialized type of knowledge not typically available within the urban planning and development teams in a city. Therefore the fundamental question remains of who should develop such models, and more importantly operate them once built in order to test future interventions. The UBEM developed for the City of Boston required in its first implementation a large expert involvement. However, given the level of automation of the process, any future application will be significantly simpler. The authors believe that it should be the role of municipal urban development and planning departments to maintain the model in the future, by improving their building archetype library as recommended in section 5.1, calibrating it with measured data and developing the intervention scenarios to be tested using the model. In the authors' vision for the future, the model should be rerun in parallel with the main updates of the main Boston databases, so that simulation results for demand can be made available for all municipal departments for their analysis in combination with data from other areas of urban governance.

6 Conclusions

This work has successfully created the first urban building energy model (UBEM) of a complete city, based on actively maintained GIS datasets in the city of Boston and for its use within a planning and urban development department. The previous sections have shown the application of an automated model generation and simulation workflow, and identified modelling challenges in the existing data structure. Results for yearly and hourly energy demands in Boston have been discussed and used to demonstrate the potential application of the model for future energy scenario analysis. It can be concluded that citywide UBEM are feasible and useful for energy demand and supply policies, but that their effective implementation still requires a combined effort of municipalities and energy utility companies to improve the available documentation of the building stock and its performance.

7 Acknowledgements

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APPENDIX 1
Complete list of selected GIS database fields for the CWES Boston model

The following table presents those fields from the BRA GIS database selected for the construction of the model, both in classification and characterization of archetypes. In the case of parcels (PRC) and buildings (BLD), datasets included geometric information associated with the main data table.

Dataset (CODE)		Selected Data Field	Field Name	Application Description
Tax Parcels FY14 (PRC)	⚷	Parcel Id	PID_PARCEL	Assign datasets to parcel geometry.
Building Footprints (BLD)*		Roof Elevation	ROOF_ELEV	Calculate building height and stories.
		Ground Elevation	GRND_ELEV	Calculate building height and stories.
		Structure Type	IEL_TYPE	Identify structures not suitable for modelling.
		Building Land Use Code	BRA_LAND_U	Classify archetypes by use type.
Tax Records Lite (TXP)	⚷	Property Id	PID	Join dataset with full tax records.
		Condominium Id	CM_ID	Group records within common parcel.
		Parcel Id	PID_PARCEL	Assign datasets to parcel geometry.
		Land Use Code	LU	Classify archetypes by use type.
		Property Type Code	PTYPE	Classify archetypes by use type.
		Max Number of Floors	NUM_FLOORS	Calculate building height and stories.
		BRA Assigned Name	BRA_NAME	Identify undefined property types.
Tax Records Full (TXR)	⚷	Property Id	PID	Join dataset with full tax records.
		Year of Construction	YEAR_BUILT	Characterize envelope and systems.
		Year Remodeled	YEAR_REMOD	Characterize envelope and systems.
		Gross Built Area	GROSS_AREA	Revise building area calculations.
		Living Built Area	LIVING_AREA	Revise building area calculations.
		Structure Type	STRUCTURE	Classify heavy vs light construction.
	**	Residential Roof Type	R_ROOF_TYP	Classify flat vs sloped roof type.
	**	Residential Exterior Finish	R_EXT_FIN	Classify heavy vs light construction.
	**	Residential Bedroom Number	R_BDRMS	Estimate number of occupants.
	**	Residential Heating Type	R_HEAT_TYP	Estimate heating efficiency.
	**	Residential Cooling Type	R_AC	Estimate cooling efficiency.
	***	Residential Units Number	S_UNIT_RES	Identify majority use type.
	***	Commercial Units Number	S_UNIT_COM	Identify majority use type.
	***	Mixed Units Number	S_UNIT_RC	Identify majority use type.
	***	Condo Exterior Finish	S_EXT_FIN	Classify heavy vs light construction.
	***	Unit Bedroom Number	U_BDRMS	Estimate number of occupants.
	***	Unit Heating Type	U_HEAT_TYP	Estimate heating efficiency.
	***	Unit Cooling Type	U_AC	Estimate cooling efficiency.

⚷   Key field used in relational database for the join of tables.

*   No data key exists for building footprints, which had to be related to their parcels through a spatial join.

**   Field only available for residential properties with a single owner.

***   Field only available condominium properties and their individual units.

APPENDIX 2
Tax assessment property types by assigned CWES use type

The following table relates the 271 original property types from BRA tax assessment data with the assigned use type for archetype classification in the CWES Boston model.

