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 [13] as a prototype. The land use of the conceptual urban environment is created based on extracted topological patterns from this redevelopment projec.

ii. The number of buildings in the model represents a typical community that can be served by a district energy system [19].

   To achieve this, the original model created under crateria i. is duplicated and thus there are in total 68 buildings within the community. This rangge is within the range of a typical district energy system service capacity of 50 to 150 [19].

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 90.1-2004 Standard [15].

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.

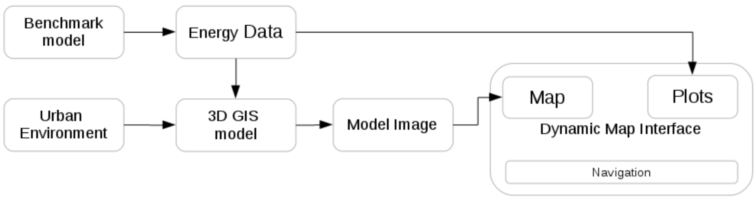


Figure 1.1: General Work Flow

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 [8].

Following the same approach, the energy profile used in the current study is retrieved from simulation results of commercial building benchmark buildings developed by U.S. Department of Energy (DOE) [15]. 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), Supermarket (SU), 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 Name	Shorthand	Floor Area (ft2)	Number of Floors
Large Office	LO	498,588	12
Medium Office	MO	53,628	3
Small Office	SO	5,500	1
Warehouse	WH	52,045	1
Stand-alone Retail	SR	24,962	1
Strip Mall	SM	22,500	1
Primary School	PS	73,960	1
Secondary School	SS	210,887	2
Supermarket	SU	45,000	1
Quick Service Restaurant	QR	2,500	1
Full Service Restaurant	FR	5,500	1
Hospital	HO	241,351	5
Outpatient Health Care	OP	40,946	3
Small Hotel	SH	43,200	4
Large Hotel	LH	122,120	6
Midrise Apartment	MA	33,740	4

TABLE 1.1: DOE Benchmark Building General Information [15]

The benchmark buildings comply with the ASHRAE Standard 90.1-2004. 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

	Heating	Cooling	Air
Small Office	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Medium Office	Furnace	PACU (packed air-conditioning unit)	MZ VAV (multizone variable air volume)
Large Office	Boiler	Chiller (2) water cooled	MZ VAV (multizone variable air volume)
Primary School	Boiler	PACU (packed air-conditioning unit)	CAV (constant air volume)
Secondary School	Boiler	Chiller (2) air cooled	MZ VAV (multizone variable air volume)
Stand-Alone Retail	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Strip Mall	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Suprmarket	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Quick Service Restaurant	Furnace	PACU (packed air-conditioning unit)	CAV (constant air volume)
Full Service Restaurant	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Small Hotel	ISH (individual space heater), furnace	IRAC (individual room air conditioner), PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Large Hotel	Boiler	Chiller (2) air cooled	FCU (Fan Coil Unit) and VAV (variable air volume)
Hospital	Boiler	Chiller (2) water cooled	CAV (constant air volume) and VAV (variable air volume)
OutPatient Healthcare	Furnace	PACU (packed air-conditioning unit)	CAV (constant air volume) and VAV (variable air volume)
Warehouse	ISH (individual space heater), furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Midrise Apartment	Furnace	PACU-SS	SZ CAV (single-zone constant air 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 [37]:

- 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" [37] (THR) in the condensing process equals to the "net refrigeration effect" [37](RE, the hourly cooling demand), plus the compressor input, it can be represented with the following equation [37]:

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

f is the "Heat Rejection Factor" and it is typically between 1.15 and 1.25 [37]. The water-based system has heat rejection factor closer to 1.15 and the air-based system closer to 1.25 [37].

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, Large Hotel, Medium Office, Midrise Apartment, OutPatient Healthcare, Small Hotel and Stand-alone Retail 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 [15]

	Electricity [kBtu]	Gas [kBtu]
FullServiceRestaurant	0.0	856637.1
Hospital	0.0	14045664.0
LargeHotel	843.6	2960506.8
LargeOffice	0.0	4741180.3
MediumOffice	450791.3	192226.8
MidriseApartment	56.9	494959.6
OutPatient	199581.9	2881638.9
PrimarySchool	0.0	1579186.5
QuickServiceRestaurant	0.0	383297.2
SecondarySchool	0.0	7746443.0
SmallHotel	52129.9	450393.2
SmallOffice	0.0	66631.5
Stand-aloneRetail	6966.5	976583.4
StripMall	0.0	1013188.1
SuperMarket	0.0	3043905.2
Warehouse	0.0	1039850.2

