Carnegie Mellon University

Master Thesis

Dynamic Energy Mapping

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Abbreviations

CMU	**C**arnegie **M**ellon **U**niversity
GHG	**G**reen**H**ouse**G**as
EPM	**E**nergy**P**otential**M**apping

Symbols

THR	condenser total heat of rejection	Btuh
RE	net refrigeration effect	Btuh
f	Heat Rejection Factor	1

Chapter 1

Methodology

1.1 Overview

The Dynamic Energy Map is created for a conceptual urban environment with the following properties:

i. Of realistic building density and land use pattern.

   To achieve this, the current study used a redevelopment project at Lower Hill District, Pittsburgh, PA [2] as a prototype. The land use of the conceptual urban environment is created based on extracted topological patterns from this redevelopment project.

ii. The number of buildings in the model represents a typical community that can be served by a district energy system [3].

   To achieve this, the original model created under criteria i. is duplicated and thus there are in total 68 buildings within the community. It is within the range of a typical district energy system service capacity of 50 to 150 [3].

The inputs to the dynamic energy map include the hourly energy consumption data and the urban environment layout. For the conceptual setting, the energy data is retrieved from the simulation of DOE Benchmark buildings of new construction which comply with ASHRAE 90.1-2013 Standard [4].

The output of the dynamic energy map is a sequence of 2D or 3D energy choropleth map images.

An interface is designed to provide an interactive inspection of the map image sequence and the corresponding energy data plot of a single buildings, building groups and the community that assists:

i. Comparing heating and cooling demand to identify energy recovery opportunities

ii. Comparing heating and electricity demand to size co-generation system

By replacing the simulated hourly energy demand data with actual metered energy consumption data and the conceptual layout with a real urban environment layout, the same method can be directly applied to the analysis of a real project.

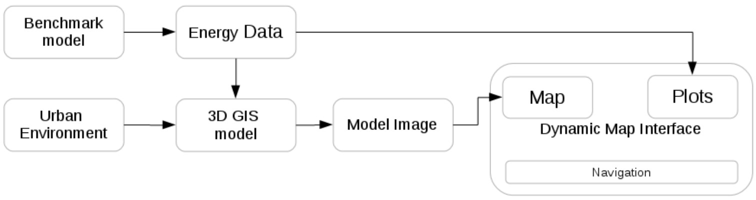


FIGURE 1.1: General Work Flow

Details in input output data and the interface design process will be explained in more details in the following sections.

1.2 Input

1.2.1 Benchmark Models and Energy Data

In the Lower Hill District project, the DOE benchmark buildings were substituted for buildings in the community model in the district system feasibility analysis. This approach allows for a fast initial assessment of the district system [5].

Following the same approach, the energy profile used in the current study is retrieved from simulation results of commercial prototype building buildings developed by U.S. Department of Energy (DOE) [4]. There are 16 building types in the benchmark models (Figure 1.1). The building types involved in the current project include: Large Office (LO), Medium Office (MO), Small Office (SO), Stand-alone Retail (SR), Strip Mall (SM), Quick Service Restaurant (QR), Full Service Restaurant (FR), Large Hotel (LH) and Midrise Apartment (MA). The two-letter shorthand in the parenthesis after each building type is used in the building label for the dynamic map display. The general information for the benchmark buildings are shown in Table 1.1:

Building Type	Building Area/ft2	Number of Floors
Small Office	5502	1
Medium Office	53628	3
Large Office	498588	12
Stand-alone Retail	24692	1
Strip Mall	22500	1
Primary School	73959	1
Secondary School	210886	2
Outpatient Healthcare	40946	3
Hospital	241501	5
Small Hotel	43202	4
Large Hotel	122120	6
Warehouse (non-refrigerated)	52045	1
Quick Service Restaurant	2501	1
Full Service Restaurant	5502	1
Mid-rise Apartment	33741	4
High-rise Apartment	84351	10

TABLE 1.1: DOE Benchmark Building General Information [1]

The benchmark buildings comply with the ASHRAE Standard 90.1-2013. The HVAC system types are shown in Table 1.2. The major heating systems of the benchmark buildings are furnace and boilers, except that the small hotel and the warehouse has individual space heaters other than furnaces. The cooling systems are chillers for Large

Hotel (air-based) and Large Office (water-based) and PACU (packed air-conditioning unit) for other building types.

Table 1.2: Benchmark Building HVAC System

Building Type	Heating	Cooling	Air
Small Office	Air-source heat pump with gas furnace as back up	Air-source heat pump	Single zone, constant air volume air distribution, one unit per occupied thermal zone
Medium Office	Gas furnace inside the packaged air conditioning unit	Packaged air conditioning unit	VAV terminal box with damper and electric reheating coil
Large Office	Gas boiler	Water-source direct expansion cooling coil with fluid cooler for datacenter and IT closets Two water-cooled centrifugal chillers for the rest of the building	VAV terminal box with damper and hot-water reheating coil non-datacenter portion of the basement and IT closets that are served by CAV units.
Stand-alone Retail	Standalone gas furnace for front_entry Gas furnace inside the packaged air conditioning unit for the rest	Packaged air conditioning unit	Constant air volume air distribution
Strip Mall	Gas furnace inside the packaged air conditioning unit	Packaged air conditioning unit	single-zone rooftop units with Constant air volume air distribution
Primary School	1. Gas furnace inside packaged air conditioning unit 2. Hot water from a gas boiler for heating	Packaged air conditioning unit	1. CAV systems: direct air from the packaged air conditioning unit 2. VAV systems: VAV terminal box with damper and hot water reheating coil
Secondary School	1. Gas furnaces inside packaged air conditioning units 2. Gas-fired boiler provide heating hot water and chilled water to these AHUs.	1. Packaged air conditioner 2. Air-cooled Chiller	1. CAV system: direct air from the packaged unit 2. VAV System: VAV terminal box with damper and hot water reheating coil
Outpatient Healthcare	Gas boiler	direct expansion cooling coil	VAV terminal box with damper and hot water reheating coil
Hospital	Gas boiler	Two water cooled centrifugal chiller	Medical critical zones: variable air volume systems with hot water reheating and electric stream humidifiers. Non-critical zones: VAV systems for general zones and one constant air volume (CAV) system for kitchen zone: VAV terminal box with damper and hot water reheating coil
Small Hotel	Guest rooms: Packed terminal air conditioner with electric resistance heating Public spaces: gas furnace inside the packaged air conditioning units Storage and stairs: electric cabinet heaters	Guest rooms and corridors: Packed terminal air conditioner Public space: Split system with direct expansion cooling	Constant air volume systems
Large Hotel	One gas-fired boiler	One air-cooled chiller	Public spaces on ground floor and top floor: VAV with hot water reheating coils; Guest Rooms: dedicated outside air system + four-pipe fan-coil units.
Warehouse (non-refrigerated)	Gas furnace inside the packaged air conditioning unit	Packaged air conditioning unit	Direct, uncontrolled air
Quick Service Restaurant	Gas furnace inside the packaged air conditioning unit	Packaged air conditioning unit	Single zone, constant air volume air distribution
Full Service Restaurant	Gas furnace inside the packaged air conditioning unit	Packaged air conditioning unit	Single zone, constant air volume air distribution
Mid-rise Apartment	Gas Furnace	Split system direct expansion (1 per apt)	Constant volume
High-rise Apartment	Water Source Heat Pumps	Water Source Heat Pumps	Constant volume

1.2.1.1 Input for Identifing Energy Recovery Opportunities

The major heat rejection sources include heating mode heat rejection and cooling mode heat rejection. The heat rejection in heating mode happens during the process of the mixing of conditioned and outside air. This source of heat rejection is more difficult to capture and is thus left out from the energy recovery potential calculation in this study. The current study will only focus on the cooling induced heat reject.

The heat rejection in cooling mode happens during the condensing process when the high temperature refrigerant gas condenses with one of the following heat rejection forms [6]:

- Air cooled unit: ambient air is blown through condensing coils and removes heat from the gas refrigerant.
- Cooling tower: cooled water flow past the condensing unit and takes away the heat from the gas refrigerant. The water is then cooled through evaporation.
- Fluid cooler: water is sprayed on the condensing coil with fan forced air flowing in the opposite direction. It causes evaporative cooling effect that takes away the heat from the gas refrigerant.

The "condenser total heat of rejection" [6] (THR) in the condensing process equals to the "net refrigeration effect" [6](RE, the hourly cooling demand), plus the compressor input, it can be represented with the following equation [6]:

$$THR = RE * f \tag{1.1}$$

f is the "Heat Rejection Factor" and it is typically between 1.15 and 1.25 [6]. The water-based system has heat rejection factor closer to 1.15 and the air-based system closer to 1.25 [6].

To help users identify energy recovery opportunities, the energy information needed to retrieve include: space heating energy demand and space cooling energy demand. The space cooling demand (RE in Equation 1.1) is an indicator for heat rejection that could be recovered and shared within a single building or a building group.

From Table 1.4, Small Office, Medium Office, Large Office, Outpatient Healthcare, Hospital, Small Hotel and High-rise Apartment use both electricity and natural gas for space heating, the rest of the building types uses only natural gas for space heating. We thus use the EnergyPlus simulation output parameters "heating:electricity" and "heating:gas" to represent the space heating demand of reference buildings.

TABLE 1.4: Annual Total Heating Demand by Fuel Type [1]

Building Type	Electricity [kBtu]	Natural Gas [kBtu]
Small Office	8189.1	5658.5
Medium Office	197799.9	264213.5
Large Office	10236.4	5047893.3
Stand-alone Retail	0	172550.1
Strip Mall	0	525450.8
Primary School	0	1099012.8
Secondary School	0	813350.2
Outpatient Healthcare	290458.5	472230.9
Hospital	805606.5	6794103.9
Small Hotel	266061.7	112117.3
Large Hotel	0	1831627.9
Warehouse (non-refrigerated)	0	645141.1
Quick Service Restaurant	0	545838.3
Full Service Restaurant	0	749543.2
Mid-rise Apartment	0	375307.1
High-rise Apartment	229712.9	831605.2

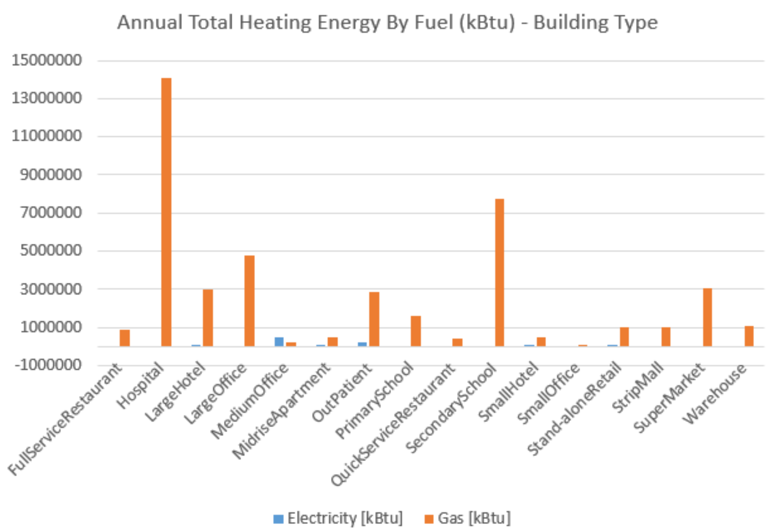


FIGURE 1.2: Heating Fuel

Electricity is the only fuel used for space cooling [1], thus the EnergyPlus output parameter "cooling:electricity" is used to represent space cooling demand. According to the suggested heat rejection factor [6], the heat recovery potential will be calculated with $f = 1.15$ for Large Office, Hospital and High-rise Apartment, and $f = 1.25$ for the remaining building types:

$$\text{Heat Recovery Potential} = \text{cooling:electricity} \times f \tag{1.2}$$

In summary, to facilitate identification of energy recovery opportunities for single buildings and within building groups, the hourly "heating:electricity", "heating:gas" and "cooling:electricity" output will be extracted from energyPlus simulation of DOE Commercial benchmark buildings.

1.2.1.2 Input for Sizing District Co-generation System

For the sizing of a district co-generation system, the relevant information needed are the total heating demand, and the total electricity demand. The general principle used in Lower Hill District project [5] is to use the minimum total heat demand (space heating and service hot water) over time to assess the minimum capacity of electricity generation (E_{heat}) such that its heat bi-product from electricity generation will always be consumed. The maximum total electricity demand (E_{elec}) is used for assessing the capacity of a backup system or a second phase system development by $C_{backup} = E_{elec} - E_{heat}$ where C_{backup} is the capacity of electricity generation for the backup system or second-phase development.