BRA Code	BRA Property Type Name	BRA Land Use	CWES Use Type	CWES Code
10	CONDO_MULTI_USE	RC	(Condominium)	- **
12	RES_OPEN_SPACE_USE	RC	(Condominium)	- **
13	RES_COMMERCIAL_USE	RC	(Condominium)	- **
19	RES_EXEMPT_USE	RC	(Condominium)	- **
25	RC_ONE_RES_UNIT	RC	(Condominium)	- **
26	RC_TWO_RES_UNITS	RC	(Condominium)	- **
27	RC_THREE_RES_UNITS	RC	(Condominium)	- **
31	COM_RES_MULTI_USE	RC	(Condominium)	- **
101	SINGLE_FAM_DWELLING	R1	Residential	1
102	RESIDENTIAL_CONDO	CD	(Condominium)	- **
103	MOBILE_HOME	R1	Residential	1
104	TWO_FAM_DWELLING	R2	Residential	1
105	THREE_FAM_DWELLING	R3	Residential	1
106	RES_ANCILL_IMPROVEMT	RL	Residential	1
107	(Undefined)_RESIDENTIAL	RL	Residential	1
108	CONDO_PARKING_RES	CP	(Condominium)	- **
109	MULTIPLE_BLDGS1_LOT	R3	Residential	1
110	CONDO_STORAGE_RES	CD	(Condominium)	- **
111	APT_4_6_UNITS	R4	Residential	1
112	APT_7_30_UNITS	A	Residential	1
113	APT_31_99_UNITS	A	Residential	1
114	APT_100+_UNITS	A	Residential	1
115	CO_OP_APARTMENT	A	Residential	1
116	RES_PARKING_GARAGE	A	Garage	14
117	DAY_CARE_USE	A	School/Daycare	4
118	ELDERLY_HOME	A	Residential	1
119	RES_PARKING_LOT	A	Garage	14
120	LUXURY_APARTMENT	A	Residential	1
121	ROOMING_HOUSE	A	Residential	1
122	LODGING_SUITES	A	Residential	1
123	RESIDENCE_HALL_FRATER	A	Residential	1
124	DORMITORY	A	Residential	1
125	SUBSD_HOUSING_S_8	A	Residential	1
126	SUBSD_HOUSING_S_231D	A	Residential	1
127	SUBSD_HOUSING_S_202	A	Residential	1
128	CONDO_APARTMENT	A	Residential	1
129	RECTORY_CONVENT	A	Residential	1
130	RESIDENTIAL_LAND	RL	Residential	1
131	RES_LAND_SECONDARY	RL	-	- *
132	RES_LAND_UNUSABLE	RL	-	- *
140	CHILD_CARE_FACILITY	A	School/Daycare	4
150	APT_STUDIO	A	Residential	1

BRA Code	BRA Property Type Name	BRA Land Use	CWES Use Type	CWES Code
151	APT_1_BEDROOM_UNIT	A	Residential	1
152	APT_2_BEDROOM_UNIT	A	Residential	1
153	APT_3_BEDROOM_UNIT	A	Residential	1
154	APT_4_BEDROOM_UNIT	A	Residential	1
202	UNDERWATER_LAND	RL	-	- *
211	NON_PRODUCTIVE_LAND	RL	-	- *
300	HOTEL	C	Hotel	9
301	MOTEL	C	Hotel	9
302	INN_RESORT_B_&_B	C	Hotel	9
303	PRIV_CITY_CLUB	C	Office	3
304	NURSING_CONV_HOME	C	Residential	1
305	HOSPITAL_PRIVATE_TAXABLE	C	Medical/Lab	5
306	LABORATORY	C	Medical/Lab	5
307	VETERINARY_HOSPITAL	C	Medical/Lab	5
309	MEDICAL_CLINIC_OUTPATIENT	C	Medical/Lab	5
310	LAUNDRY_OPERATION	C	Retail	2
311	LAUNDROMAT_CLEANER	C	Retail	2
312	SELF_STORAGE_WHSE	C	Warehouse/Storage	15
313	LUMBER_YARD_STORAGE	C	Warehouse/Storage	15
314	TRUCK_TERMINAL	C	Warehouse/Storage	15
315	STORAGE_ANCILLARY	C	Warehouse/Storage	15
316	WAREHOUSE_DISTRIBUTION	C	Warehouse/Storage	15
317	STORAGE_WHSE_GARAGE	C	Garage	14
318	COLD_STORAGE_WHSE	C	Warehouse/Storage	15
319	STRIP_RETAIL_OFFICE	C	Office	3
320	RETAIL_WHLSALE_SERVIC	C	Retail	2
321	DISCOUNT_STORE	C	Retail	2
322	DEPARTMENT_STORE_MAL	C	Retail	2
323	SHOPPING_CENTER	C	Retail	2
324	SUPERMARKET	C	Supermarket	8
325	RETAIL_STORE_DETACHED	C	Retail	2
326	RESTAURANT_CAFETERIA	C	Restaurant	10
327	RESTAURANT_LOUNGE	C	Restaurant	10
328	FAST_FOOD_RESTAURANT	C	Restaurant	10
329	BAR_TAVERN_PUB	C	Restaurant	10
330	SHOWROOM_AUTO	C	Retail	2
331	AUTO_SUPPLY_SERVICE	C	Retail	2
332	REPAIR_GARAGE	C	Warehouse/Storage	15
333	SELF_SERV_STATION	C	Retail	2
334	SERVICE_CENTER_RETAIL	C	Retail	2
335	CAR_WASH	C	Retail	2
336	COM_PARKING_GARAGE	C	Garage	14
337	PARKING_LOT	CL	Garage	14
338	SUBTERRANEAN_GARAGE	C	Garage	14
339	PARKING_GARAGE_HV	C	Garage	14
340	OFFICE_ATTACHED	C	Office	3
341	BANK_BUILDING	C	Office	3

