CITY SCALE MODELING WITH OPENSTUDIO

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ABSTRACT

Assessing the impact of energy efficiency technologies at a district or city scale is of great interest to local governments, real estate developers, utility companies, and policymakers. This paper describes a flexible framework that can be used to create and run district and city scale building energy simulations. The framework is built around the new OpenStudio City Database (CityDB). Building footprints, building height, building type, and other data can be imported from public records or other sources. Missing data can be inferred or assigned from a statistical sampling of other datasets. Once all required data is available, OpenStudio Measures are used to create starting point energy models and to model energy efficiency measures for each building. Together this framework allows a user to pose several scenarios such as "what if 30% of the commercial retail buildings added rooftop solar" or "what if all elementary schools converted to ground source heat pumps" and then visualize the impacts at a district or city scale. This paper focuses on modeling existing building stock using public records. However, the framework is capable of supporting the evaluation of new construction, district systems, and the use of proprietary data sources.

INTRODUCTION

The amount of information collected about the built environment is increasing every day. The potential to extract value from these data increases as more data are collected and made available. Local governments hope to use this information to meet energy performance goals at the city level. Real estate developers hope to design net zero energy districts. Utilities hope to better target incentives that will save more energy for less money. Local policymakers hope to know how new rules and regulations will impact energy use and greenhouse gas emissions.

In order to provide these stakeholders with the data that they need, many cities are adopting open data policies that aim to make public data as accessible as possible. One significant new development is the adoption of energy use disclosure laws, which require that certain buildings publicly disclose their energy use. As the value of this energy use data becomes more clear (Krukowski 2014) and the challenges of making energy use information public are addressed (Krukowski and Majersik 2013), local governments are adopting positions that are pro-public disclosure of energy information (NASEO 2015).

As more information becomes publicly available and computational resources continue to become more affordable, it is no surprise that detailed modeling at the district and city scales is becoming more common for a wide range of analyses. Issues such as transportation, air quality, urban heat island effect, electrical power distribution, and building energy performance can now be examined in new ways. In the case of urban building energy modeling (UBEM), it appears that the trend is towards bottom-up modeling in which each building is modeled individually. Trends and simulation methodologies for this bottom-up UBEM are explored in detail by Cerezo and Cristoph (2016).

Several UBEM software solutions have been developed. In Germany, an energy simulation of more than 14,000 buildings in the city of Ludwigsburg was performed (Nouvel et al. 2014) using the ISO 13790 heat balance algorithm (CEN/ISO 2008). CitySim (Robinson et al. 2009) simulates building energy using a simplified energy model and plans to incorporate water, transportation, and urban climate modeling in the future. The urban modeling interface (UMI) tool (Reinhart et al. 2013) performs operational energy, daylighting, and walkability evaluations of complete neighborhoods using EnergyPlus (Crawley et al. 2000) and Radiance (Larson and Shakespeare 1998). The work discussed in this paper is different from the work by Nouvel et. al. and CitySim in that this work uses the detailed simulation engines EnergyPlus and Radiance rather than simplified models. While this work and the UMI tool both use EnergyPlus and Radiance, UMI's user interface depends on the commercial Rhino software, whereas the user interface developed in this work is open source and freely available. Finally, this work is unique in that it is designed to provide a flexible, open source framework that others can use to implement custom district or city scale modeling applications.

OVERVIEW

The OpenStudio City Modeling Framework described in this paper is designed to enable rapid development of district and city scale energy modeling applications, in much the same way that the OpenStudio Software Development Kit (SDK) was designed to enable rapid development of energy modeling tools (Weaver et al. 2012). This paper describes the process of assembling open source projects into a framework that can be easily used for city scale modeling. This framework uses the existing OpenStudio Analysis (Long et al. 2014) project. The new OpenStudio City Database (CityDB) stores district and city scale building information. Just as the OpenStudio Application is a demonstration of the OpenStudio SDK, a reference implementation of the OpenStudio City Modeling Framework is available to jumpstart new projects and can easily be customized.