Heating demand assessed in the sizing of co-generation system is different from the energy recovery use case in Section 1.2.1.1 . It contains the space heating demand and the service hot water demand. From the summary files of benchmark models, we can see Small Office, Strip Mall, Warehouse and Mid-rise Apartment use electricity to produce service hot water; Medium Office, Large Office, Stand-alone Retail, Outpatient Healthcare, Small Hotel, Quick Service Restaurant and High-rise Apartment use gas for service hot water; Primary School, Secondary School, Hospital, Large Hotel and Full Service Restaurant use both electricity and gas for service hot water (Table 1.5). Thus the variable "Water Heater:WaterSystems:Electricity" and "Water Heater:WaterSystems:Gas" are used for representing energy demand for service hot water.

The output parameter "electricity:facility" was extracted to represent the total electricity demand.

TABLE 1.5: Service Hot Water by Fuel Type

Building Type	Electricity [kBtu]	Natural Gas [kBtu]
Small Office	17070.2	0
Medium Office	0	76090.7
Large Office	0	543231.8
Stand-alone Retail	0	91113.6
Strip Mall	61475.4	0
Primary School	24491.6	119823
Secondary School	146352.4	501006.6
Outpatient Healthcare	0	126524.1
Hospital	25098.2	1199178.1
Small Hotel	0	603797.3
Large Hotel	86004.9	2050241.9
Warehouse (non-refrigerated)	24719.1	0
Quick Service Restaurant	0	188473.4
Full Service Restaurant	71550.7	326902.1
Mid-rise Apartment	394917.4	0
High-rise Apartment	0	1116452.6

1.2.2 Simulation Data Analysis of the benchmark models

The output of EnergyPlus simulation of 16 benchmark buildings are read, processed and plotted with a python program. The data loading and processing utility is used in both data analysis and the dynamic plot in the interface design.

The energy output retrieved from EnergyPlus include "Heating:Gas", "Heating:Electricity", "Cooling:Electricity", "Water Heater:WaterSystems:Gas", "Water Heater:WaterSystems:Electricity" and "Electricity:Facility". This section will include some basic aggregated analysis of the data distribution. The meaning of each output variable is listed in Table 1.6:

TABLE 1.6: Table of EnergyPlus output and their meaning

EnergyPlus Output	Meaning
Heating:Gas	Total gas for space heating
Heating:Electricity	Total electricity for space heating
Water Heater:WaterSystem:Gas	Total gas for service hot water
Water Heater:WaterSystem:Electricity	Total Electricity for service hot water
Cooling:Electricity	Total electricity for space cooling
Electricity:Facility	Total electricity

1.2.2.1 Single Output

By analysing the EnergyPlus [7] simulation result of the output above, we anticipate to gain a basic understanding of the energy profile data distribution involved in the current project. We would also want to use this as a basis to compare with the additional analysis one can perform in a dynamic energy map in the following sections.

To analyse general distribution of each output variable, we created a box plot for each of the five variables. By analyzing each single output, we discovered a great difference between different building types.

Hourly gas heating demand of the benchmark buildings range from 0 to 8000 kBtu. The majority (75%) of all hourly consumption are below 1000 kBtu. All building types have a large amount of outliers above the 75% quartile. This indicates gas heating demand of all building types are severely right skewed. Hospital has the highest median gas heating demand of about 800 kBtu. Large Hotel has the second larges hourly gas heating demand. In terms of peak demand, Large Office and Secondary School have the highest peak hourly gas heating demand (Figure 1.3).

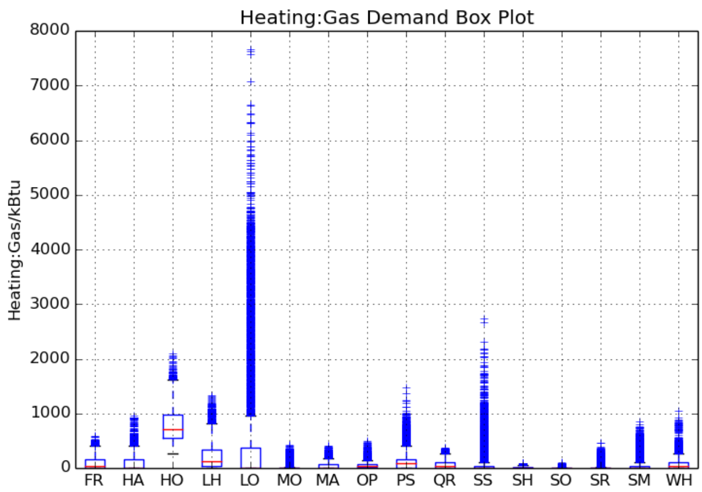


Figure 1.3: Heating:Gas Box Plot

Hourly hot water demand of the benchmark buildings range from 0 to 600 kBtu, about 1/12 of the range of space heating gas demand. Most buildings have median hot water hourly demand below 150 kBtu. Primary School and Secondary School has a large amount of outliers above the 75% quartile. This indicates hot water demand of these two types of buildings are severely right skewed. High-rise Apartment and Large Hotel has the largest median hot water demand of about 150 kBtu, indicating that these two building types have year round high hot water demand. First Service Restaurant, Hospital, Large Office, Mid-rise Apartment and Small hotel all has a median service hot water demand of about 50 kBtu. The remaining building types have almost zero median hot water demand. Large Hotel and Secondary School has the highest peak demand for service hot water.

(Figure 1.4).

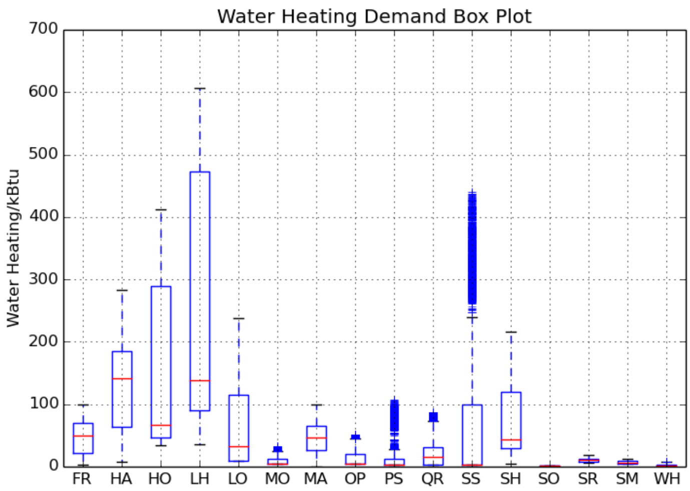
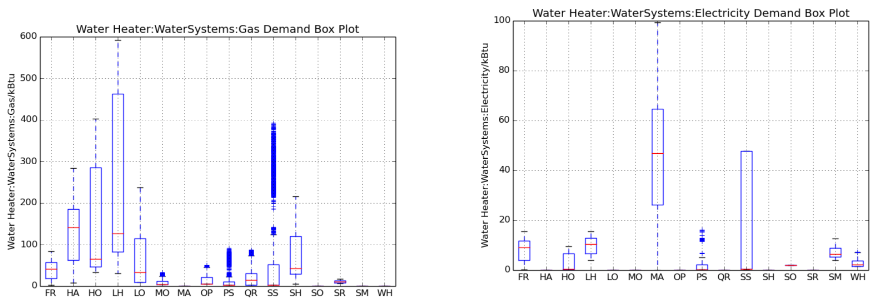


FIGURE 1.4: Service Hot Water Box Plot



(A) Gas Water Heating Box Plot

(B) Electricity Water Heating Box Plot

FIGURE 1.5: Comparing Heating:Gas and Space Heating

From Table 1.4, Small Office, Medium Office, Large Office, Outpatient Healthcare, Hospital, Small Hotel and High-rise Apartment use electricity besides natural gas for space heating. Hourly electricity heating demand of these buildings range from about 0 to 630 kBtu. Almost all of them has nearly zero median electricity heating demand, except the median demand for Outpatient Healthcare is around 30 kBtu. Almost all building types have a large amount of outliers above the 75% quartile except for hospital. This indicates electricity heating demand of all of these building types are severely right skewed. Medium Office has the highest hourly electricity heating peak demand and Outpatient Healthcare and Small Hotel have the second largest hourly electricity heating peak demand (Figure 1.6).

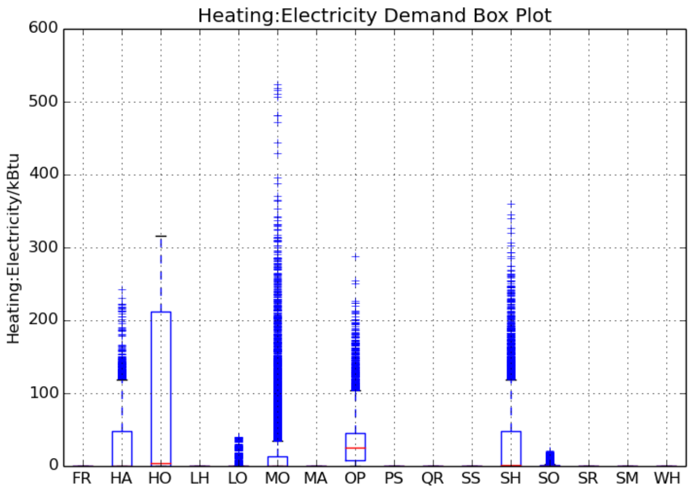


Figure 1.6: Heating:Electricity Box Plot

Hourly cooling demand benchmark building types range from 0 to 2000 kBtu, which is about 25% of that of the peak gas heating demand. The Hospital has the largest median cooling demand of about 150 kBtu. Large Office has the second largest median cooling demand. All building types have a large amount of outliers above the 75% quartile, indicating a severe right skew for their hourly cooling demand distribution. There are five building types with non-zero median hourly cooling demand: Hospital, Large Office, Outpatient Health Care, Large Hotel and Small Hotel. This means they need space cooling for at least 50% of the year. The constant cooling demand creates the opportunities for energy recovery of cooling induced reject heat. The building types with zero median hourly cooling demand then require cooling only in the cooling season. In terms of hourly cooling peak demand, the Large Office has the highest peak demand of about 1900kBtu and the Secondary School has the second largest peak demand of about 1500 kBtu (Figure 1.7).

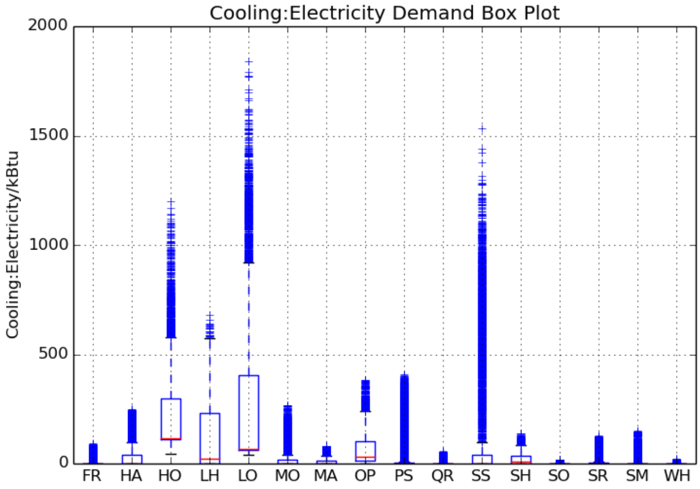


Figure 1.7: Cooling:Electricity Box Plot

The hourly electricity demand of benchmark buildings range from 0 to 8000 kBtu, which is about the same as that of the peak gas heating demand. Comparing with other output variables, the electricity demand distribution has less outliers in general. The Large Office has the largest median hourly electricity demand (about 3400 kBtu). The Hospital has the second largest median hourly electricity demand (about 2000 kBtu). Large Office has the largest electricity hourly peak demand.