BRA Code	BRA Property Type Name	BRA Land Use	CWES Use Type	CWES Code
342	MEDICAL_OFFICE	C	Office	3
343	OFFICE_1_2_STORY	C	Office	3
344	OFFICE_3_9_STORY	C	Office	3
345	OFFICE_CLASS_B	C	Office	3
346	OFFICE_CLASS_B+	C	Office	3
347	OFFICE_CLASS_A	C	Office	3
348	OFFICE_TOWER_CLASS_A	C	Office	3
350	POSTAL_SERVICE	C	Office	3
351	TRAINING_EDUCATION	C	Office	3
352	DAY_CARE_USE_COM_BLDG	C	School/Daycare	4
353	SOCIAL_CLUB	C	Office	3
354	MAUSOLEUM	C	Office	3
355	FUNERAL_HOME	C	Office	3
356	COMM_CONDO	CC	(Condominium)	- **
357	RETAIL_CONDO	CC	(Condominium)	- **
358	OFFICE_CONDO	CC	(Condominium)	- **
359	CONDO_PARKING_COM	CC	(Condominium)	- **
360	MUSEUM_GALLERY	C	Museum	12
361	NIGHT_CLUB	C	Restaurant	10
362	MOVIE_THEATER	C	Convention/Assembly	7
363	DRIVE_IN_THEATER	C	Convention/Assembly	7
364	STAGE_CONCERT_THEATE	C	Convention/Assembly	7
365	AUDITORIUM_SPORT_CTR	C	Convention/Assembly	7
366	FIELDHOUSE_TRACK	C	Athletic Facility	11
367	RACE_TRACK	C	Athletic Facility	11
368	FAIRGROUND_PARK	C	Athletic Facility	11
369	ARTIST_STUDIO	C	Office	3
370	BOWLING_ALLEY	C	Restaurant	10
371	ARENA_ICE_SKATING	C	Athletic Facility	11
372	ARENA_ROLLER_SKATING	C	Athletic Facility	11
373	SWIMMING_POOL_ENCLOSED	C	Athletic Facility	11
374	HEALTH_SPA_CLUB	C	Retail	2
375	TENNIS_RACQUET_CLUB	C	Athletic Facility	11
376	GYM_ATHLETIC_FACILITY	C	Athletic Facility	11
377	RECREATION_BLDG_AREA	C	Athletic Facility	11
378	SCHOOL	C	School/Daycare	4
379	CHURCH_SYNAGOGUE	C	Worship	13
380	GOLF_COURSE	C	Athletic Facility	11
381	TENNIS_COURTS	C	Athletic Facility	11
382	STABLE_KENNEL	C	Athletic Facility	11
383	SWIMMING_POOL_OUTDOOR	C	Athletic Facility	11
384	BOAT_HOUSE_MARINA	C	-	- *
385	TAXABLE_BLDG_ONLY	C	(Undefined)	- ***
386	CAMPGROUND_FACILITY	C	-	- *
387	PAY_PARKING_LOT	CL	Garage	14
388	AIR_RIGHTS_PROPERTY	C	-	- *
389	BLDG_CHAP_61_A_LAND	AH	Warehouse/Storage	15

