Carnegie Mellon University

Master Thesis

Dynamic Energy Mapping

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in the

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Declaration of Authorship

I, Yujie Xu, declare that this thesis titled, 'Dynamic Energy Mapping' and the work presented in it are my own. I confirm that:

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Abstract

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Dynamic Energy Mapping

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The project aims at implementing a Dynamic Energy Demand Map that holds, visualizes and analyzes high spatial (each building, building group and the community) temporal (hourly) resolution energy demand data of a community with the focus on creating a highly integrated visualization and an interface is designed to serve this purpose. The target user of the interface is researchers in energy related fields with the basic abilities of map reading, understanding moderately complicated map legend and data plot and understanding building energy performance attributes and their implications. A general purpose design is created to provide both qualitative and quantitative information and to suit different research interests of this user group.

The approach is demonstrated with a conceptual community model created in CityEngine based on the land use pattern of a mixed-use redevelopment project at Lower Hill District, Pittsburgh, PA. The hourly energy demand profile is retrieved from the simulation of DOE Commercial Prototype Building ASHRAE90.1-2013. The interface is written in Python.

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Abbreviations

CMU	**C**arnegie **M**ellon **U**niversity
GHG	**G**reen**H**ouse**G**as
DOE	the U.S. **D**epartment **O**f**E**nergy
HTPR	**H**eat**T**o**P**ower **R**atio
EPM	**E**nergy**P**otential**M**apping
EMIOFN	**E**nergy **M**apping to **I**dentify **O**pportunities for **F**uture

Symbols

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

Chapter 1

General Introduction

1.1 Project Overview

The burning of fossil fuels produces green house gases (GHG) and causes significant global climate changes including global sea level rise, temperature rise, ocean warming, ice sheet melting and extreme weather events [3]. Fossil fuels are finite: studies have shown that if the consumtion rate of fossil fuels remain the same, the major fossil fuels including oil, gas and coal will run out by the end of this century [4, 5]. Governments have begun to make reducing GHG as one of their major development goals: UK launched the "Climate Change Act" that aims at reducing GHG emissions by 80% comparing to 1990 by 2050 [6]; the City of Calgary aims at reducing CO_2 emission rate by 50% by 2050 [1]. In the U.S., the Climate Action Plan was lauched by President Obama in Jun. 2013. The plan has set the GHG reduction goal to 26 to 28% by 2025 comparing with the 2005 level of emissions [7].

Reducing GHG emissions and fossil fuel consumption also takes place at the community level. Community Energy Management (CEM) is a combination of community level design strategies and energy management strategies aiming at providing quality of life in an urban environment with minimized energy consumption and environmental impact [8]. It contains "land use planning", "transportation management", "site planning" and "local energy supply and delivery planning" [8]. Community level energy planning and management achieves GHG reduction by means of :1) improving energy efficiency, 2) limiting the use of high quality energy and 3) using renewable energy source [9].

Energy Mapping makes community energy planning alternatives visible to planners and policy makers [10] and thus becomes increasingly popular with the increasing attention to community energy planing. Emerging explorations of the role and power of Energy Mapping in assisting community energy planning are taking place all over the world. The City of Calgary carried out an Energy Mapping Study that aims to "encourage the use of alternative energy systems, through considerations such as the design of buildings and encouragement of more compact, mixed-use and high density communities." [10]. The "London Heat Map" project helps developers and planners to "identify opportunities for decentralized energy projects" [11].

Energy mapping is still a developing field with variations in the information included and its display. The Calgary Energy Mapping study depicts annual average energy use intensity and alternative renewable energy supply regions [1]. The London Heat Map contains mainly heating energy related features: high heating energy consumers, suppliers and district heating networks. The Dutch Heat Map, an application of the Energy Potential Mapping (EPM) method developed by Dobbelsteen et al. [12], contains information of annual heating energy demand (or demand density), heating energy supply (or supply density), the infrastructure network layout and CHP and biomass plant locations.

However, as suggested by Baird et al. , existing Energy Mapping practices are mainly static, i.e. the time-dependent changes of energy demand and supply information is not included in these Energy Maps nor do they support more advanced community energy system analysis and comparison. Thus the concept of "Dynamic Energy Mapping" [10] was brought about. A dynamic energy map can:

i. Act as a geo-database that efficiently holds
    - hourly energy profile data for each building and the aggregated energy profile data for the whole community [10];
    - hourly energy supply data of community [10].

ii. Visually display the dynamic energy demand and supply changes with high spatial and temporal resoltion [10].

iii. Allow data analysis and support district system sizing [10].

iv. Be connected to simulation tools that can support instant performance analysis [10].