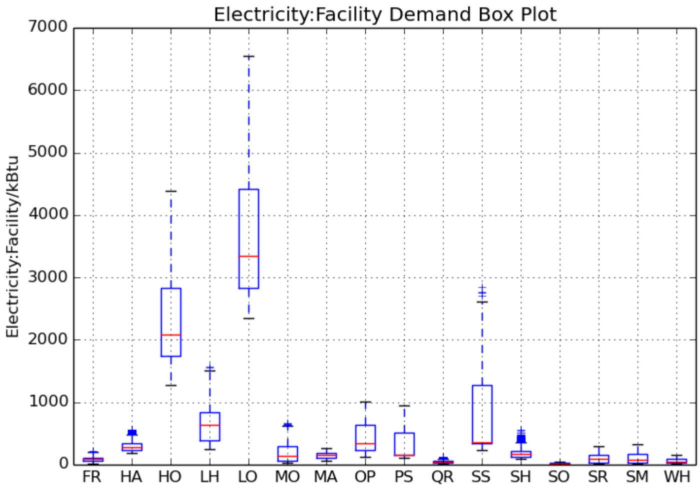
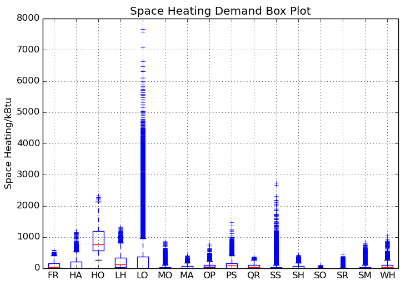


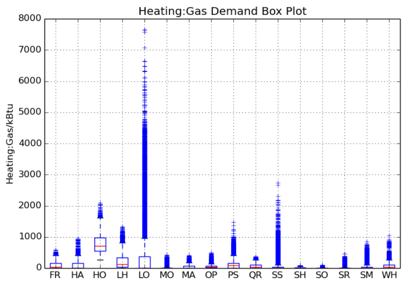
Figure 1.8: Electricity:Facility Box Plot

1.2.2.2 Space Heating Demand vs. Space Cooling Demand

Hourly space heating demand of the benchmark buildings mainly closely follows the distribution of gas heating demand, with minor demand increase in Hospital, Medium Office and Outpatient Health Care (Figure 1.10a).



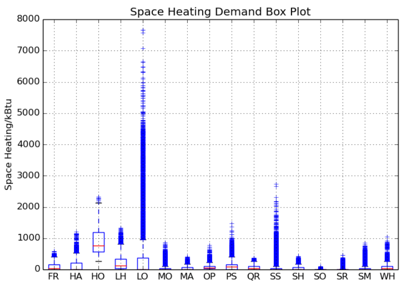
(A) Space Heating Demand Box Plot



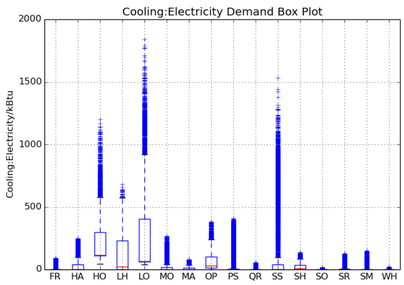
(B) Heating:Gas Box Plot

FIGURE 1.9: Comparing Heating:Gas and Space Heating

Comparing the space heating (Heating:Gas and Heating:Electricity) with space cooling (Cooling:Electricity), we can see that the heating peak demand is larger than cooling peak demand for all building types. The Hospital, Large Hotel and Outpatient Health Care have both the highest median space heating and cooling demand, indicating a potential for single building level energy recovery.



(A) Space Heating Demand Box Plot

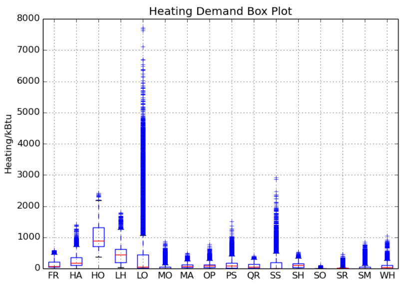


(B) Cooling:Electricity Box Plot

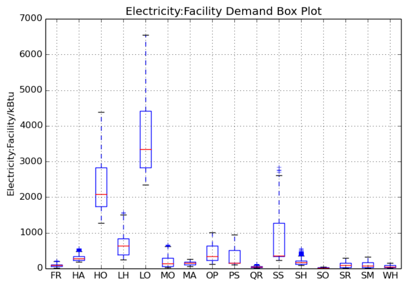
FIGURE 1.10: Comparing Space Heating and Space Cooling Demand

1.2.2.3 Heating Demand vs. Electricity Demand

Comparing the heat and power demand of each benchmark building type with the "heat to power ratio"(HTPR), one of the important parameters of a CHP plant. Depending on the prime mover types, a CHP plant can produce 0.6 to 10 unit of waste heat for one unit of electricity generation [8]. From Figure 1.12, we can see the range of HTPR is from 0 to 25. The building with highest median of HTPR is Quick Service Restaurant (about 1.5), all below 1. The remaining building types have a median HTPR below one. Increase the number of buildings with high HTPR ratio is helpful in more fully reuse of the waste heat from power generation. In addiction, the large range of Heat to Power ratio also indicates the necessity of heat storage equipment.



(A) Heating Demand Box Plot



(B) Electricity Demand Box Plot

FIGURE 1.11: Comparing Heating and Electricity Demand

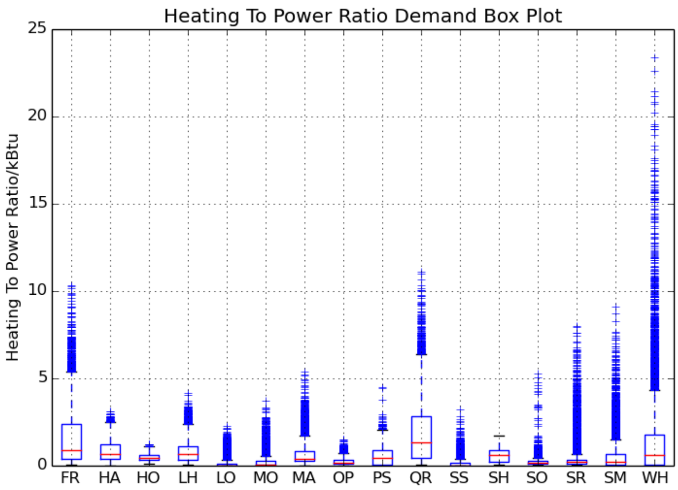


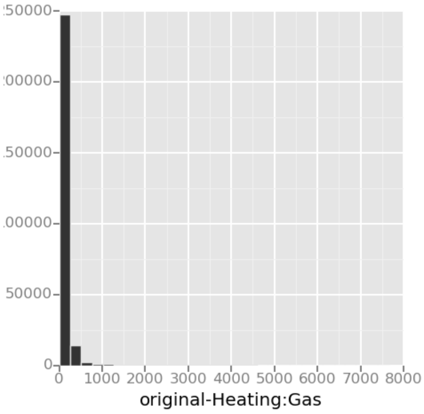
FIGURE 1.12: Heat to Power Ratio Box Plot

1.2.2.4 Aggregated Demand Distribution

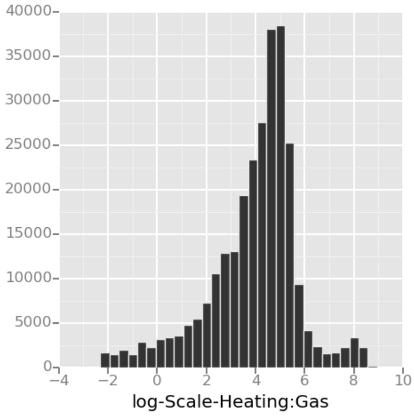
This section analyzes the energy demand distribution of the hourly energy demand (gas heating, electricity heating, service hot water, cooling and electricity demand) of all buildings in the community. All histogram show the distribution are very right skewed, so we paired the histogram of the original data with a histogram with log scaling. Interestingly, the log-scale distribution of gas heating demand, space heating demand looks like normal distribution while the others do not.

The difference in data distribution might influence the data classification and energy data color-encoding, which then influences the map display design, but for current map design, they are not taken into consideration yet. A closer look at how different energy data distribution can be better visually inspected could one of the topics for the next stage of the project.

- Heating:

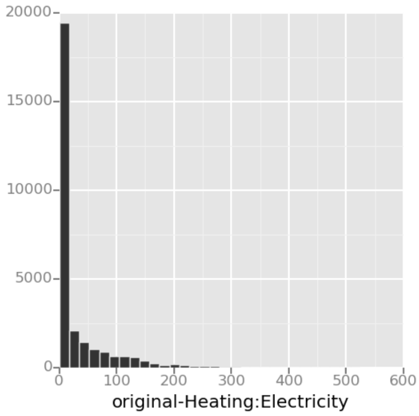


(A) Gas Heating Demand

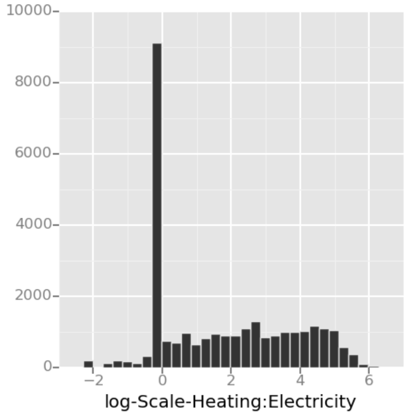


(B) Gas Heating Demand in Log Scale

FIGURE 1.13: Gas Heating Demand in Log Scale

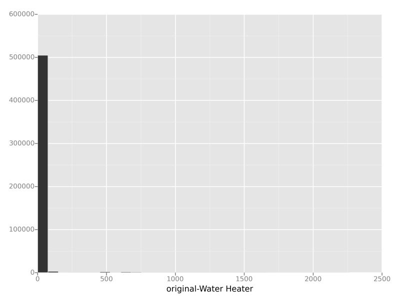


(A) Electricity Heating Demand

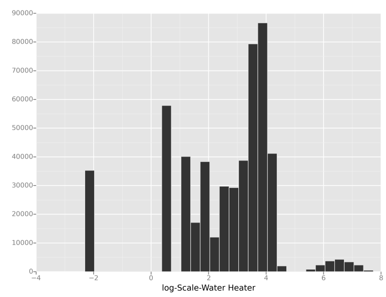


(B) Electricity Heating Demand in Log Scale

FIGURE 1.14: Electricity Heating Demand in Log Scale

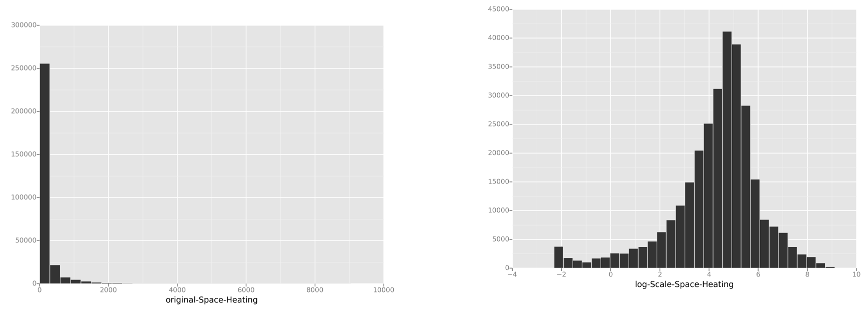


(A) Service Hot Water Demand



(B) Service Hot Water Demand in Log Scale

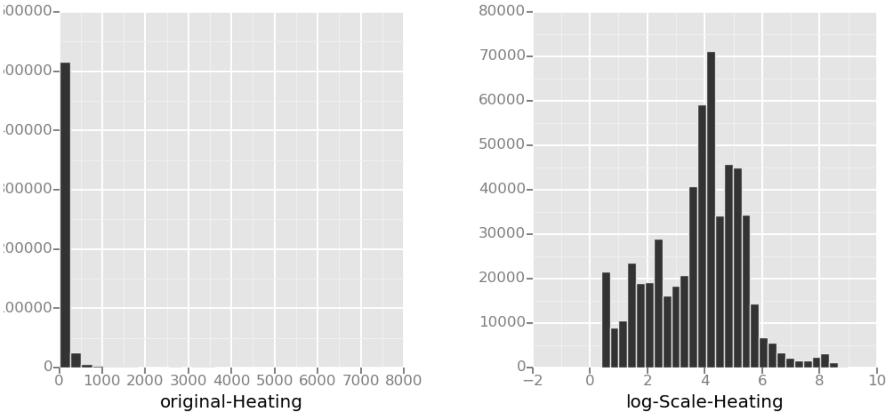
FIGURE 1.15: Service Hot Water Demand in Log Scale