BRA Code	BRA Property Type Name	BRA Land Use	CWES Use Type	CWES Code
390	COMMERCIAL_LAND	CL	Office	3
391	COM_LAND_SECONDARY	CL	-	- *
392	COM_LAND_UNUSABLE	CL	-	- *
393	COM_UNDERWATER_LAND	CL	-	- *
394	UTILITY_BLDG_SHED_HVAC	CL	-	- *
395	AIR_FREIGHT_TERMINAL	C	Transport	18
396	HANGAR_STORAGE_MAINT	C	Warehouse/Storage	15
397	BUS_RAIL_TERMINAL	C	Transport	18
398	AIRPORT_TERMINAL	C	Transport	18
399	COM_GREENHOUSE	C	Warehouse/Storage	15
400	OLD_MANUFACTURING	I	Industrial	19
401	OLD_INDUSTRIAL_WHSE	I	Warehouse/Storage	15
402	OFFICE_INDUSTRIAL_USE	I	Office	3
403	NEW_MANUFACTURING	I	Industrial	19
404	LIGHT_MFG_R_&_D	I	Industrial	19
405	INDUSTRIAL_LOFT	I	Office	3
406	COMPUTER_EQUIP_BLDG	I	Office	3
407	MACHINE_SHOP_SMALL	I	Industrial	19
408	NEWSPAPER_PLANT	I	Industrial	19
410	MINING_QUARRYING	I	Industrial	19
412	METAL_PROCESSING	I	Industrial	19
413	AUTO_SALVAGE_YARD	I	Industrial	19
414	FOOD_PROCESS_PLANT	I	Industrial	19
415	BOTTLING_PLANT	I	Industrial	19
416	CANNERY	I	Industrial	19
417	DAIRY	I	Industrial	19
420	TANKS_ABOVE_GROUND	I	-	- *
421	TANKS_UNDER_GROUND	I	-	- *
422	ELEC_POWER_PLANT	I	-	- *
423	ELEC_TRANS_R_O_W	I	-	- *
424	ELEC_SUBSTATION	I	-	- *
425	GAS_MANUFACTR_PLANT	I	-	- *
426	GAS_PIPELINE_R_O_W	I	-	- *
427	GAS_STORAGE	I	-	- *
428	GAS_PRESSURE_STATION	I	-	- *
430	TELEPH_EXCHG_STATION	I	-	- *
431	TELEPH_RELAY_TOWER	I	-	- *
432	CABLE_T_V_FACILITY	I	-	- *
433	RADIO_TV_TRANS_FACIL	I	-	- *
435	RADIO_TV_STUDIO	I	-	- *
436	STUDIO_REMOTE_CONTR	I	-	- *
437	CELL_ANTENNA	I	-	- *
438	TELECOM_EQUIP_MULTIPLE	I	-	- *
439	BANK_ATM	C	-	- *
440	INDUSTRIAL_LAND	CL	-	- *
441	IND_LAND_SECONDARY	CL	-	- *
442	IND_LAND_UNUSABLE	CL	-	- *

BRA Code	BRA Property Type Name	BRA Land Use	CWES Use Type	CWES Code
445	RAILROAD_PROP	I	-	- *
446	WATER_SEWER_UTILITY	I	-	- *
450	INDUSTRIAL_CONDO	I	(Condominium)	- **
465	COM_BILLBOARD	C	-	- *
900	US_GOVERNMENT	E	Office	3
901	COMMONWEALTH_OF_MASS	E	Office	3
902	CITY_OF_BOSTON	E	Office	3
903	BOST_REDEVELOP_AUTH	E	Office	3
904	PRIV_SCHOOL_COLLEGE	E	Residential	1
905	CHARITABLE_ORGANIZTN	E	(Undefined)	- ***
906	RELIGIOUS_ORGANIZATN	E	(Undefined)	- ***
907	121_A_PROPERTY	EA	Residential	1
908	BOSTON_HOUSING_AUTH	E	Residential	1
910	MASS_DEPT_CONSERVATION	E	Office	3
911	MASS_DIVISION_OF_WILDLIFE	E	Office	3
912	MASS_DEPT_OF_YOUTH_SERVICES	E	Office	3
913	MASS_DEPT_OF_PUBLIC_HEALTH	E	Office	3
914	MASS_DEPT_OF_MENTAL_HEALTH	E	Office	3
915	MASS_DEPT_CONSERVATION	E	Office	3
916	MASS_MILITARY_DIVISION	E	Office	3
917	MASS_DEPT_EDUCATION_COLLEGE	E	Office	3
918	MASS_ENVIRONMT_PROTECTION	E	Office	3
920	MASS_DEPT_CONSERVATION	E	Office	3
921	MASS_ENVIRONMT_PROTECTION	E	Office	3
922	MASS_CORRECTIONS_POLICE	E	Office	3
923	MASS_DEPT_OF_PUBLIC_HEALTH	E	Office	3
924	MASS_HIGHWAY_DEPT	E	Office	3
925	METROPOLITAN_DIST_COM_MDC_	E	Office	3
926	MASS_DEPT_JUSTICE_JUDICIARY	E	Office	3
927	MASS_DEPT_EDUCATION_COLLEGE	E	Office	3
928	MASS_DIV_CAPITAL_ASSET_MGMT	E	Office	3
929	MASS_(Undefined)_PROPERTY	E	Office	3
937	DORMITORY_BEDS	E	Residential	1
941	AUDITORIUM_THEATER	E	Convention/Assembly	7
942	CLASSROOM	E	College/Academic	17
943	COMPUTER_SCIENCE_LAB	E	-	- *
944	DINING_FACILITY_CAFETERIA	E	Restaurant	10
945	ACTIVITY_SOCIAL_CENTER	E	Office	3
946	RETAIL_USE_EXEMPT_	E	Retail	2
947	ATHLETIC_SPORTS_CTR	E	Athletic Facility	11
948	LAUNDRY_FACILITY	E	Retail	2
949	STORAGE_AREA_SUPPLIES	E	Warehouse/Storage	15
950	APARTMENT_BLDG	E	Residential	1
951	DORMITORY_RESIDENCE_HALL_R_M	E	Residential	1
952	OFFICE_ADMINISTR_BLDG	E	Office	3
953	MEDICAL_CLINIC_OUTPATIENT	E	Medical/Lab	5
954	MEDICAL_OFFICE	E	Office	3