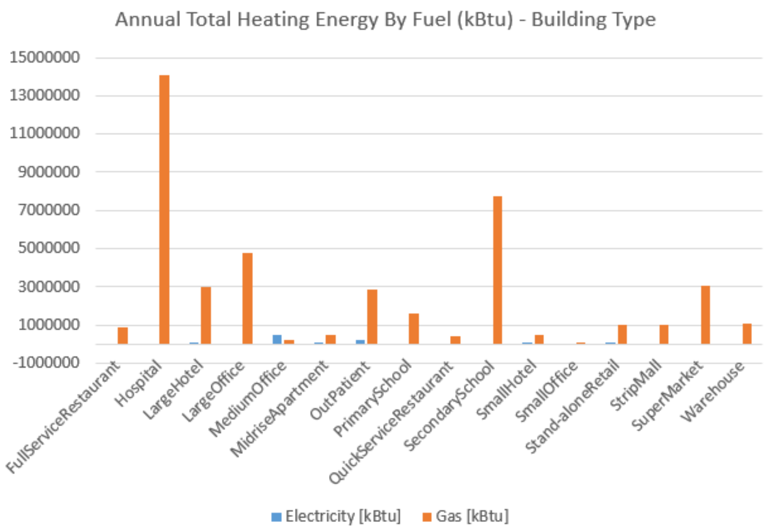


Figure 1.2: Heating Fuel

Electricity is the only fuel used for space cooling [15], thus the EnergyPlus output parameter "cooling:electricity" is used to represent space cooling demand. According to the suggested heat rejection factor [37], the heat recovery potential will be calculated with $f = 1.15$ for Large Office and Hospital, 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 [8] 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, the fuel used for providing service hot water is natural gas for all building types (Table 1.5)

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

TABLE 1.5: Service Hot Water by Fuel Type

	Electricity [kBtu]	Gas [kBtu]
FullServiceRestaurant	0	253664.3
Hospital	0	719402.7
LargeHotel	0	6793934.2
LargeOffice	0	231381.1
MediumOffice	0	34178.3
MidriseApartment	0	289719.3
OutPatient	0	44054.5
PrimarySchool	0	174768.0
QuickServiceRestaurant	0	82071.5
SecondarySchool	0	441512.2
SmallHotel	0	394017.1
SmallOffice	0	10928.3
Stand-aloneRetail	0	0.0
StripMall	0	0.0
SuperMarket	0	23799.7
Warehouse	0	0.0

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” 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
Cooling:Electricity	Total electricity for space cooling
Electricity:Facility	Total electricity

1.2.2.1 Single Output

By analysing the EnergyPlus [38] 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 performed 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 14000 kBtu. The majority (75%) of all hourly consumption are below 2000 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 1100 kBtu. Outpatient Health Care has the second larges hourly gas heating demand. In terms of peak demand, Secondary School and Large Office have the highest peak hourly gas heating demand (Figure 1.3).

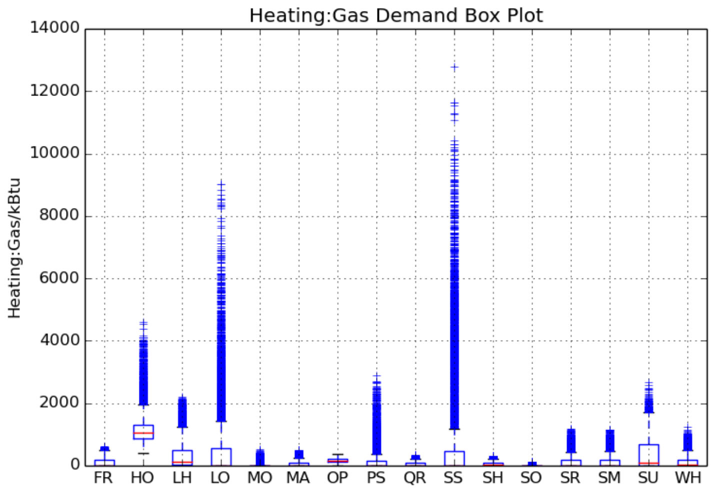


FIGURE 1.3: Heating:Gas Box Plot

Hourly hot water demand of the benchmark buildings range from 0 to 2500 kBtu, about 1/6 of the range of space heating gas demand. Most buildings have median hot water hourly demand below 100 kBtu, except that the median hot water demand of Large Hotel is around 700 kBtu. From Table 1.5, we can see that Stand-alone Retail, Strip Mall and Warehouse has zero demand for service hot water. Large Hotel also have a large amount of outliers above the 75% quartile. This indicates gas hot water demand of the Large Hotel is severely right skewed. Hospital has the second largest median gas hot water demand of about 100 kBtu. Large Hotel also stands out in peak demand. (Figure 1.4).