(A) Space Heating Demand

(B) Space Heating Demand in Log Scale

Figure 1.16: Space Heating Demand in Log Scale

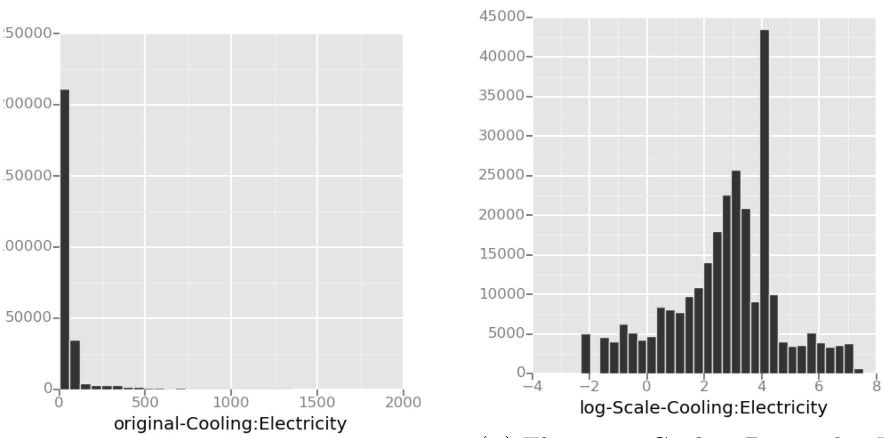


(A) Heating Demand

(B) Heating Demand in Log Scale

Figure 1.17: Heating Demand in Log Scale

- Cooling

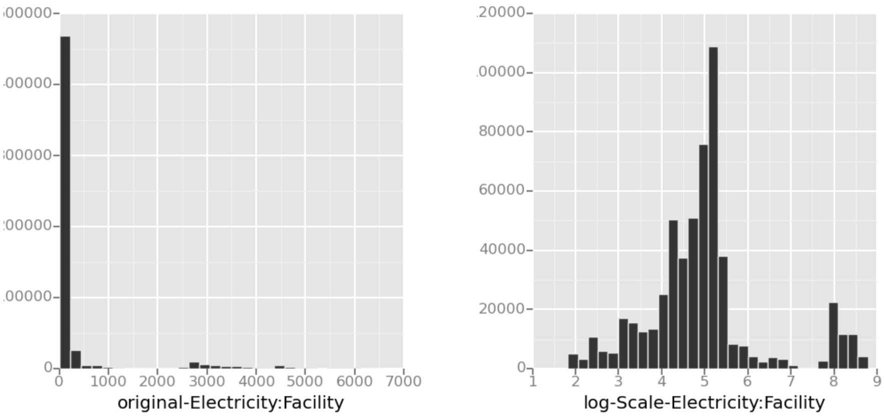


(A) Electricity Cooling Demand

(B) Electricity Cooling Demand in Log Scale

Figure 1.18: Electricity Cooling Demand in Log Scale

- Electricity



(A) Electricity Demand (B) Electricity Demand in Log Scale

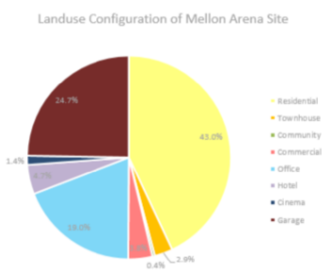
FIGURE 1.19: Electricity Demand in Log Scale

1.2.3 3D GIS Model Geometry

The conceptual community model is constructed in CityEngine [9]. CityEngine is a software developed by Esri [10]. It can aggregate geographic information into buildings and is capable of smoothly transition models to ArcGIS[11], one of the widely applied tools for Geo-referenced data presentation and analysis. Buildings in CityEngine is defined with "rules" using CGA (Computer Generated Architecture) shape grammar that is unique to CityEngine. The rule-based modeling of urban environment enables fast construction and easy adjustability of urban density, skyline and terrain control. It also enables easy aggregation of Energy profile data into 3D urban environment models, which is difficult to do in the current ArcGIS, the technical details will be explained in Appendix **??**.

Although the urban environment in this study is a conceptual setting, we still want it to reflect the topological and density pattern in a real urban environment. To construct the model, we first extracted the topological pattern from an existing urban design project, the Mellon Arena Project [5] (Figure 1.20a. There are eight building types in the project: Residential (43%), Town House (2.9%), Community Center (0.4%), Commercial (3.8%), Office (19%), Hotel (4.7%), Cinema (1.4%) and Garage (24.7%).

(A) Mellon Arena Project Site Plan View



(B) Mellon Arena Site Land use Configuration

The 16 building types in DOE commercial benchmark models do not perfectly correspond to those in the Mellon Arena Site. In order to adapt the topological pattern of the Mellon Arena Project, a mapping (function) from building types of Mellon Arena Site to building types of DOE models is created as is shown in Table 1.7.

The four major building sectors involved in the current project are residential, commercial, office and hotel. Their topological pattern is represented in Figure 1.21. The

Mellon Arena Type	Probability	DOE Building Type
Hotel	50%	Large Hotel
	50%	Small Hotel
Office	30%	Large Office
	30%	Medium Office
	30%	Small Office
Residential	100%	Midrise Appartment
Townhouse	100%	
Commercial	25%	Full Service Restaurant
+ Cinema +	25%	Quick Service Restaurant
Community	25%	Strip Mall
Center	25%	Stand-alone Retail

TABLE 1.7: Mapping of Mellon Arena to Building Types of DOE benchmark model

conceptual model construction follows the building type topological pattern and the urban density as the Lower Hill District Project (Figure 1.22)

After the land use is assigned (Figure 1.22), one rule file is applied to all the building lots and generates building geometries by extruding the building lot (with an offset to the interior) according to the number of floors of the benchmark buildings. We intend to make the building geometry simple in order to highlight the color of each building that encodes its energy demand.

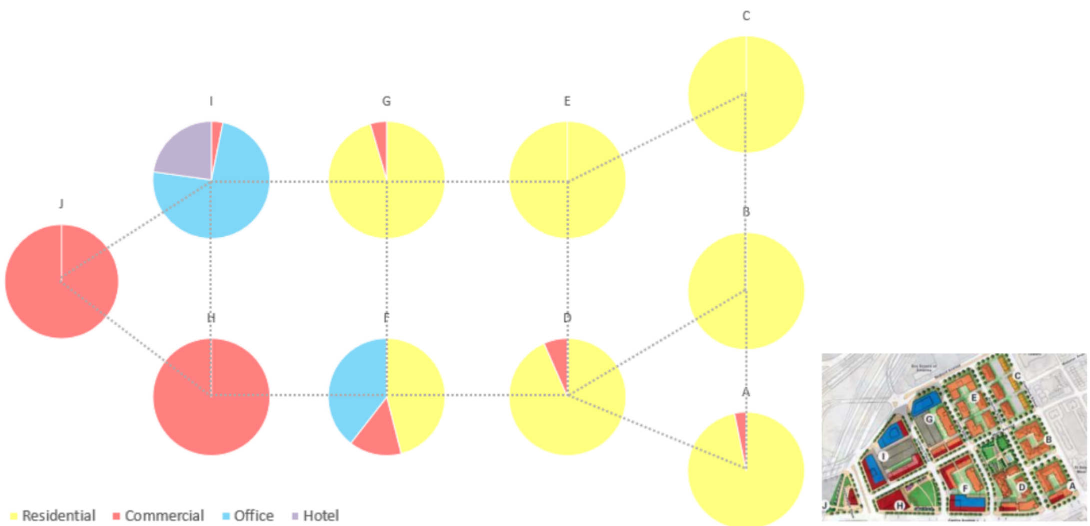


FIGURE 1.21: Building Type Topological Pattern, Mellon Arena

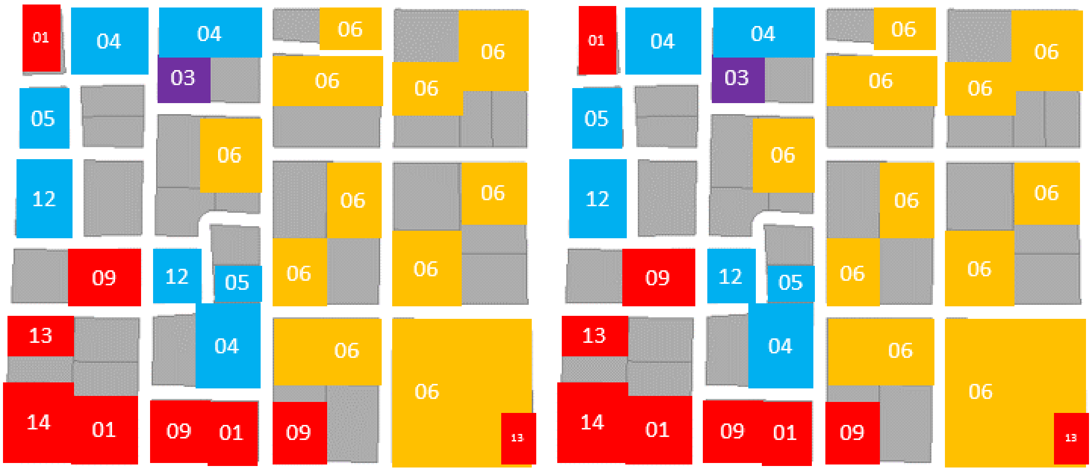


FIGURE 1.22: Site Plan of Conceptual Model
(01: Full Service Restaurant, 03: Large Hotel, 04: Large Office, 05: Medium Office, 06: Midrise Apartment, 09: Quick Service Restaurant, 12: Small Office, 13: Stand-alone Retail, 15: Strip Mall)

1.2.4 Aggregating Hourly Energy Data to 3D GIS Model

1.2.4.1 Comparing Different Approaches

The authors have experimented with two approaches to aggregate energy profile data into the conceptual model constructed in CityEngine

1) Importing 3D models from CityEngine to ArcScene and aggregate the energy data (in the form of a table) into the 3D feature with "one-to-many" join. For more details please refer to Appendix **??**

2) Write the energy profile data directly in the rule file for building generation in CityEngine. For more details please refer to Appendix **??**

3) Process the color encoding outside of CityEngine and write the generated color encoding representations in CityEngine. This method allows for more specialized symbol and color map design.

The second approach has the advantage of 1) ready-to-use data classification method and map symbol templates that facilitates choropleth map design 2) the "time-slider" function for creating a time-wise navigation and animated map. Figure 1.23 shows the interface slider and the dynamic map of heating energy demand for the conceptual model using ArcGIS. There are several problems of this approach: 1) its high requirement of computational power makes it infeasible to model or view on a typical PC. The authors only succeeded in importing the hourly energy profile data when using point features to represent building geometry. Even for the relatively simple 3D models in the current study, with a relatively higher performance machine (Dell Precision T1600 Quad Core Intel Xeon, 3.10GHz RAM - 16GB was used) for importing the data, the authors only suceeded in importing one month of data. This technical issue makes it impossible to using the current ArcGIS platform to implement high temporal resolution dynamic maps without either truncating time range or reducing the complexity for building geometry representation. 2) The time dimension only exists inside the map file. This means even one produced a dynamic energy map, one cannot share it without packing all related files and send to others. This requires the viewer end to also have a high performance computer to view and manipulate the map. Although the animated map can be exported as an animation, the output animation contains neither any form of temporal label nor the control of playback. Without time legend, when and for how long the dynamic changes happen are not shown. 3) For 3D GIS model, it does not contain a proper function to extract single frames of map images, making it impossible to implement exterior interface that deals with 3D maps images.

The first and third approach, on the contrary, provides more flexibility but also requires much user-end work including: pre-processing of energy profile data, implementing data classification method and the bivariate color ramp. An interface is also needed for visualizing the image sequence. Comparing these two approaches, since CityEngine does not provide the bivariate color ramp, the color encoding cannot be directly computed inside CityEngine, so the authors chose the method 3) for the final energy data aggregation method.

FIGURE 1.23: ArcGIS Time Slider for Temperal Data Display

Due to limited time, the experimented GIS software are only restricted to ArcGIS and CityEngine. There could be better alternatives to achieve a dynamic map with more elegance. Find a better alternative software to implement a dynamic map could be part of the work of the next stage of the project.

1.2.4.2 Data Classification

A function from energy data value to its color representation should be decided in order to visualize energy data in a map display. A common approach is to create a series of graduated color or symbol and classify the data into a few groups and assign each group one color or symbol in the series of symbols.