BRA Code	BRA Property Type Name	BRA Land Use	CWES Use Type	CWES Code
955	LABORATORY_MEDICAL_BIOLOGY	E	Medical/Lab	5
956	MORGUE	E	-	- *
957	MAINTENANCE_SERVICE_BLDG	E	-	- *
958	REHAB_CONVALESCENT_FACILITY	E	Medical/Lab	5
959	ASSISTED_LIVING_ELDERLY_HOME	E	Residential	1
960	-	E	(Undefined)	- ***
961	PARKING_GARAGE	E	Garage	14
962	PARKING_LOT	E	Garage	14
963	HVAC_EQUIP_UTILITIES_BLDG	E	-	- *
964	-	E	-	- *
965	GOV_OFFICE_BLDG	E	Office	3
966	INDUSTRIAL_MFG_BLDG	E	Industrial	19
967	LOFT_BLDG_COMMERCIAL_USE	E	Office	3
968	WAREHOUSE	E	Warehouse/Storage	15
969	BOAT_REPAIR_STORAGE	E	Warehouse/Storage	15
970	CHURCH_SYNAGOGUE	E	Worship	13
971	RECTORY_CONVENT	E	Residential	1
972	CORRECTIONAL_BLDG	E	-	- *
973	ADMINISTRATIVE_BLDG	E	Office	3
974	FIRE_STATION	E	Fire/Police	6
975	POLICE_STATION	E	Fire/Police	6
976	SCHOOL_ELEMENTARY_&_HIGH_S	E	School/Daycare	4
977	COLLEGE_ACADEMIC_	E	College/Academic	17
978	LIBRARY	E	Library	16
979	HOSPITAL_EXEMPT	E	Medical/Lab	5
980	WATER_TREATMT_PLANT	E	-	- *
981	INCINERATION_PLANT	E	-	- *
982	ARMORY_MILITARY	E	-	- *
983	CEMETERY	E	-	- *
984	PUBLIC_BEACH	E	-	- *
985	(TAXEXEMPT)_EXEMPT_BLDG	E	(Undefined)	- ***
986	(TAXEXEMPT)_PUBLIC_LAND	E	(Undefined)	- ***
987	EXM_NON_PUBLIC_LAND	E	(Undefined)	- ***
988	CONVENTION_CTR_HOTEL	E	Hotel	9
989	PASSENGER_TERMINAL	E	Transport	18
990	RETAIL_CONDO_EXEMPT	E	(Condominium)	- **
991	OFFICE_CONDO_EXEMPT	E	(Condominium)	- **
992	RESIDENTIAL_CONDO_EXEMP	E	(Condominium)	- **
993	INDUSTRIAL_CONDO_EXEMPT	E	(Condominium)	- **
995	CONDO_MAIN	CM	(Condominium)	- **
999	PARTIAL_EXEMPT	E	-	- *

*   Property type not suitable for building energy modeling.

**   Condominium property use in a single or multi use parcel.

***   Use type undefined or only defined as tax exempt.

APPENDIX 3
Archetype characterization of thermal simulation parameters

(Section in preparation. Available in future complete version of this document.)