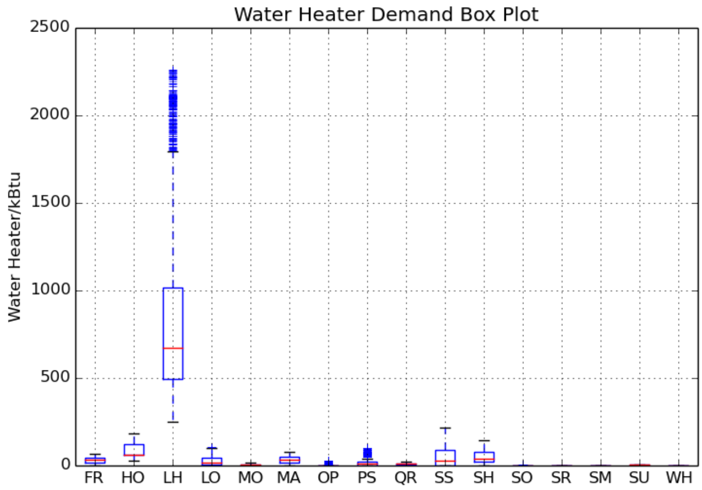


FIGURE 1.4: Water Heater:WaterSystem:Gas Box Plot

From Table 1.4, only Large Hotel, Medium Office, Midrise Apartment, OutPatient Healthcare, Small Hotel and Stand-alone Retail use electricity besides natural gas for space heating. Hourly electricity heating demand of these buildings range from 0 to 1000 kBtu. All of them has nearly zero median electricity heating demand and a large amount of outliers above (except for Midrise Apartment) the 75% quartile. This indicates electricity heating demand of all the five building types are severely right skewed. Medium Office has the highest hourly electricity heating peak demand and Outpatient Healthcare has the second largest hourly electricity heating peak demand (Figure 1.5).

Hourly cooling demand benchmark building types range from 0 to 3000 kBtu, which is about 20% of that of the peak gas heating demand. The hospital has the largest median cooling demand of about 1500 kBtu. Large Hotel has the second largest median cooling demand. Both Hospitals and Large Hotels do not have outliers, indicating their hourly cooling demand distributions are less skewed. On the contrary, all other 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 four building types with non-zero median hourly cooling demand: Hospital, Large Hotel, Outpatient Health Care 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

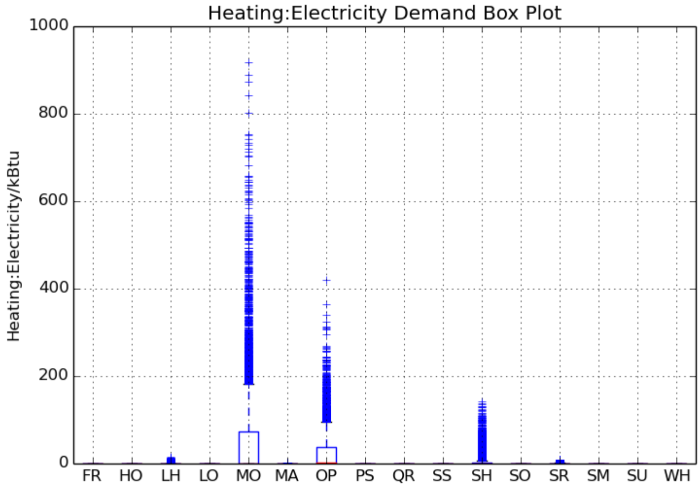


FIGURE 1.5: Heating:Electricity Box Plot

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 Secondary School has the highest peak demand of about 2700kBtu and Hospital has the second largest peak demand(Figure 1.6).