In order to write the data classification routine for the demonstration of dynamic energy map in the current study, the authors conducted a brief survey of the commonly used GIS software for commonly applied data classification methods. The software surveyed in the study include: ArcGIS [12], GRASS GIS [13], gvGIS [14], and QGIS. The data classification method adopted by the surveyed software in creating a thematic map include: 1) equal interval, 2) quantile 3) Jenks 4) Standard Deviation 5) pretty breaks and 6) manual interval (use context specific break point values). The common data classification method shared by all surveyed instances are "Equal Interval", "Quantile" and "User Defined". Therefore we chose to implement the "Equal Interval" and "Quantile" method in the current project.

	Equal Interval	Quantile	Jenks	Pretty Breaks	StDev	User Defined
ArcGIS	o	o	o	x	o	o
GRASS GIS	o	o	x	x	o	o
GVSIG	o	o	o	x	x	o
QGIS	o	o	o	o	o	o

Table 1.8: Data Classification Method (o: yes, x: no)

From the distribution of energy data in Chapter 1, we observed a severe right skew in energy data distribution of single buildings and the community, if using the "Equal Interval" method, the display will lack variation between different frames because the majority of data points will be concentrated in low-energy demand end. For "User Defined" breakpoints, further study or survey will be necessary to decide the set of robust breakpoints based on specific building energy context. The "Quantile" method is thus chosen as the data classification method for the demonstration of the functions of the dynamic energy map interface.

Take the Heating-Cooling dynamic energy map for example, the hourly space heating demand of all buildings in the community are classified based on the "Quantile" method into seven classes. There are $n = 68$ buildings in the community model. Each building has an $t = 8760$ hour space heating demand profile. For the space heating demand of the ith hour ($i \in 8760$) for the jth building ($j \in 68$) in the community, $H_{i,j}$ is mapped to an integer value from 0 to 6. Similarly, the space cooling demand of the ith hour for the jth building in the community, $C_{i,j}$ is also mapped to an integer value from 0 to 6. The color of the $i$hour for the jth building will be the color in the $C_{i,j}$th row $H_{i,j}$th column in the bivariate choropleth legend (Figure 2.14).

The color for every building type in every hour of the year is computed with a Python program from the input energy demand data of heating, cooling and electricity. The output of the program is a text file that could be directly copied into CityEngine.

1.3 Output Map Images

After the energy information was aggregated into the CityEngine model, map images are ready to be generated. The map images are extracted as snapshots from CityEngine with Python script by iterative setting the time step and extract snapshot of that time step:

```
'''
Created on Jun 5, 2015
@author: yujie
'''
from scripting import *
import time

# get a CityEngine instance
ce = CE()

def main():
    x = ce.getObjectsFrom(ce.scene, ce.withName("'LOT'"))  # < 1s
    for i in range(2):
        for item in x:
            ce.setAttribute(item, 'time', i) # 28 s
            views = ce.getObjectsFrom(ce.get3DViews())  # < 1s
        if i < 10:
            views[0].snapshot(ce.toFSPath('images')+("/img000"+str(i)+".png"))
        elif i < 100:
            views[0].snapshot(ce.toFSPath('images')+("/img00"+str(i)+".png"))
        elif i < 1000:
            views[0].snapshot(ce.toFSPath('images')+("/img0"+str(i)+".png"))
        else:
            views[0].snapshot(ce.toFSPath('images')+("/img"+str(i)+".png"))

if __name__ == '__main__':
    main()
```

After this step, a sequence of 8760 3D (if using perspective view) or 2D (if using top view) energy images will be extracted and named according to their time stamp ("imgxxxx.png" represents the energy demand for the xxxx-th hour)

1.4 Interface Specification

As is addressed in Section 1.2.4, an interface is needed to combine the map image sequence with data plot and to provide more complicated data visualization analyzing utilities. In this section we provide some abstract specification of the functions of the interface and in Chapter 2 we will provide more detailed illustration of the design and application of the interface.

1.4.1 User Definition

First we want to specify a user profile in order to best convey the information with the Dynamic Energy Map.

The potential category of user group for the Dynamic Map includes: 1) policy makers, 2) urban planners with the interest in executing community level energy strategies 3) researchers in energy related fields 4) public groups or individuals that are involved or interested in the decision making process of community energy planning.

The target user for the current interface design is restricted to researchers in energy related fields. The assumption on this user group about their skill level and background knowledge is that 1) they have the basic ability to read and understand the layout of a map environment and can associate it with the urban environment setting they are associated with 2) they have the ability to correctly understand moderately complicated map legend and data plot 3) they have the basic understanding of related concept of building energy performance attribute and the general implications of these attributes. The assumptions about their intention is that they might have different research interest and focus. These assumptions implies the interface design should: 1) provide both qualitative and quantitative information; 2) allow for some degree of user control over data classification, legend selection and full control over time navigation

1.4.2 Goal Function

The goal function of the interface is in general defined as: "**Revealing the spatial-temporal heating, cooling and electricity demand variation of the conceptual model with Dynamic Energy Map**."

More specific sub-goal-functions of the dynamic energy map in the current study is defined as:

Function 1. Assisting users to identify the energy recovery opportunities through multi-dimensional visualization of the space heating and cooling demand. To achieve this function, the interface should have the following properties:

- Map display: The space heating and cooling demand should be represented on the same map that better reveals their correlation.
- Data display: Space heating and cooling demand of single buildings, building groups, and the community should be ready to viewed and compared with a variety of time steps and time duration.
- Data analysis: The energy recovery potential should also be computed in order to provide more quantitative insight.

Function 2. Assisting the sizing of a district energy system CHP plant. To achieve this function, the interface should have the following properties:

- Map display: The heating and electricity demand should be represented on the same map that better reveals their correlation.
- Data display: heating and electricity demand of single buildings, building groups, and the community should be ready to viewed and compared with a variety of time steps and time duration.
- Data analysis: The power generation that covers the heating demand of the community should be computed based on user specified heat to power ratio.

Chapter 2

Interface Design

This section provides detailed illustration of the non-interactive (map animation) and interactive dynamic energy map implementation and design choices regarding the interactive dynamic energy map. The section starts with a general overview that explains possible approaches to add the time dimension in an energy map. Then the non-interactive energy map (map animation) approach was presented. For the non-interactive animation, we briefly discussed the advantages and disadvantages between different symbol or color representation on the effectiveness of information convey.

Then a detailed documentation of the dynamic energy map interface is presented. In this section, we first explained the layout and functions of each components of the interace and how each component is designed based on literature studies of dynamic map design. Then we demonstrated how the dynamic energy map could help to achieve the two goal functions: 1) identify energy recovery opportunities 2) help design and sizing of a district energy system

2.1 Overview

Dorling and Openshaw pointed out that dynamic map provides new potential and possibilities for data analysis but also poses a great challenge as a result of the less developed theory in space-time pattern detection and measurement [15]. In order to better conduct a space-time visualization of the space-time energy demand information in the dynamic energy map, we based the dynamic energy map implementation on some literature studies on space-time map visualization.

Brownrigg mentioned several methods of representing time on a map: 1) a graph or chart that represents a function over time or a time line for displaying chronological events 2) sequence of snapshots displayed over time (animated map) 3) small-multiples of snapshots of changing states [16].

Based on the classification above, we applied method 1) and 2) in time representation for the dynamic energy map project. The dynamic plot of temporal time series is using method 1) to anchor the quantitative information. The sequential map image display is using method 2). We did not used the small multiple method (method 3)). The choice is based on the following points mentioned by Brownrigg: 1) the number of snapshots in one display is limited and the finer the detail per snapshot, the less snapshots one can contain in one display. Since the 3D representation is chosen as one of the major map display methods (2D map is also available), the level of details per image is relatively high. This will result in a very small number of multiples per display [16] 2) the subtle changes are easier to be noticed in the form of animation than with small-multiples [16]. Both drawbacks of small-multiple method will impair the ability of conveying the rapid temporal changes of community energy behavior, hence is not suitable for the current project.

2.2 (Non-interactive) Map Animation

Map animation was introduced to cartography in 1930s [17]. Its major application include: 1) demonstrating the dynamic process of geographic events (weather maps in weather forecasting is such an example) 2) assisting pattern recognition and knowledge development for scientific researches. The study by Dorling and Openshaw is an example of application 2), where they discovered new leukaemia hotspots through animated maps [15]. Animated maps are proven to be more powerful in conveying the spatial-temporal pattern than static maps [18].

We used a continuous color encoding method in the creation of non-interactive animation of a univariate gas heating energy demand map. A red to blue color ramp is used in the map display. Each color within this red-to-blue color ramp is represented as a real number between 0 and 1 with 0 representing pure red and 1 representing pure blue. A log-scaling was performed to the energy data to "flatten" the distribution. Then the normalized distance between the current demand and the maximum demand is calculated with Equation **??**. A snapshot of the animation is shown in Figure 2.2. The animation can be viewed and downloaded through this link

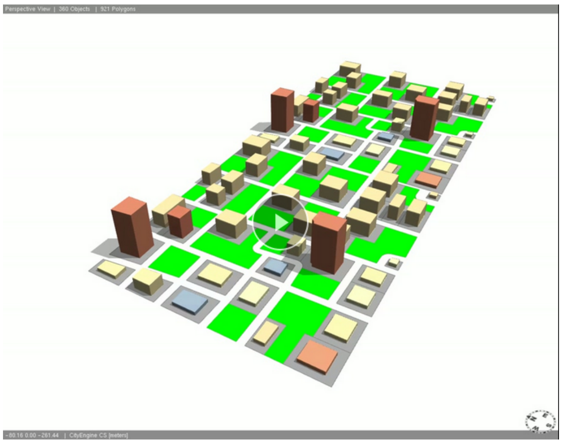


FIGURE 2.1: Animated Map with Continues Encoding

In the dynamic energy map interface design, we applied a discrete color encoding with a seven-class bivariate choropleth representation This allows for a quantitative legend that can depict more specific energy demand information. An animation with this discrete color scheme is also created and can be viewed and downloaded through this link.

Although the initial conditions of the map instances using the continuous and discrete encoding method are different, we observed that the continuous color encoding method seems to be better in demonstrating the general pattern of energy changing behavior. Further evaluations are needed to compare these two approaches and justify the design choice of a discrete or continuous color scheme.

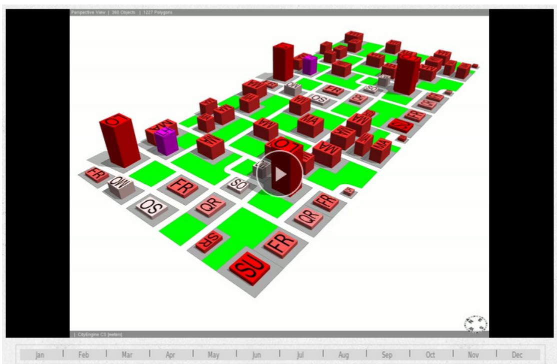


FIGURE 2.2: Animated Map with Discrete Encoding

Dong et al. identified that the optimal frame rate for a color symbol map is 3 per second for a 1024×768 display [19]. They suggested to increase frame rate for larger display size. The non-interactive animated map display has size of 1213×950, a little larger than that of the suggested display, we thus chose the frame rate to be 4 per second.

2.3 Interactive Dynamic Map Interface

2.3.1 General Layout

The general layout of the dynamic map interface is displayed in Figure 2.3. It contains the following major sections :

(A) A snapshot of the dynamic energy map interface

(B) Dynamic Map Interface Layout

FIGURE 2.3: Dynamic Map Interface Layout

- A main map display on the upper left that shows the 2D or 3D view of the dynamic energy map with energy data encoded as the color of buildings.

- Four sliders that controls the linear and periodical navigation of the map image display and data plot.

- A "Building Initial Look-up Table" in the center bottom that explains the building type initials on the main map display window.

- A series of energy demand plots for four major building sectors (top right) and the whole community (lower right).

- A series of buttons and option menus on the lower right.

  The top row of the buttons performs forward (+) or backward (-) time navigation with time step of 24h or 1h. The bottom row of the buttons contains a "plot" button that plots the energy profile graphs of the 16 benchmark buildings (if "single" is chosen for option menu") or the plot of the aggregated community (if "community" or "group" is chosen), a "legend" button that shows the current legend, and a "clear" button that clears the selection in the 2D mode (Figure 2.4).

Figure 2.4: The option menu contains a 2D/3D toggle, several plotting options determining the plotting topic (space heating, cooling, energy recovery potential, heating and electricity), the plotting time step and duration (month, week, day) and the buildings involved in the plot (single, group, community)

The following sections will provide more detailed explanation of the interface.