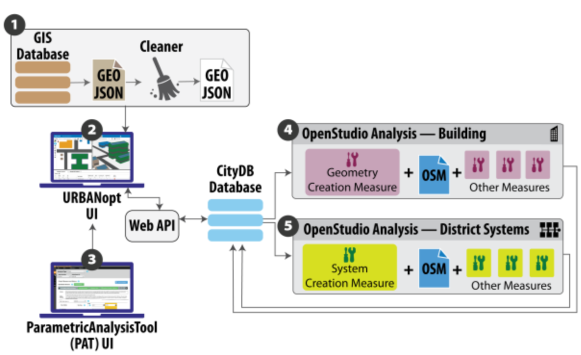

Figure 1 OpenStudio City Modeling Framework

An overview of the OpenStudio City Modeling Framework is shown in Figure 1. The workflow for using this framework is outlined below, and each step is further explained in subsequent sections:

1. Building data, from public records or other sources, are collected in GeoJSON format. Cleanup scripts align terms with the CityDB schema and infer missing data.
2. Building data in GeoJSON format is uploaded to the CityDB using a simple Web interface.
3. An OpenStudio Analysis describing workflows to simulate baseline buildings as well as energy-efficient alternatives using OpenStudio Measures (Roth et al. 2016) is developed using the Parametric Analysis Tool and uploaded to the CityDB using the simple Web interface.
4. Scenarios are created that assign specific design alternatives to each building in the CityDB. These design alternatives are simulated by applying a series of OpenStudio Measures to generate the baseline building and to model energy efficiency options. Simulation results are pushed back to the CityDB. If desired, simulation results can also be pushed to a DEnCity database (Roth et al. 2012).
5. If the scenario includes district systems, a separate simulation is run for each district system. The district system analysis includes a system creation measure that pulls time-series of loads for each building on the system from the CityDB and assembles an energy model of the district system. The district system model is simulated and results are pushed to CityDB and, if desired, DEnCity.
6. After simulations are complete, a scenario exporter gathers simulation results for each building and district system in the scenario and exports a GeoJSON file containing simulation results.

INPUT DATA SOURCES

The first step in applying the OpenStudio City Modeling Framework is to gather building information for the regions of interest. This initial work is focused on using publicly available data for existing buildings. Public records were collected for three cities: San Francisco, California; Denver, Colorado; and Portland, Oregon. All three cities are following a nationwide trend to increase availability of public data while encouraging third parties to build applications on top of this data. San Francisco has an open city data initiative with more than 340 public datasets (City and County of San Francisco 2016). Denver has 203 public datasets (City and County of Denver 2016). Portland has an open data initiative (City of Portland 2016) with 149 public datasets. For this initial work, the only datasets considered for each city were the building footprint datasets (City and County of San Francisco 2012), (Denver Regional Council of Governments 2014), (City of Portland 2013). A selection of building footprints available for the city of Portland, Oregon, is shown in Figure 2.

Figure 2 Portland building footprints

Merging these footprint datasets with other datasets (either public or proprietary) would result in richer sets of information that would support more detailed and accurate energy models. One dataset of particular interest is San Francisco's dataset of publicly disclosed energy usage for select commercial buildings (SF Environment 2016). The Standard Energy Efficiency Data (SEED) Platform™ (Alschuler et al. 2014) has been developed specifically for cities to manage this type of disclosed energy data. Furthermore, SEED provides many data cleansing and merging features that would be ideal for merging multiple datasets. However, merging multiple datasets was out of the scope of this work.

Each footprint dataset was evaluated for the minimal pieces of information required for energy simulation. Building footprint is required to generate the overall shape and size of the building. Building area is required to capture the useful area within the building. Building height is required to capture the building volume and exterior wall area. The number of stories is related to building height and floor area. Building type is required to assign interior loads and schedules. Building address is not required to perform an energy simulation. However, building address is often a key identifier used to join multiple datasets.

If some of the information required for simulation is missing, it can be estimated using other information. If the floor area is not available, the number of stories may be estimated based on building height. If the number of stories is not available, the ratio of floor area to footprint area can serve as a surrogate. If the number of stories is not known it can be estimated from the building height. If building area is not available it can be estimated using footprint area and number of stories. If building type is not available, it can be inferred using zoning, building size, or other information.