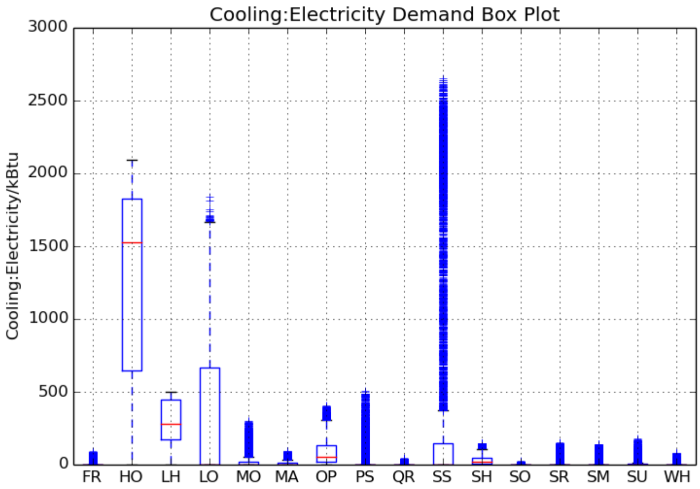


FIGURE 1.6: Cooling:Electricity Box Plot

The hourly electricity demand of benchmark buildings range from 0 to 6000 kBtu, which is about 40% of that of the peak heating demand. Comparing with other output variables, the electricity demand distribution has less outliers in general. The Hospital has the largest median hourly electricity demand (about 3400 kBtu). The Large Office has the second largest median hourly electricity demand (about 1800 kBtu). Secondary School has the Largest electricity hourly peak demand.

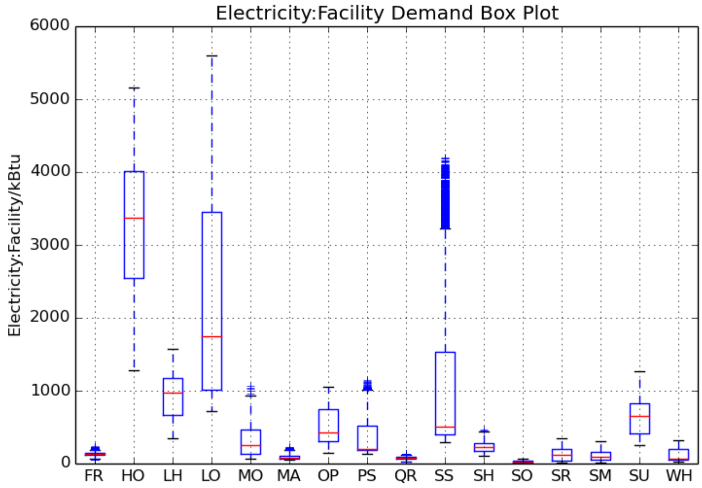
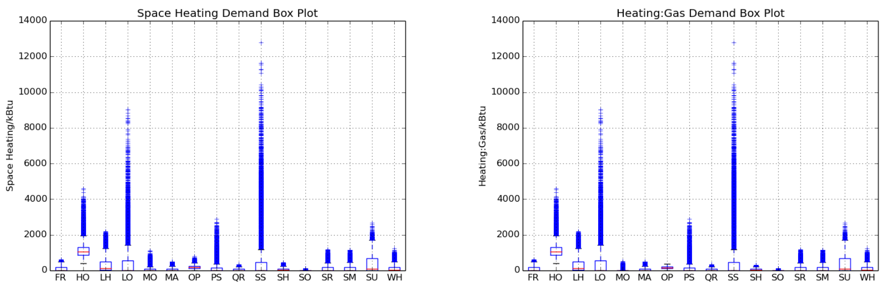


FIGURE 1.7: Electricity:Facility Box Plot

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 Medium Office and Outpatient Health Care (Figure 1.9a).

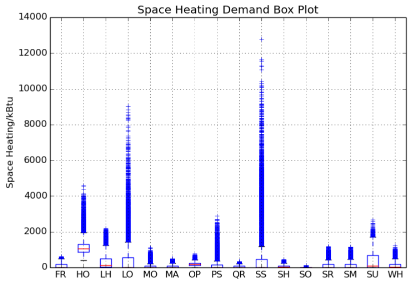


(A) Space Heating Demand Box Plot (B) Heating:Gas Box Plot

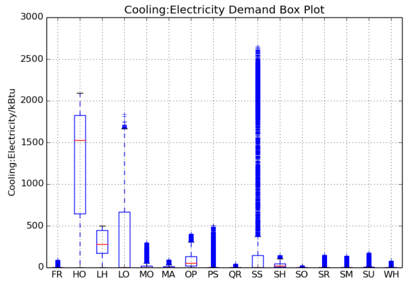
FIGURE 1.8: Comparing Heating:Gas and Space Heating