2.3.2 Main Display Window

As is mentioned in [16], the choice of 2D representation vs. 3D representation is one of the debating decisions in the world of cartographic data visualization [16]. 2D maps are 1) easier to navigate through and 2) easier to perform selection and manipulation. Another important advantage of 2D map is that it has better theory support [20] while the principles and variables of 3D or 4D maps (space-time map) are not thoroughly investigated [20]. This situation makes the design of 3D maps more difficult. However 2D maps “drastically simplify reality and thus do not give credit to the highly complex capabilities of human spatial cognition” [20]. Regarding this, 3D map is rich in geometry representation and can provide realistic scenes. This feature can both be an advantage or disadvantage based on the actual map usage. According to Tufte’s data-ink ratio theory, the extra non-crucial richness of information should be eliminated to make the most important information stand out [21].

For the current dynamic energy map interface, both 2D and 3D representations are provided for the users to select. The main map display window on the top left is used for displaying the 2D / 3D dynamic map of the conceptual model. The lower left of the main map display window displays the current time for the image and data plots. By selecting the 2D / 3D option in the option menu on the lower right, the user can choose between 2D and 3D display. The 3D display provides a more realistic view of the community model. The building geometry is simplified in the current model in order to emphasize the color changing between frames without introducing distraction from complicated building geometry. Additional building details or features could be added to make the display more realistic. In the 2D display, user can click on a single building or select a group of buildings to display their energy profile plots or the aggregated energy profile plots (Figure 2.5).

2.3.3 Bivariate Map Legend

2.3.3.1 Symbol Chosen

Our major intention for choosing the 3D energy dynamic map display is to use it to provide a more realistic urban environment context. In the Dutch Heat map by Dobbelsteen et al. , the quantity of energy demand of each building or region is represented by

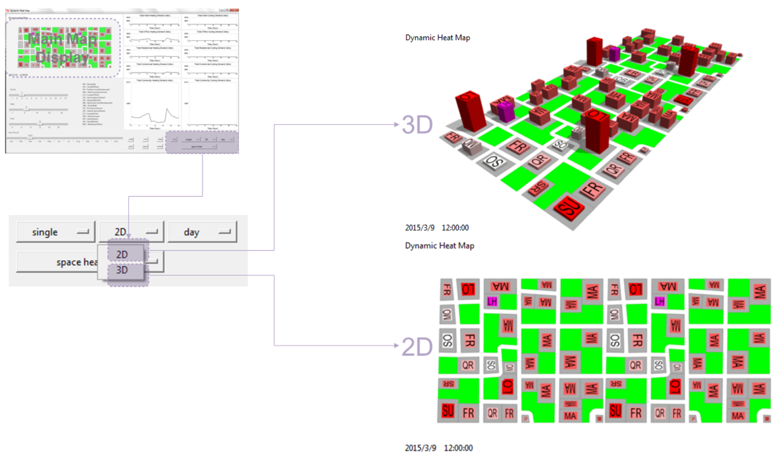


FIGURE 2.5: The current interface provides the choices of viewing 2D and 3D map display by toggling the 2D/3D option menu

extruding the building or region by a corresponding height encoding its energy demand or supply [22]. This approach provides an easy way of aggregating energy demand and supply by adding up geometry height, but this approach is not suitable for our map design because it creates shape distortion and will impair our goal of providing a realistic urban environment vision.

In order to represent space heating demand and cooling demand on the same map, a common map design problem is encountered in the current project: bivariate map design problem. Elmer presented eight possible types of representation for bivariate maps (Figure 2.6): "shaded cartographer, rectangle map, bar chart, value by alpha, choropleth with graduated symbol, bivariate choropleth, spoke glyph and shaded texture" [23]. In order to incorporate the bivariate map symbols to the current 3D model without introducing too much shape distortion, we did not choose the representation with dimensional changes. The only choices are the ones that only involves color or texture, i.e. "bivariate choropleth, value by alpha and shaded texture" (Figure 2.6). Among these three choices, bivariate choropleth representation has the highest accuracy rate [23], hence we choose bivariate choropleth as the representation of the current map interface design.

In the current interface design, users can click on the "Legend" button and a legend used for encoding the 2D and 3D map will be displayed. To assist legend reading and color comparison between the map and the legend, tick marks of "x" are added to the legend to indicate the color appeared in the map Figure 2.7.

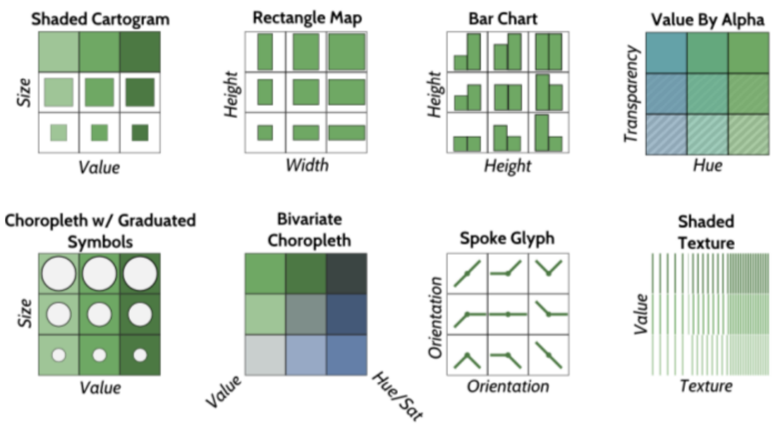


FIGURE 2.6: The eight bivariate map display approaches tested in Elmer's [23] study

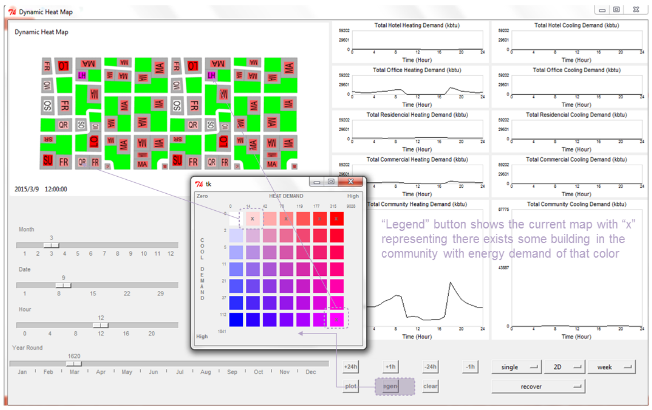


FIGURE 2.7: The seven-class-bivariate choropleth legend is used in the dynamic energy map interface design with red representing high space heating demand, blue representing high space cooling demand. "x" in the legend corresponds to colors appear in the current map display window

2.3.4 Time Sliders and Navigation Buttons

The lower left section contains a series of sliders for controlling interactive navigation of the image sequence and corresponding data plot.

Harrower and Fabrikant classify time into two types: linear and cyclic [17]. The former represents the periodical changes and the latter represents the linear changes of spatial temporal variables. Upon this consideration, the design of the current interface include both an overall time navigation utility and time navigation utilities that facilitate jumps with time steps corresponding to the natural period of energy data, such as month, day and hour. This design choice is anticipated to facilitate the representation of both linear changes and periodical changes of energy usage in the community.

There are three shorter "periodical" sliders on the lower left of the interface. One unit of position change in the "month" slider results in a forward or backward jump of one month in time. The total number of positions in the "month" slider equals to the number of months in a year (which is the next level of time unit regarding month). The jump step for "date" slider is one day and the number of positions in the "date" slider is the number of days per month. Similarly for the "hour" slider, the jump step is one hour and the number of positions in "hour" slider is the number of hours per day. Suppose the current time in display is 2015/1/1 12:00:00, by moving the month slider, viewers can see the energy demand in the from of map image and data plot for 2015/2/1 12:00:00, 2015/3/1 12:00:00, . . . , 2015/12/1 12:00:00. Similarly, if views pull the "date" slider, they can compare the different energy demand of this hour (12:00:00) throughout the whole month. For hour slider, viewers can compare the energy demand between different hours of a day.

There is a longer "linear slider" on the bottom left of the interface. It has a time step of an hour and a navigation range of a year (8760 hours). It allows users to globally navigate through all 8760 hours of the year.

There are four buttons (+24h, +1h, -24h, -1h) on the bottom right of the interface. They provide a micro level adjustment of time.

2.3.5 Data Plot

2.3.5.1 Methods to Show Plot

There are three ways to view energy data plots in the dynamic energy map interface:

1) By viewing the right hand side of the interface.

   The dynamic data plot are directly shown on the right of the interface. They depict the energy demand of the four major building sectors (Hotel, Office, Residential and Commercial buildings) and the community.

   Space heating and cooling energy demand is displayed in Figure 2.3. The interface can also display the electricity and heating demand for the CHP plant sizing application. These plots starts from the current time showing on the time sliders with a fixed plotting range of 24h.

2) By clicking on the "plot" button on the lower right of the interface.

   If the "single" option in the option menu is chosen before one clicks the "plot" button, a data plot will be created for each building type (Figure 2.8). If the "community" option in the option menu is chosen before one clicks the "plot", a data plot for the community will be created (Figure 2.9).

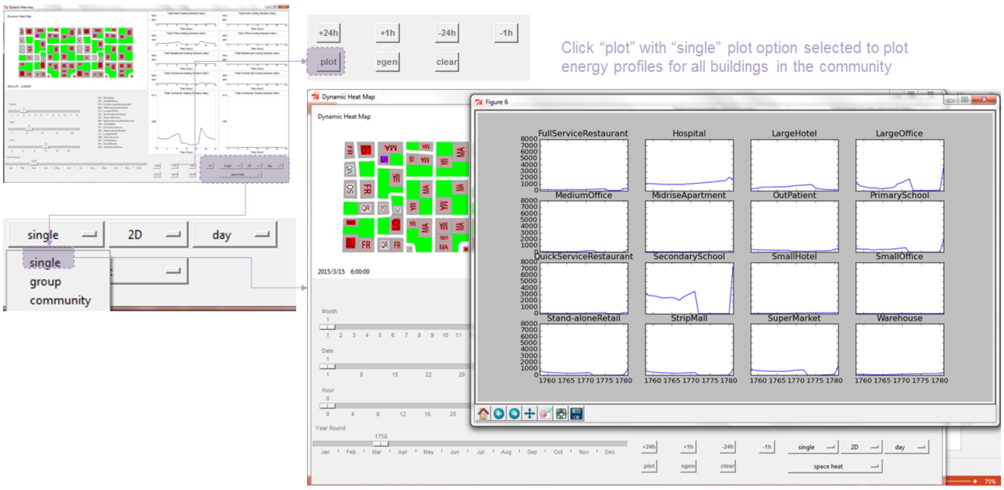


FIGURE 2.8: The plot shows the space heating energy demand plot of each of the 16 benchmark buildings

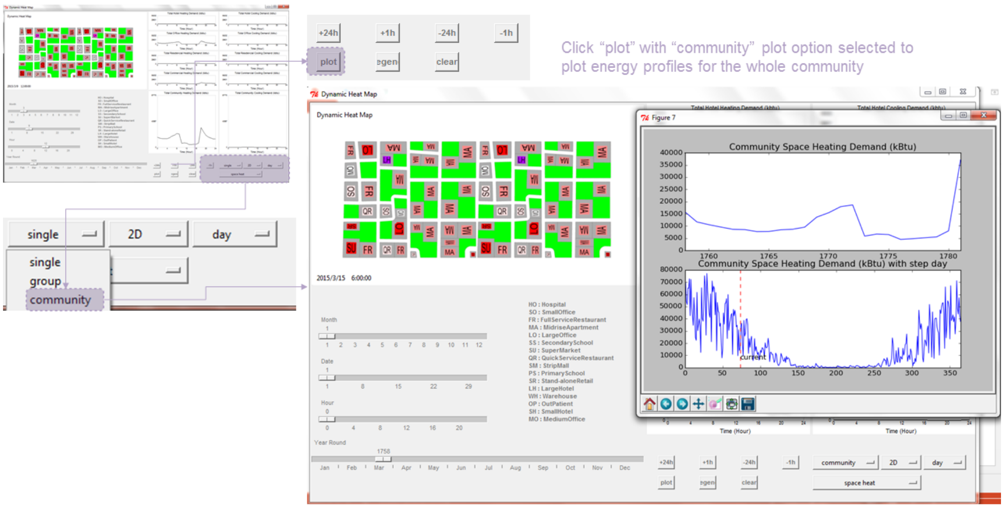


FIGURE 2.9: The plot shows the aggregated space heating energy demand for the whole community

3) By clicking on the building foot print in the 2D map display.