Table 1 Summary of public data for three cities

City	Foot-print	Area	Num Stories	Height	Type	Address
San Francisco	Yes[1]	No	No	Yes[1]	Yes[2]	No
Denver	Yes	No	No	Yes	Yes[2]	No
Portland	Yes	Yes	Yes	Yes	Yes[2]	Yes

[1] Complicated by merged footprints
[2] Not directly available, inferred from zoning data

As shown in Table 1, footprint data from each city contained the minimal information to support simulation. The San Francisco building footprints offered one particular challenge that the other cities did not have. Close inspection found that the footprints in the San Francisco dataset often spanned tax lots and individual footprints actually represented multiple buildings. It is likely that the footprint generation process merged adjacent buildings due to the close proximity of buildings in San Francisco. To separate these merged footprints, the footprints in the dataset were intersected with tax lot boundaries and the resulting shapes were taken to represent individual buildings. All of the original footprints in the San Francisco dataset included minimum and maximum roof height information generated by Light Detection And Ranging (LiDAR) measurements. However, this information was only available for the merged footprints and was not available for individual buildings. The hilly topology of San Francisco further compounded this problem as a significant portion of the elevation gain over a merged footprint could come from change in elevation of the street.

Detailed building type information was not present in the footprint data for any city. However, zoning information (commercial, residential, open space, etc.) was available for all cities along with identifiers separating real buildings from other features (e.g., sheds, water tanks, etc.). Several approaches to infer more detailed building type from the available information are possible. One option explored was to separate the buildings into commercial and residential buildings and take a statistical sampling of the same, or slightly higher, number of buildings from the Commercial Buildings Energy Consumption Survey (CBECS) (EIA 2012) or the Residential Energy Consumption Survey (RECS) (EIA 2009). The buildings in the statistical sample were then assigned to the buildings in the floorprint dataset such that the difference in floor area was minimized. Alternatively, datasets from proprietary sources such as CoStar

(CoStar 2016) could be merged with the building footprints to provide building type information.

After reviewing all the footprint datasets, the authors concluded that Portland had the best footprint dataset of the three cities investigated in this work. The Portland building footprints did not have the same issues with merged footprints that San Francisco did. All of the buildings in the Portland dataset had detailed zoning information (e.g., high-density residential, low-density residential, etc.). A total of 1,921 buildings were sampled in Portland as shown in Figure 2. Of these, 855 are residentially zoned, 646 are commercially zoned, 394 are industrial, 15 are open space, and 11 are zoned as mixed commercial and residential. Eight hundred seventy-two buildings have the number of residential units defined (ranging from 1-284). However, many buildings with residential units are commercially zoned rather than mixed commercial/residential. A large percentage of buildings, 92%, had address information. Most buildings, 99%, had information about the number of stories (ranging from 1-42). All of the buildings had floor area information and 96% of the buildings also had height information.

Because buildings in the Portland dataset had address information, it was easy to spot check information about particular buildings. However, these spot checks revealed that information in the dataset was not always accurate. For example, the number of stories for single family homes often appeared incorrect when looking at street level imagery. The Portland dataset included more than the minimal amount of information to support energy simulation. This additional information can be used to identify buildings that may contain incorrect information. These buildings can be flagged for manual inspection before simulation.

OPENSTUDIO CITY DATABASE

The OpenStudio City Database (CityDB) is central to the OpenStudio City Modeling Framework. The CityDB is a NoSQL Mongo database with a RESTful Application Program Interface (API). Because the Mongo database does not have a strict schema, building properties can be customized for each instance of the OpenStudio City Modeling Framework. However, these properties must be coordinated with the set of OpenStudio Measures used for building model articulation and modeling energy efficiency measures. To facilitate this coordination, the building properties can be specified with a JSON schema defining the properties that are allowed for each structure as well whether each property is required or optional. The reference implementation defines one such schema, but this may be customized for any other instance of the framework. When possible, property names should be aligned with entries in the Building Energy Data Exchange Specification (BEDES) (Mercado et al. 2014).