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

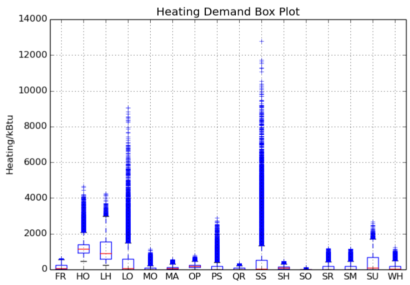


(B) Cooling:Electricity Box Plot

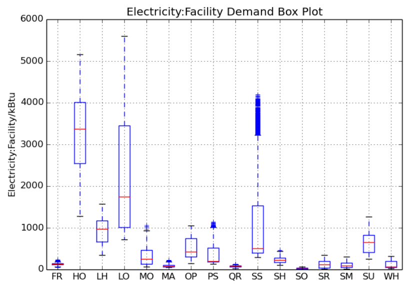
FIGURE 1.9: Comparing Space Heating and Space Cooling Demand

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 [39]. From Figure 1.11, we can see the range of HTPR is from 0 to 25 and the median of HTPR are all below 1. The building types with a high median HTPR include Large Hotel, Midrise Appartment, Outpatient Health Care and First Service Restaurant. 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 1.10: Comparing Heating and Electricity Demand

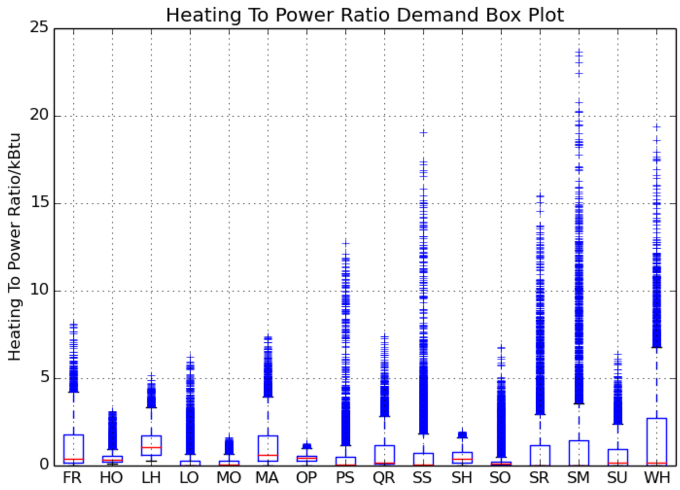


FIGURE 1.11: Heat to Power Ratio Box Plot

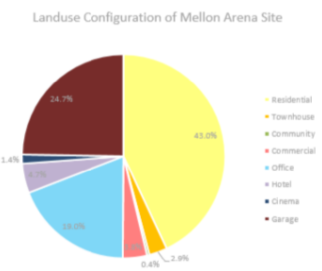
1.2.3 3D GIS Model Geometry

The conceptual community model is constructed in CityEngine [12]. CityEngine is a software developed by Esri [40]. It can aggregate geographic information into buildings and is capable of smoothly transition models to ArcGIS[41], 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 [8] (Figure 1.12a. 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%).

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

(A) Mellon Arena Project Site Plan View



(B) Mellon Arena Site Land use Configuration

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.

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 + Cinema + Community Center	25%	Full Service Restaurant
	25%	Quick Service Restaurant
	25%	Super Market
	25%	Stand-alone Retail

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

The four major building sectors involved in the current project are residential, commercial, office and hotel. Their topological pattern is represented in Figure 1.13. The conceptual model construction follows the building type topological pattern and the urban density as the Lower Hill District Project (Figure 1.14)

After the land use is assigned (Figure 1.14), 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.