With a Dynamic Energy Map, the temporal behavior of the demand and supply of heating, cooling and electricity can be revealed and compared, analyzed and updated. One can see how well the supply meets the demand over time. One can also use it as a key component of Geo-design that encompasses "geo-spatial modeling, impact simulations, and real-time feedback to facilitate holistic designs and smart decisions" [13]. The development of data-driven approaches and machine learning methods could also be coupled with the Energy Map to allow more complicated analysis of the spatial-temporal behavior of energy data and provide more informative design or management support.

1.2 Objective and Problem Definition

An initial instance of Dynamic Energy Map was created by Johnstone and Baird and described in [10]. The map consists of two parts: a geo-database that holds general building information annual and monthly energy usage information; and an Excel screening tool that holds hourly energy usage information of each building and district system components and pricing data. It performs analysis and alternative system comparison of a district energy system [10].

In [10], the GIS map realized the function of holding spatial-temporal (although with low temporal resolution) energy data by processing the energy simulation data with Microsoft excel and importing the csv file including "building name, total conditioned area, energy use intensity, annual and monthly peak demand". The high temporal resolution 8760 hourly energy demand profile of each building and the whole community is held in the screening tool. One goal of the current project is to make the geo-database (GIS map) hold higher resolution energy data, i.e. the 8760 hourly energy data of each building and the whole community will be contained in the dynamic energy map.

The function of connecting to building simulation data is also realized by importing simulation result csv files to the geo-database (although with low temporal resolution).

The function of data analysis, the feasibility analysis of a district energy system is performed in a stand-alone excel tool [10] but it is possible that the analysis result could be linked in to the geo-database with using the same approach as aggregation of energy simulation result.

For the function visualization, the spatial and temporal information are visualized separately in the GIS Map and the screening tool [10]: the geo-database visualizes only spatial information: 3D building geometry and location could be visually inspected in the geo-database but not the hourly energy consumption information; The Excel-based screening tool visualizes only the temporal information: hourly energy demand is visualized as 3D data plot but no spatial context is present.

I thus identified the crucially missing function: the visualization of such a spatial-temporal changing of energy behavior as the major goal of the current project.

The objective of the project is thus to:

1. Implement a Dynamic Energy Demand Map with the focus on creating a high-resolution spatial-temporal visualization of hourly energy demand (thermal energy and electricity) data for each building, major building sectors and the whole community
2. Demonstrate how such a Dynamic Energy Demand Map can support
   (a) Identification of energy recovery opportunities of single buildings or building groups
   (b) Helping the understanding of the heating and electricity demand over time on the level of single buildings, building groups and the whole community and help. Helping the sizing of a district energy system CHP plant.

The community model is created in City Engine [14] based on the land use pattern of a mixed-use redevelopment project at Lower Hill District, Pittsburgh, PA [15]. The model contains 68 buildings, comparable to a typical service area of a district thermal energy system (combined heating and cooling), about 50 to 150 buildings [16].

The hourly heating cooling and electricity energy consumption profile is retrieved from the simulation DOE Commercial Prototype Building of ASHRAE90.1-2013 [17].

An interface was designed to combine the 8760 heating-cooling (or heating-power) energy choropleth map images from City Engine and the 8760 hourly heating-cooling (or heating-power) energy data from EnergyPlus to form a Dynamic Energy Map. The interface provides users with the functions of navigating through the dynamic map images and dynamic data plots of heating cooling and electricity demand on the level of single buildings, building sectors and the whole community.

1.3 Related Concepts

Some related key concepts will be discussed in this section: the district energy system, the Energy Map and the Dynamic Energy Map.

1.3.1 District Energy System

A district energy system is one form of decentralized energy system, a "local or sub-regional supply of energy from a local source." [18]. It brings the energy generation near to the end users and reduces the energy transmission and distribution loss [19].

A district energy system produces thermal energy and possibly electricity in a local plant. It delivers the thermal energy to nearby buildings through a closed-loop pipe network. Thermal energy is delivered in the form of steam, hot water, chilled water [10]. The central power plant can take on one of the following forms: 1) thermal plant that generates thermal energy, which can be heating and/or cooling energy 2) co-generation system, or combined heat and power (CHP) system, that generates electricity and reuses the reject heat from electricity generation to provide space heating and service hot water demand of local buildings [16] 3) tri-generation system, where the local plant uses the heat to produce chilled water and supply both heating and cooling energy [20].