A building is "selected" if the user clicks on its foot print. Each new click of a building foot print will add a new copy of that building to the selection set. The selection set can be cleared by pressing the "clear" button. If "single" option is chosen in the option menu before clicking on a building's foot print, a data plot will be created for the building the viewer just clicked on (Figure 2.10). If "group" is chosen in the option menu, each click of a building's foot print will create a data plot for the current selection set (Figure 2.11).

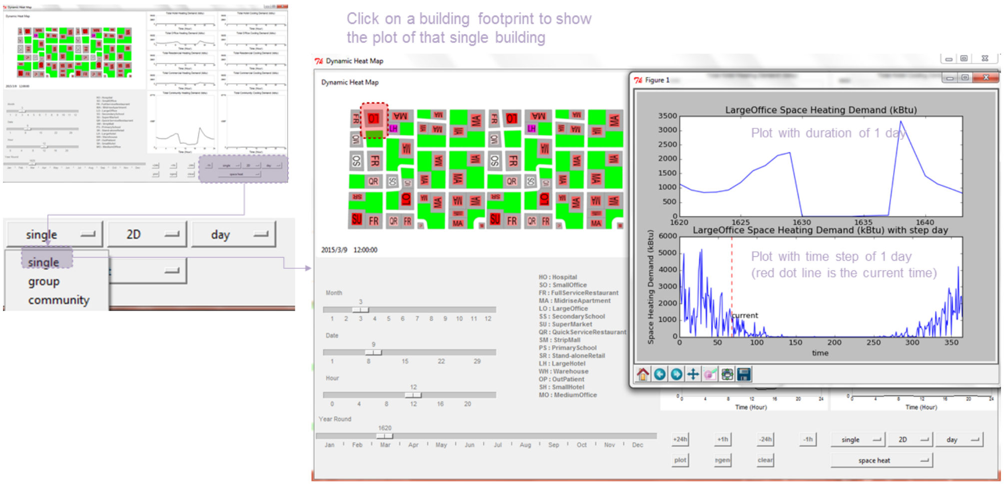


FIGURE 2.10: Click on a building foot print shows the energy plot of this building

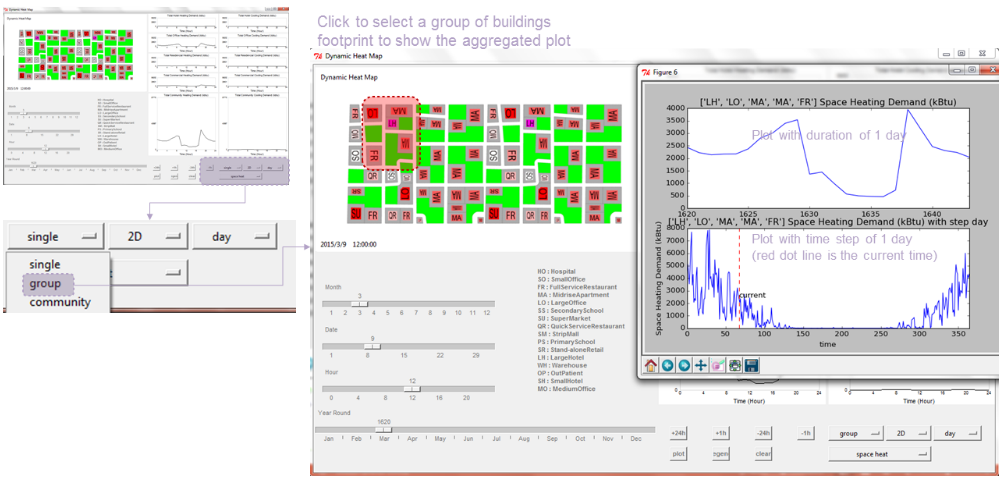


FIGURE 2.11: Click on a building foot print shows the energy plot for the selected building group

2.3.5.2 Providing Temporal Context in Data Plot

Brownrigg suggested that it is necessity to provide the "temporal context" in a space-time map: "To comprehend how drastically or subtly something is changing, how fast or slow, in what direction, in relative to its environment, etc., demands some knowledge of the history of the change, an awareness of the objects' properties before and after the change." [16].

In the current map image display, the temporal context is created by providing three "periodical" slider bars that allows the user to jump with time steps of month, day and hour.

In data plots, the temporal context is created by providing a "longitude" and "latitude" comparison of energy demand. "Longitude" here refers to the comparison of adjacent time spots. It shows what the states of the direct future or past comparing to the state of the current time. "Latitude" here refers to the comparison of the current time spot with all similar time instances, for example, all 12:00:00 energy demand of the year. It shows how the current instance differ from similar instances.

For the current interface design, the top plot presents a longitude temporal context of the energy demand of the incoming 24h, week or month. Corresponding to the duration of time of the top plot (24h or one week or one month), the bottom plot presents the latitude demand context of the same hour with a step of one day, one week or one month. For example, in Figure 2.13, the top plot shows the Space Heating Demand for Large Office from 2015/3/9 12:00:00 to 2015/3/10 11:00:00, with a duration of 24h. The bottom plot shows the energy demand of the Large Office for all 12:00:00 of the 365 days of the year (the red dot line indicates the 12:00:00 of around the 70th day of the year, which is the date of Mar. 9th).

By providing the temporal context, we would like to provide viewers with a general understanding of whether the changing of energy demand behavior is drastic or subtle and whether a drastic change is coming and whether the current demand is high, low or moderate comparing to the overall distribution over time and space.

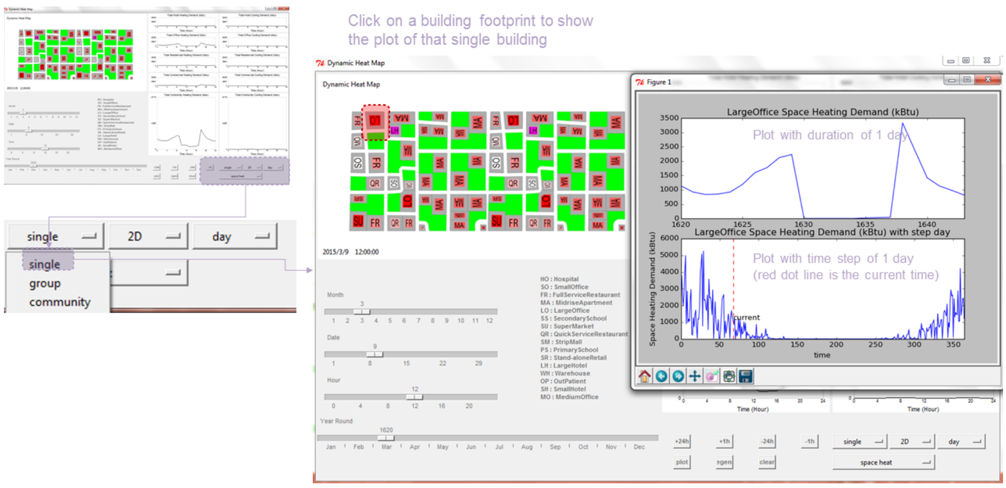


FIGURE 2.12: The data plot presents the longitude and latitude comparison of energy demand, the top plot presents a temporal context of the energy demand of the next 24h, the bottom plot presents the time context of the demand of the same hour throughout the 365 days of the year

FIGURE 2.13: By changing option in the option menu. User can choose to display a longitude latitude comparison with the time unit of day, week or month. The top plot shows the energy demand for the next day, week and month from left to right; the bottom plot shows the energy demand of this hour in the 365 days of year, 52 weeks of a year or the 12 months of a year from left to right

2.4 Use Case Demonstrations

2.4.1 Use Case I: Identification of Energy Recovery Opportunity

In this section, we present a general approach on how to use the dynamic energy map interface to identify the energy recovery opportunities. The process of space cooling will produce reject heat. As is explained in Section 1.2.1.1, the ammount of cooling induced reject heat is positively corelated to the cooling demand. Thus a building with high cooling demand will also has a large amount of reject heat. The reject heat from this building or group of buildings could be recovered by itself or be transmitted to surrounding buildings that has space heating demand so that the total space heating demand of the group of buildings could be reduced.

For the interface design in the current study, the authors used a bivariate color ramp in space heating and cooling energy demand data representation that depicts the hourly space heating and space cooling demand on the same map (Figure 2.14). Red represents high heating demand and blue represents high cooling demand. The closer the color cell is to the top, the less cooling demand it has. The closer the color cell is to the left, the less heating demand it has. The cells on the diagonal line (purple colored cells) represent the building has relatively similar amount of heating and cooling demand. The cells to the upper right of the diagonal represents buildings that are heating dominated and the cells to the lower left of the diagonal represent buildings that are cooling dominated. The current breakpoints are decided through the "Quantile method" [12] for demonstration.

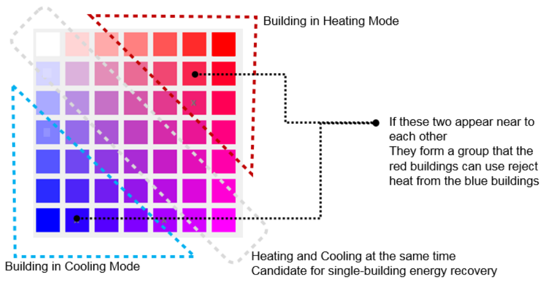
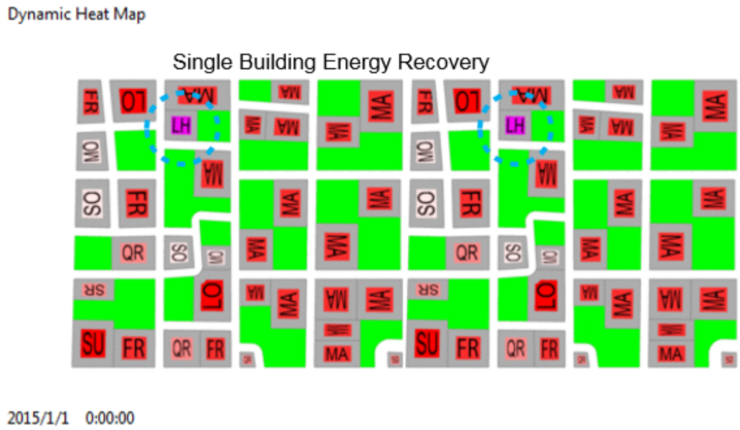


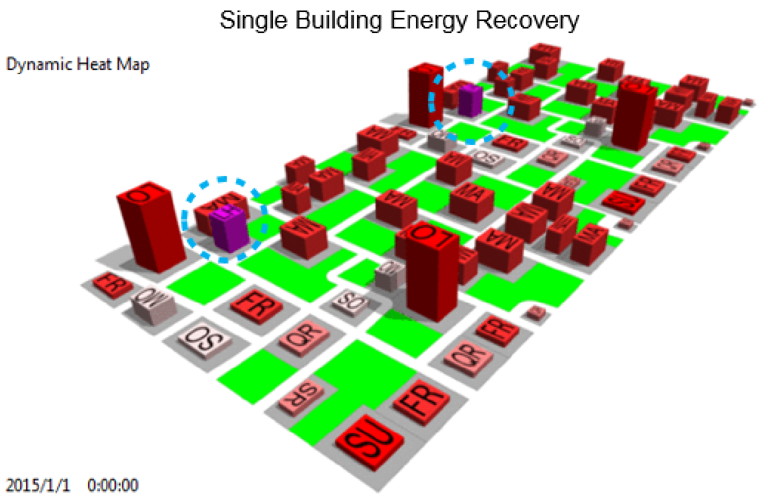
FIGURE 2.14: The bivariate color ramp displays two variables at the same time: space heating and space cooling. It better displays the co-relation between these two variables and thus helps users to identify energy recovery opportunities

With the dynamic energy map, the user can first identify single buildings with coincident cooling and heating demand: users will be able to identify those purple colored buildings directly from the 2D or 3D map as candidates for building level energy recovering by redirecting the reject heat from its cooling device condensing coils or cooling towers to the space that needs heating (Figure 2.15).

The user can identify a group of adjacent buildings for reject heat sharing. First, the buildings colored in one of the colors in the bottom rows of the legend are buildings with high cooling demand. With the dynamic energy map, one can identify the potential reject heat suppliers and consumers over time (Figure 2.16).