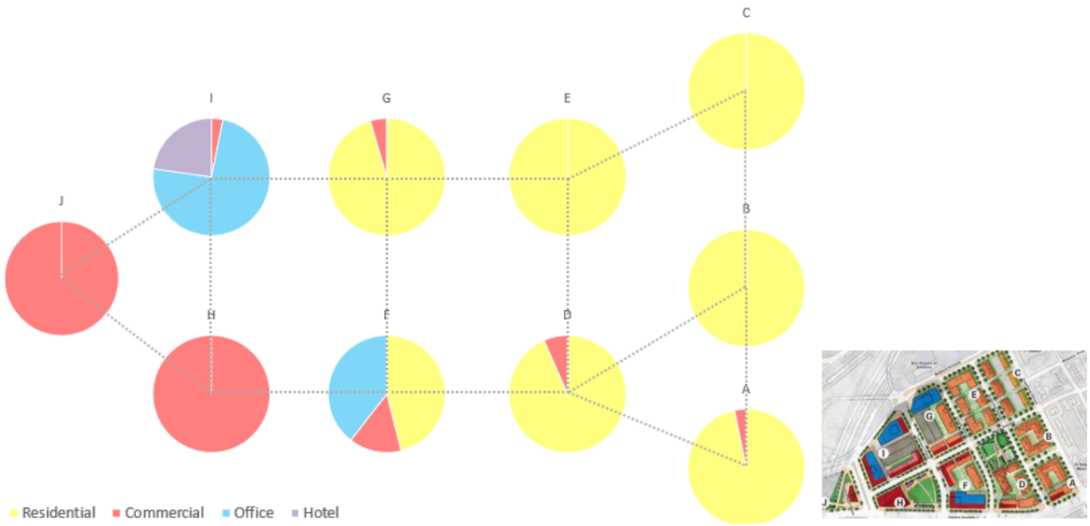


FIGURE 1.13: Building Type Topological Pattern, Mellon Arena

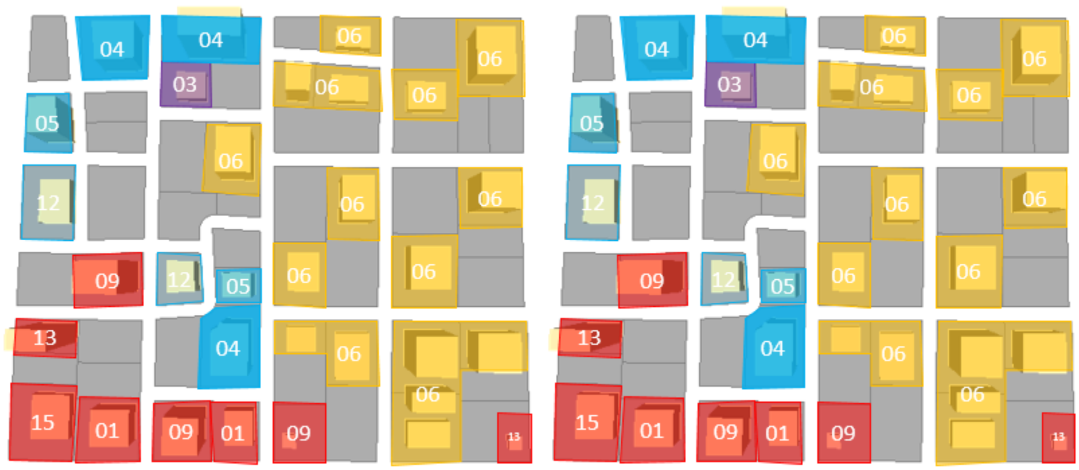


FIGURE 1.14: Site Plan of Conceptual Model
(01: Full Service Restaurant, 03: Large Hotel, 04: Large Office, 05: Medium Office, 06: Midrise Apartment, 09: Quick Service Restaurant, 12: Small Office, 13: Stand-alone Retail, 15: Super Market)

1.2.4 Aggregating Hourly Energy Data to 3D GIS Model

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. More specific information will be included in the interface section X (interface 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 1.15 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, a relatively higher performance machine (Dell Precision T1600 Quad Core Intel Xeon, 3.10GHz RAM - 16GB was used) was used in importing the data, the authors only suceeded in importing one month of data, never for one year. 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 exist 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 have the same high performance computer. Although the animated map can be exported, 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 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 visualising the image sequence.

Figure 1.15: 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.

1.3 Output Map Images

Select all the building lot and change their names to "LOT" so that we'll be able to use the python script to select them all with the filter "`ce.withName(\'LOT'")`". Then the map images are extracted as snapshots from CityEngine with Python script by iteratively 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

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 strategys 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 key goal functions of the dynamic energy map in the current study is defined as:

1) Assisting users to visualize the time dependent hourly thermal and electricity demand of each building, each builing sectors and the whole community so that they can have a better understanding of the importance and the potential of arranging land use pattern and building density on the aggregated thermal energy and electricity demand of single buildings, building sectors and the whole community.

2) Assisting users to identify the energy recovery opportunities through multi-dimensional visualization of the space heating and cooling demand.

3) Assisting the sizing of a district energy system CHP plant.

1.4.2.1 Function 1: Assisting Energy Recovery

To achieve this, the space heating and cooling demand should be represented on the same map that better reveals their correlation.

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 1.16). 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" [42] for demonstration.

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 1.17).