A district energy system reduces community level GHG emissions as follows:

- A district energy system with thermal energy and electricity generation has high energy generation efficiency

  Higher energy generation efficiency means with the same amount of input energy, more useful energy is produced and less is wasted. Buildings' electricity supply are mainly from centralized power plant that are far away from cities. Heat produced in power generation is normally dumped into oceans and lakes [10, 21]. It not only causes negative environmental impact [22], but also reduces the energy generation efficiency to only about 1/3 [21]. District Energy System has high energy generation efficiency as a result of 1) it can utilize high efficiency large-scale energy generation equipment [16] and 2) it is closer to the energy end user which reduces the energy loss due to transmission and distribution [21].

- A districty energy system can have better exergy performance

  The quality of energy is usually described with exergy. It is defined as "maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir" [23]. It represents the energy one can get out of the system. One example of a District Energy system helps improving exergy performance and better match the thermal energy supply and the low and medium-quality building energy demand [12] is the low-temperature (or low-energy) district heating system [24] which has a supply temperature of around 50 ^{o}C and return temperature of around 25^{o} C [24].

- A district energy system has multiple fuel choices including renewable energy sources

  The local plant of a district energy system can use a broad range of fuel choices including natural gas, oil, coal, waste, and renewable energy sources including geothermal, solar thermal and biomass, in the generation of thermal energy. This makes the switch to large scale renewable energy source possible. It also makes the district thermal energy system more flexible and more competitive in the market and increases the energy system resilience [16, 21].

Apart from the environmental benefits, a district energy system also reduces the space and cost dedicated to installation and maintenance of HVAC systems in single buildings. It also reduces harmful gas emission of NO_x, SO_x by using non-combustion energy sources as lake body and by filtering [21] the flue gas [25].

1.3.2 Heat Map

Although "heat map" is generally accepted as "graphical representation of data where the individual values contained in a matrix are represented as colors" [26], with respect to buildings, a "heat map" may be defined as "a spatial plan of existing and planned building heat demand, and decentralized energy networks and generation equipment" [19]. It is also a GIS "live database" that allows new development information to be incorporated. It is a key component to the decentralized energy master plan [19]. Heat Mapping is one of the most common instance of Energy Mapping and there are many existing examples in Europe such as the "London Heat Map" [11], the "National Heat Map" [27] in UK, the Dutch Heat Map [12] and the Scotland Heat Map [28].

1.3.3 Energy Map

International District Energy Association (IDEA) define Energy Map as: "a tool that can be used to organize/present data as the basis for defining energy character areas as part of energy planning" [21]. It is a "GIS based system" that can be used to develop energy strategies, prioritize project, identify potential growth opportunities and impose planning restrictions [21]. Dobbelsteen et al. adopted the term "Energy Potential Mapping (EPM)" [12]. EPM assists the development and plan of a sustainable built environment. It is a method that "visualizes local energy potentials and demand in order to support spatial planning towards more energy-efficient urban or rural environment" [12]. UK used the "Decentralized Energy Masterplanning" as a method that helps local authorities identify low carbon strategies that "maximises the opportunity for large-scale schemes to capture and use waste heat from major energy sources" [19].

With respects to the various definitions above, an Energy Map could be understood as a generalization of a heat map that includes energy supply, demand and infrastructure information of various energy forms and technologies. Some existing use cases suggest an Energy Map could be used to visualize the community or city level energy demand reduction with high performance building design [1] or adoption of alternative energy supply technologies such as the Calgory Map [1]. It can be used in supporting district heating system design such as the London Heat Map and Scotland Heat Map [19, 28, 29] by visualizing the heat sources and sinks, and how they can be efficiently connected to reduce GHG emissions and energy cost. It can also be used to assess the energy potential of renewable energy sources such as NYC Solar Map [30] and "Find My Solar Suitability" map [31].

1.3.4 Dynamic Energy Map

According to the study of Baird et al. , a Dynamic Energy Map is an Energy Map equipped with high resolution temporal energy information of energy supply and demand. This is the key difference between Static and Dynamic Energy Map. It enables spatial-temporal comparison, aggregation and query of energy demand and supply. It is coupled with energy simulation tools, and design alternatives would be evaluated and compared at each given time spot or time period [10]. By performing advanced data analysis method, the dynamic map makes patterns that are omitted in static maps visible and analyzable. Both aspects enable more detailed energy analysis and design support.