DATA TRANSFER FORMAT

Footprint data for all three cities was available in ESRI Shapefile format. The shapefile format is widely used but is not ideal for data processing. Therefore, data was exported from the footprint datasets to an intermediate file format for data processing and transfer to the OpenStudio CityDB. For city scale applications, geographical information needs to be included with the other building physical and energy properties. There are two prominent file formats capable of transferring building properties with geographical data structures: CityGML and GeoJSON. Both of these formats were considered as potential data transfer formats for the CityDB API.

CityGML (Kolbe et al. 2005) was investigated as a potential data transfer format, especially given the development of the Energy Application Domain Extension (ADE) (Wate and Saran 2015). However, the development of the Energy ADE is subject to a standards process and fairly inflexible, so it would not suit the need to provide custom data for different applications. Additionally, CityGML is not as widely supported in the United States as it is in Europe. If CityGML becomes a more widely adopted standard, then it could be added as an additional import/export format for CityDB.

The GeoJSON format was chosen as the data transfer format for the OpenStudio City Modeling Framework. GeoJSON is a widely used format for encoding a variety of geographic data structures as well as a flexible set of properties for each structure. GeoJSON supports the following geometry types: Point, LineString, Polygon, MultiPoint, MultiLineString, and MultiPolygon. The Coordinate Reference System is an additional feature that easily describes the data's geographic coordinate reference system. At the time of this writing, GeoJSON is supported by numerous mapping and GIS software packages, including OpenLayers, Leaflet, MapServer, Geoforge software, GeoServer, GeoDjango, GDAL, Safe Software FME, CartoDB, PostGIS, Mapnik, Github, Bing Maps, Yahoo! Maps, and Google Maps. Several databases, including MongoDB, support queries based on GeoJSON directly.

For this work, footprint data was exported from the original shapefile to many GeoJSON files, with one GeoJSON file per census tract. This resolution provided a nice balance between file size and the amount of content contained in each file. After exporting to GeoJSON, data cleaning scripts were run on each GeoJSON file. These scripts take a GeoJSON file as input and write a modified GeoJSON file as output. Additionally, these scripts map property names from those in the original data set to those in the CityDB schema. Finally, these scripts infer missing required data. Properties that are inferred are marked as such.

Because GeoJSON is a widely supported format, many tools already exist for generating, inspecting, and editing data in GeoJSON format. One such tool is freely available at http://geojson.io. This website allows a user to upload a GeoJSON file, plot the data on a map, view and edit properties, and save updated files. The authors found this website very useful for inspecting raw GeoJSON files exported from the public datasets as well as for inspecting cleaned GeoJSON files written by the data processing scripts. The website also allows users to delete existing features, modify vertices, and create new footprints. While not used in this work, these features could be leveraged for new construction projects.

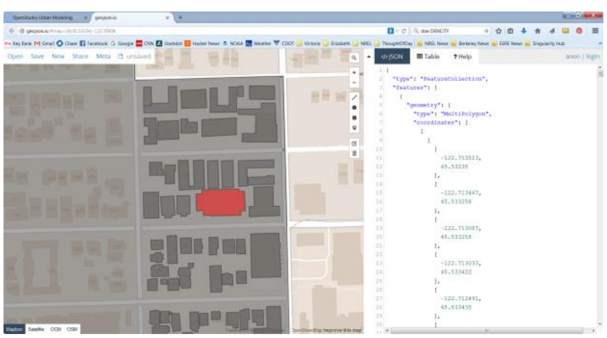

Figure 3 Portland footprints in geojson.io Web interface

OPENSTUDIO MEASURES

Like many applications built on OpenStudio, the OpenStudio City Modeling Framework uses OpenStudio Measures heavily. OpenStudio Measures are small scripts that automate portions of the energy modeling workflow (Hale et al. 2012). These scripts conform to a specific interface (NREL 2014) that takes an energy model as well as user arguments as input. The scripts leverage the OpenStudio Ruby API to alter the energy model and the output is a modified energy model. OpenStudio Measures can be chained together to implement a complete building energy modeling workflow.