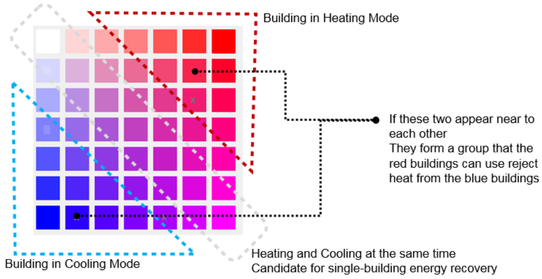
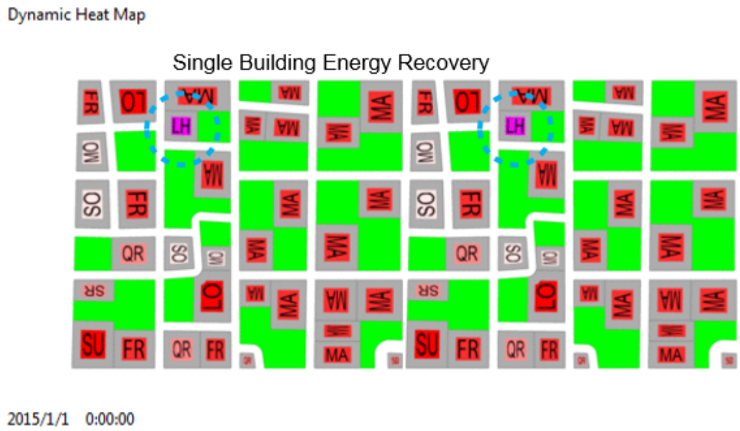
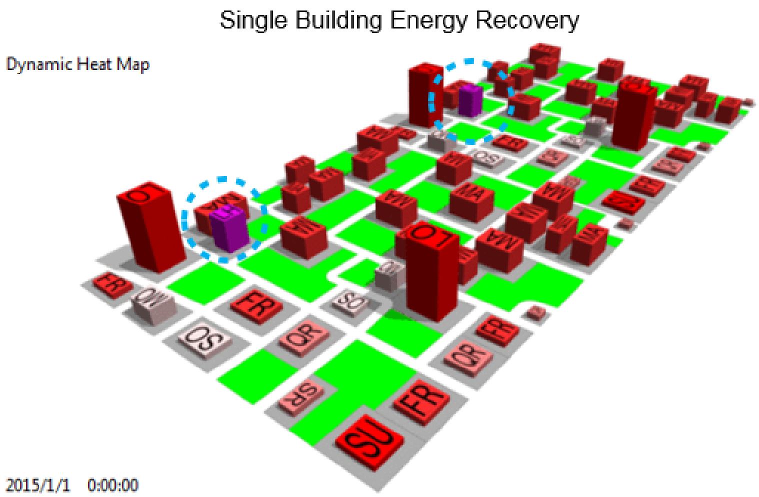


FIGURE 1.16: The bivariate color ramp displays two variables at the same time: space heating and space cooling. It better displays the co-relation between these two variables and thus helps users to identify energy recovery opportunities



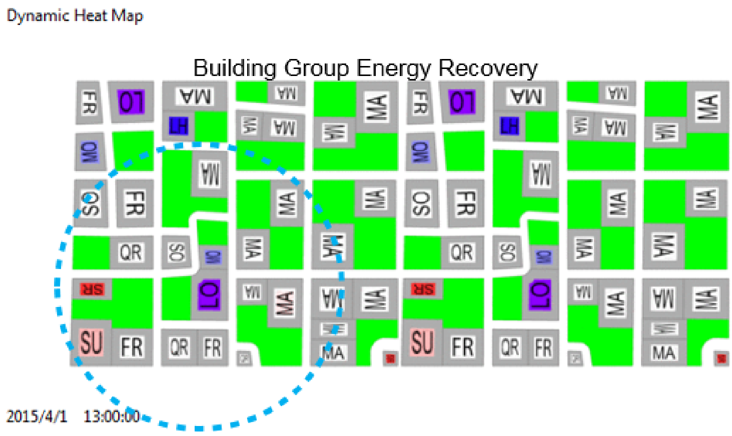
(A) 2D map display that helps user to identify the energy recovery opportunities for single buildings



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

FIGURE 1.17: Dynamic Energy Map helps user to identify the energy recovery opportunities for single buildings

The user can identify a group of adjacent buildings for reject heat sharing: in the following example, the center building is with high cooling demand (since it is blue) and the surrounding buildings are with medium or high heating demand (they are with a redish color). By transmitting the reject heat from the center building to the surrounding buildings, the total energy consumption of the building group (within the dotted circle) could be reduced. In the following example, if the land use is planed so that Large Office (LO) is directly next to Stand-alone Retail (SR) and Supermarket (SU), it would be easier for the cooling reject heat from LO to be captured and transmitted to SU and SR with less distance and thus with less transmission loss (Figure 1.18).