1.4 Why "time" dimension is important

1.4.1 Strong Temporal Variation of Energy Demand

Different building types often indicates different energy demand profile. For example, the residential building heat demand profile has two major peaks, morning and evening, and is relatively low for the rest of the day. For office buildings, there is a peak heat demand in the morning and a relatively high heat demand through the day time but drops in the evening. Hospitals usually have a more flattened demand throughout the day. Within a mixed-used urban environment, the arrival of peak demand for different buildings are usually not simultaneous [19].

In the design of a district energy system, mixing building types with different time-of-use energy profile can be helpful in creating a less variate aggregated energy demand. This allows the central CHP plant in a district energy system to a have higher utilization rate and reduces the need for backup plant that accounts for high peak demand [19].

1.4.2 More Detailed Description of Energy Behavior Supports Better Design

A simple annual or monthly average cannot effectly represent the real energy consumption behavior of an individual building and the whole urban environment. In order to

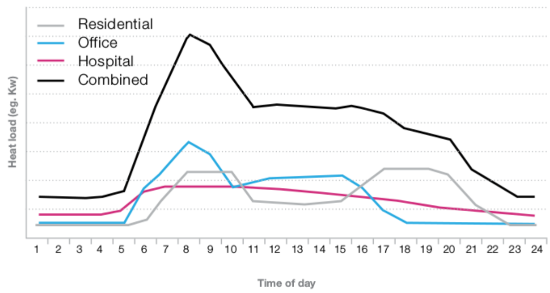


FIGURE 1.1: Mixing Load of Different Building Type [19]

present this complicated behavior of time-dependent energy demand, the time dimension is necessary.

This can be explained in a concrete example. Hospitals are usually constant heat consumers with very stable heat demand throughout a year (see Figure 3.3), while a performance center is, on the other hand, an occasional huge heat consumer with very high peak demand occuring occasionally at event time and with almost zero demand in the remaining time. It is reasonable to apply different energy planning strategy for building groups involving one of these two types of buildings. However, if time dimension is omitted, one has to choose some aggregated description of the energy consumption of the two building types, be it average, maximum, minimum or annual total. For most cases, annual total demand is used for representing a building's energy demand, especially in the case of District System design. With this approach, the different energy usage pattern of a hospital and a performance center might look the same, which results in a simplified energy plan decision.

1.4.3 Aggregation of Peak Value Becomes Tricky for Data with Time Variation

One common mistake for sizing a district thermal energy system is to add up the peak demand of each terminal users. Since the peak demand of individual buildings do not occur at the same time, the end result of summing up the peak demand at each end point exceeds the actual total demand peak of the community. Hence with this approach, the whole district system becomes excessively over-sized, which reduces the whole system efficiency. A Dynamic Energy Map can reveal the problem of such approaches by directly providing the aggregated thermal energy and electricity demand for single buildings, building sectors or the whole community. It allows a side by side comparison of single building demand and aggregated demand and eliminates the misunderstanding of the demand aggregation. With the direct information of aggregated thermal energy and electricity demand, it also assists actually sizing a district thermal energy system.

Chapter 2

Related Works

This section provide an overview of the existing instances of static energy maps and dynamic energy maps. Section 2.1 and Section 2.2 presents a general information of the energy mapping instanceses. Then the summary of demand side information, supply side information and techniques used to produce these Static and Dynamic Energy Map instances are shown in Section 2.3.

2.1 Static Energy Map

2.1.1 London Heat Map

Under the goal of supplying 25% of the total energy with decentralized energy (DE) by the year 2025, the Decentralised Energy Master Planning Program (DEMaP) was conducted between 2008 to 2010 to "identify opportunities for district heating networks through heat mapping and energy masterplanning" [11]. In this study, the term DE only refers to "combined heat and power systems connected to district heating networks" [19].

London Heat Map is a publicly accessible interactive map developed as part of the DEMaP project. It is completed for the London Boroughs in 2012. It can act as a starting point of Energy Master Plan for local authorities, and can assist developers to make connections to existing DE networks to meet policy requirements (London Plan DE policy) [11, 19]. Point features of high heating energy consumers and suppliers, existing and emerging energy networks are depicted on the interactive map. High DE potential regions ("focus area" [19]) are identified and depicted on the map to highlight the opportunities of utilizing the heat supply in the community planning and development (Figure 2.1). The "live-database" property of London Heat Map allows new data of energy consumption be uploaded by users.