(A) 2D map display that helps user to identify the energy recovery opportunities for single buildings



(B) 3D map display that helps user to identify the energy recovery opportunities for single buildings

FIGURE 2.15: Dynamic Energy Map helps user to identify the energy recovery opportunities for single buildings

In the following example, Large Office and Large Hotel are with high cooling demand (since their color are on the bottom row of the legend) and the surrounding buildings (two Midrise Apartment, two Full Service Restaurant and one Small Office) have space heating demand (they are with a redish color). By transmitting the reject heat from the Large Office and the Large Hotel in the center to the surrounding buildings, the total energy consumption of the building group (within the red dotted circle) could be reduced. (Figure **??**).

The dynamic energy map also provides the quantitative insight on how much heat recovery one could achieve: per Equation 1.2 and the analysis in Section 1.2.1.1, the heat recovery potential of each building or building group will be calculated with f = 1.15

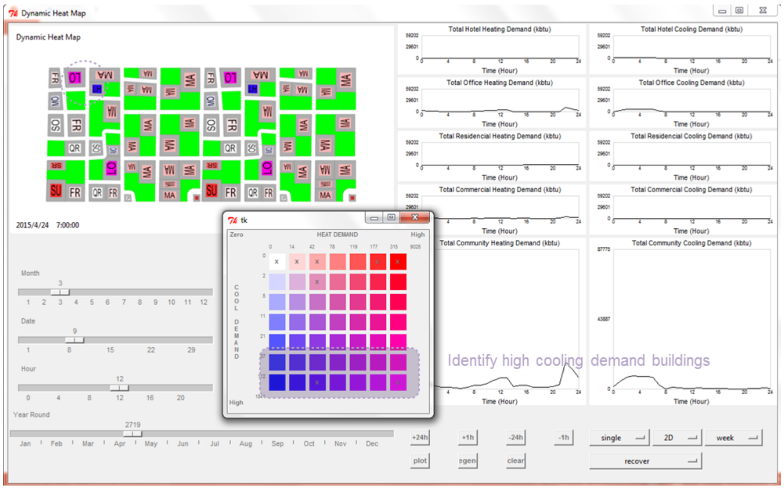


FIGURE 2.16: In the demonstration, buildings with a high cooling demand have colors on the bottom rows of the legend, thus Large Hotel and Large Office are identified as potential reject heat energy suppliers

for Large Office, Hospital and High-rise Apartment, and $f = 1.25$ for the remaining building types.

Users can calculate the "energy recovery potential" of the center buildings (Large Office and Large Hotel in this example) and the total space heating demand of surrounding buildings (two FirstService Resturant, two Midrise Apartment and one Small Office) in the dynamic energy map with a specified time duration and step. In Figure 2.17, the energy recovery potential and space heating demand for the next week is compared. Users can see about the 12th week to the 13th week, the energy recovery potential of the center buildings and the heating demand of surrounding buildings are both high. This could be a good period for energy recovery of the group of buildings. From the 20th to the 37th week, the energy recovery potential is high but the heating energy demand is zero. This indicates a potential need for reject heat storage devices to shift the reject heat supply peak to meet the heating demand peak need.

2.4.2 Use Case II: Sizing CHP Plant

With the Dynamic Energy Map that depict the spatial temporal load variation, one will idealy be able to 1) idendify anchor load buildings, 2) conduct better design of local load balancing, 3) size the co-generation CHP plant

1). Identify anchor load building

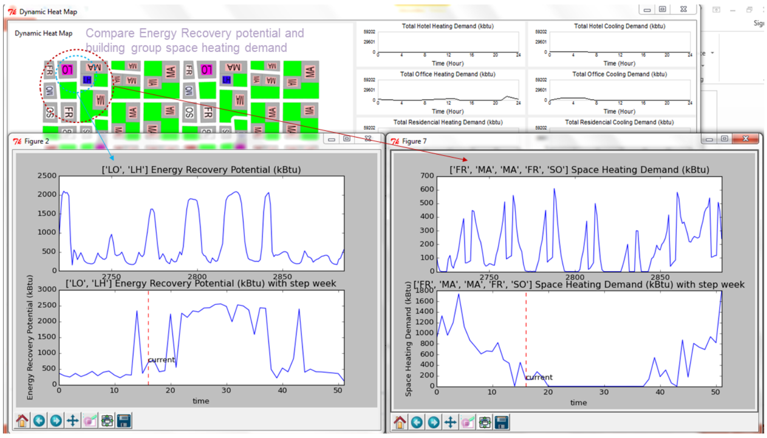


Figure 2.17: The users can calculate the energy recovery potential of the group of reject heat suppliers (Large Office and Large Hotel). They can also calculate the total heat demand of the surrounding buildings with space heating demand (two FirstService Resturant, two Midrise Apartment and one Small Office).

To achieve this function, the map should be able to make the building with persistant high heating or cooling demand stand out. Thus the design of color scheme that assigns vibrant colors to high demand and white to low demand. The break points of "high" demand remains to be decided in further project development. For the current implementation, the break point is acquired with quantile classification method with.

Although with the box plot of heating demand (Figure 1.11a), the buildings with high consistent heating demand can be seen through its high median and 25 percentile, but a more intuitive interpretation is still needed to convey information to people with less statistical background. From the animated version of the dynamic energy map (link to 2d map, link to 3d map)

2). Local load balancing

To achieve this, the first step would be to enable users to select a subset of the existing buildings and the program will calculate the aggregated load and plot the curve for the aggregated load of the selected building group (within the specified time period).

The user will first identify some cluster of buildings, in which there is a pattern of building that turn red one after another but not together. Then they can check the building demand profile by clicking on the building footprint in the 2D map (Figure 2.18).

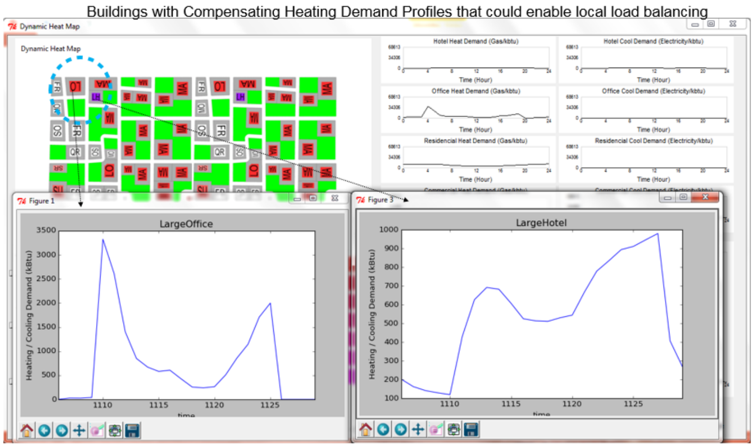


FIGURE 2.18: Users can check the building energy demand (thermal or electricity) by clicking on the building foot print in the 2D map and the interface will show the plot of the energy demand profile within a period (the example is showing the demand for a 24h hour period)

Alternatively, they can first open the window that displays the 24h period energy demand graph (hourly gas heating energy in the following example) for all of the 16 benchmark buildings and see if there are some building types that has their demand compensating each other (so they have a rough idea of what is a "good building combination" (Figure 2.19) at this time that could be a candidate for load balancing) and they will look at the map and search for this "good combination".

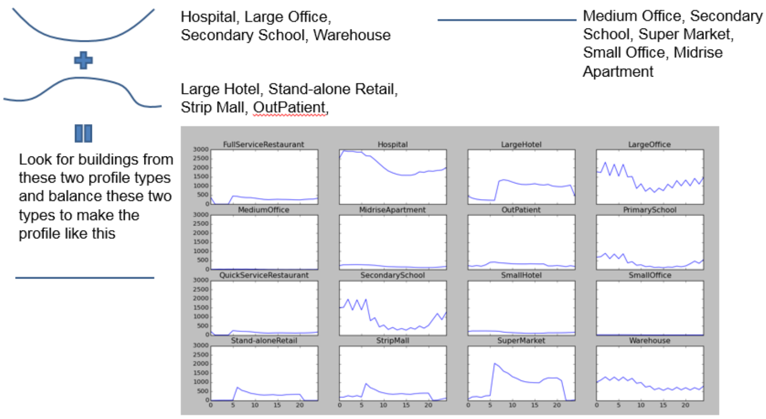


FIGURE 2.19: Users can plot all building energy demand profile (heating gas demand for the example) and search for "good cobimations" that have compensate load profile

After the qualitative experimentation, users can select a group of building by clicking on the building foot print and the program will output a graph of aggregated load (Figure 2.20).

3). Sizing the CHP plant

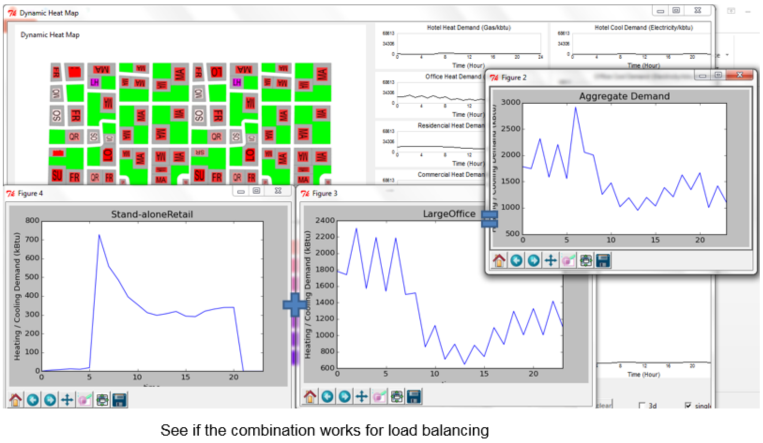


FIGURE 2.20: In this example, users selected the Stand-alone Retail and the Large Office and plots of each single building and the aggregated demand of the two buildings are displayed

Two variables are crucial in sizing a CHP plant: 1) the heating demand including space heating and service hot water 2) electricity demand. For the current dynamic energy map interface, a 2D/3D choropleth map are presented in the main map display window with the heating demand and electricity demand encoded with a seven-class bivariate choropleth legend as in Figure 2.21. The dynamic plot on the

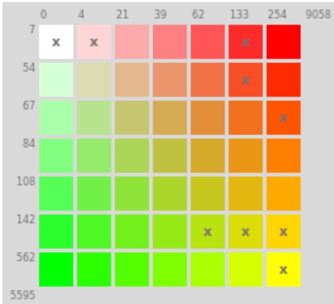


FIGURE 2.21: Legend for Heat and Power Map

right of the interface depicts the heating and electricity demand of the four building sectors and the community (Figure 2.22).

The user can inspect more detailed heating energy and power demand of the community with the "plot" button with the "community" option in the option menu selected.

FIGURE 2.22: The interface displays the heating and electricity demand on the right

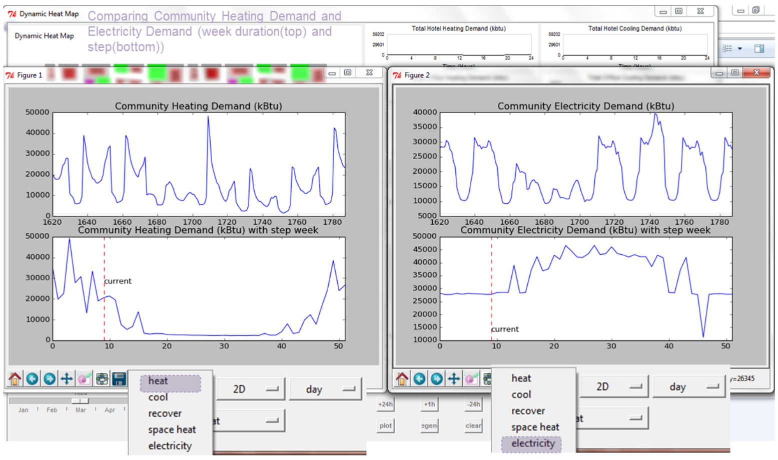


FIGURE 2.23: In this example, the users compare the week-wise heating and electricity demand

2.5 Implementation tools and strategy

The software or platform involved in the project include EnergyPlus for building simulation, CityEngine for 3D modeling and image generation.

Imagemagic is used for converting and resizing images. For the creation of animated maps, "ffmepeg" was used for connect image sequences to animation.

Python 2.7 for interface design. The interface is written in Python2.7 with standard Tkinter graphic package including the data plot section. Pandas and numpy packages are used in data manipulation. Matplotlib and ggplot are used for creating data plots.

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