The reference implementation includes OpenStudio Measures that can generate a starting point building for each building in the dataset. The first measure constructs building geometry from the data in a GeoJSON file. This measure has the option to include surrounding buildings as shading surfaces. If the GeoJSON structure is of type Polygon or Multipolygon, this geometry is used as the building footprint and extruded up. If the structure is of type Point, then basic box geometry is created. Methods that convert latitude and longitude in the WGS84 (NIMA 1997) coordinate system to and from a local Cartesian coordinate system have been added to the OpenStudio SDK to support this work. ***Figure 4*** shows OpenStudio geometry created from the dataset shown in ***Figure 3***. The building of interest is modeled in full detail while surrounding buildings are included for shading purposes only.

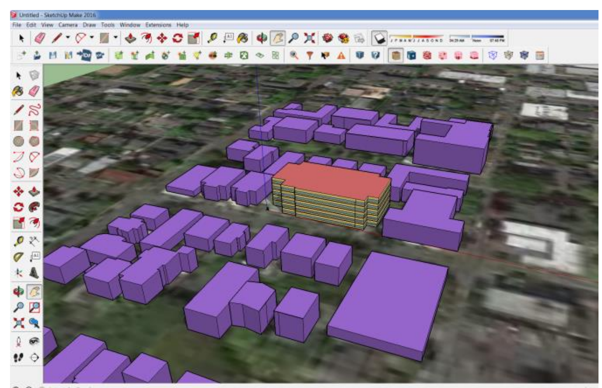

Figure 4 OpenStudio geometry for Portland dataset

Once the geometry has been generated, building type information is used to generate other energy modeling content. A building type measure is included in the reference implementation, which covers both commercial and residential buildings. For commercial building types, the baseline automation features of the OpenStudio standards gem are used to generate an ASHRAE 90.1 Appendix-G compliant baseline model. For residential buildings, a series of OpenStudio Measures implementing logic originally written for the BeOpt software (Christensen et al. 2006) are applied to generate a baseline building. Other OpenStudio Measures for modeling energy efficiency measures are left to the user. Examples include lighting retrofit, elevator retrofit, install solar photovoltaics, etc. OpenStudio Measures can be found in the Building Components Library (Fleming et al. 2012) and users can also write their own.

After all baseline generation and energy efficiency OpenStudio Measures have been run, the building energy model is simulated in EnergyPlus. After the energy simulation is complete, a series of OpenStudio Reporting Measures are run. These OpenStudio Reporting Measures access simulation results to calculate specific metrics or perform quality control checks. One OpenStudio Reporting Measure gathers high level results and sends them back to the CityDB. Another OpenStudio Reporting Measure pushes time-series data from the simulation (e.g., hourly electrical usage) to the CityDB database.

OPENSTUDIO ANALYSIS

This work leverages the OpenStudio Analysis format to define and run parametric analysis for each building. If the simulation includes district systems such as central chilled water plants, then a separate OpenStudio Analysis can be specified for each type of system. An OpenStudio Analysis defines a workflow of OpenStudio Measures that are applied to a starting point model. There are two types of OpenStudio Analysis; algorithmic and manual. Algorithmic analyses use a sampling or optimization algorithm to determine which combinations of variables to run. Manual analyses allow the user to create named combinations of variables. OpenStudio Analyses are currently defined using the OpenStudio Analysis Spreadsheet format. However, work is underway on the next version of the OpenStudio Parametric Analysis Tool, which will provide a graphical interface to the OpenStudio Analysis Format. Users will be able to define both algorithmic and manual analyses and perform simulations locally or using cloud resources.

The first version of the OpenStudio City Modeling Framework uses the manual analysis type. Users define simulation workflows for named design alternatives (e.g., “Baseline”, “30% Reduction”, “Net Zero”, etc). The “Baseline" simulation workflow would include OpenStudio Measures that construct a baseline building for simulation. The “30% Reduction” workflow would include OpenStudio Measures to construct the baseline building as well as additional OpenStudio Measures to reduce energy use. The “Net Zero” workflow would add further OpenStudio Measures to achieve a net zero performance level. The user then defines named scenarios in which each building is assigned a named design alternative. The scenario creation interface is shown in ***Figure 5***.