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

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

FIGURE 1.18: Dynamic Energy Map helps user to identify the energy recovery opportunities for building groups

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 $f = 1.15$

for Large Office and Hospital, and $f = 1.25$ for the remaining building types. A heat demand plot will be shown for the total heating energy demand before and after the recovering of the reject heat for single buildings or building groups (neet to be implemented)

1.4.2.2 Function 1: Assisting Sizing of District Energy System

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

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 1.10a), 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 1.19).

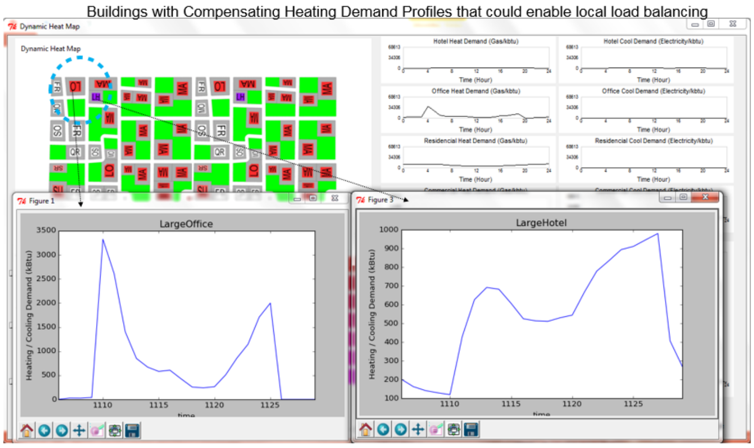


FIGURE 1.19: Users can check the building energy demand (thermal or electricity) by clicking on the building foot print in the 2D map and the interface will show the plot of the energy demand profile within a period (the example is showing the demand for a 24h hour period)

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 1.20) at this time that could be a candidate for load balancing) and they will look at the map and search for this "good combination".

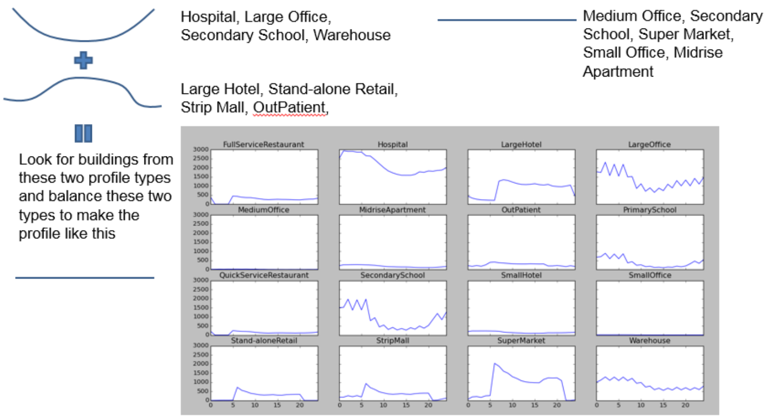
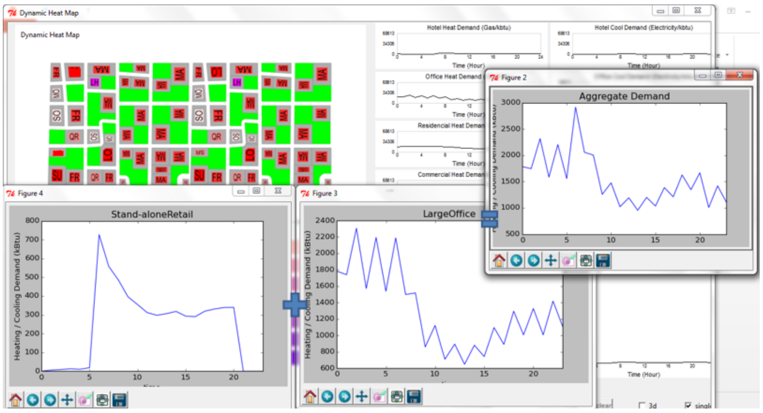


FIGURE 1.20: Users can plot all building energy demand profile (heating gas demand for the example) and search for "good cobimations" that have compensate load profile

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 1.21).



See if the combination works for load balancing

FIGURE 1.21: 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

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