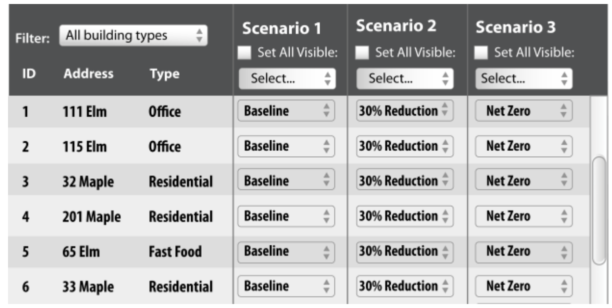

Figure 5 Mockup of scenario editor

In the future, the OpenStudio City Modeling Framework will be extended to support algorithmic analyses. This will allow buildings to be automatically calibrated to disclosed energy usage or optimized for energy given life cycle cost constraints.

SCENARIO EXPORT

After all simulations have been completed, each scenario can be exported as a GeoJSON file. This export will include building footprints, input parameters, and simulation results. Part of this work has been dedicated to the exploration of state-of-the-art virtual reality displays to manipulate, visualize, and analyze output of the OpenStudio City Modeling Framework. NREL’s Insight Center Visualization Lab provides a two-surface, optically tracked, stereoscopic immersive environment. This exploration is motivated by evidence that suggests interaction with and understanding of complex spatial data can be improved in these types of immersive virtual environments (Gruchalla 2004).

After the simulations are run and scenarios exported to GeoJSON format, these scenarios may be loaded into the NREL Insight Center, where the building structures are presented in three dimensions optionally overlaid with their energy properties and their time-series results. While the three-dimensional buildings have a direct mapping into the space, the selection and manipulation of the energy properties and simulation results associated with those structures can be cumbersome in three-dimensional space. To facilitate selection and manipulation of these data, we have integrated a Web server with a RESTful mode into the immersive visualization application. This allows the rich immersive environment to be controlled with an intuitive tablet interface. The aim is to further enhance researchers’ ability to interact and explore these scenario data in real time.

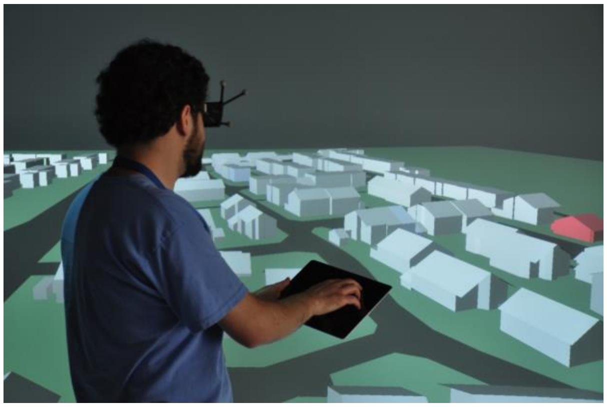

Figure 6 Initial NREL Insight Center interface

CONCLUSION AND FUTURE WORK

Bottom-up building energy modeling at the district and city scale is sure to remain a hot topic in the near future. The OpenStudio City Modeling Framework provides a flexible framework that others can use to build custom city scale modeling applications. Future work includes integrating CityDB with the SEED Platform. If disclosed energy usage is publicly available for buildings, the OpenStudio City Modeling Framework can use this information to first remove any universal bias in the modeling assumptions and then to calibrate individual buildings against past data.

The first application to be built on the OpenStudio City Modeling Framework is URBANopt (Polly et al. 2016). URBANopt is being developed to provide a complete user interface to the building and district system capabilities discussed in this work. In addition to being able to import data for existing buildings, URBANopt will allow users to define floorprints and building properties for new construction. URBANopt will also allow users to define district systems on the map to calculate the length of piping, which is an important component of the cost for district water systems. Finally, URBANopt will be able to display results for scenarios after the simulations are complete. The user can select a scenario, e.g., “High Performance Schools” or “2030 Goals,” to export from the CityDB as GeoJSON. Static values can be overlaid onto building geometry for annual metrics such as energy use intensity or carbon emissions. Time-series data can be explored with an interactive time dial.

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