The criteria applied for identifying focus area include: 1) near to existing or emerging DE network, 2) high heat demand density 3) anchor load building, 4) diverse heating demand profile 5) has public ownership with policy concerns to make connections to the DE network [19]. The physical constraint are also considered in finalizing the high DE potential regions.

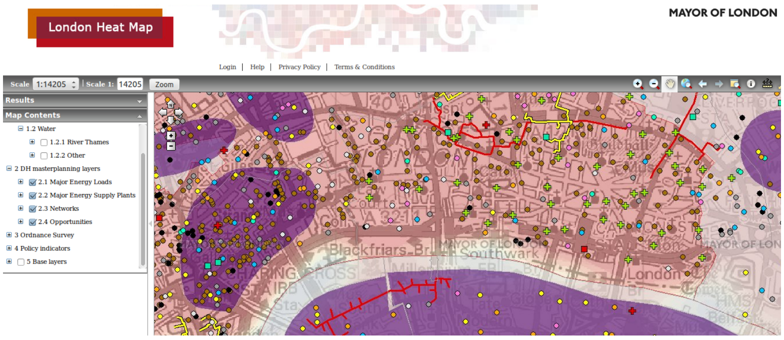


FIGURE 2.1: London Heat Map [32]

2.1.2 National Heat Map

National Heat Map (Figure 2.2) is another UK energy mapping project that focuses more on the industry side [19]. It is a "high resolution web-based" heating energy interactive map, developed by the Department of Energy and Climate Change (DECC). It aims at "support planning and deployment of local low-carbon energy projects in England" [27]. Power plant developers can use this map to consider the feasibility for a CHP plant under policy requirements [19]. Heating demand density (kWh/m^2) of four major building sectors: public buildings, commercial buildings, industry buildings and residential buildings, together with the total demand is plotted on the map as a 2D raster image with a discrete color scheme from blue to red representing low to high heating demand. Heat source of CHP stations and thermal power stations are plotted as point features in the map. Address level heat demand data in csv format is also available for local authorities upon request [33].

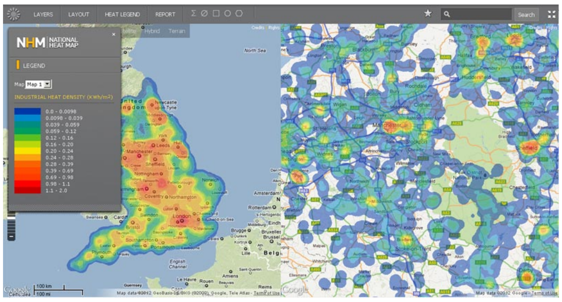


Figure 2.2: National Heat Map [34]

2.1.3 Water Source Heat Map

The "Water Source Heat Map" (Figure 2.3) is an added layer group to the existing National Heat Map with information about the the heat potential of the 4041 waterways in England. Heat potential of waterways are represented in temperature, surface area, flow rate and heat capacity (kJ/m^3 for coastal and estuary, kW for canal, river and settlement). It aims at supporting the plan of water-based thermal system as water-based heat pump [35]. The map revealed the large thermal capacity of water bodies that could serve over one million buildings in the UK [35].

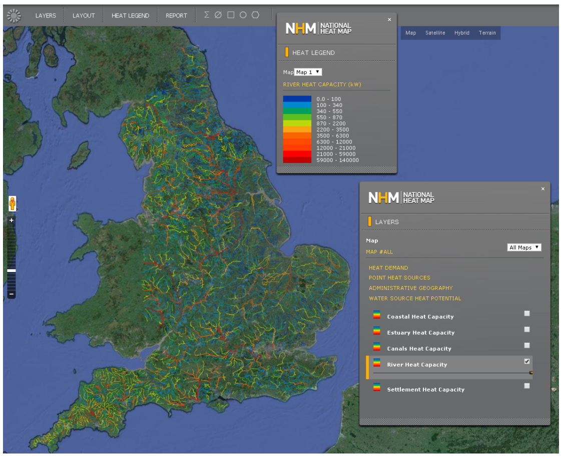


Figure 2.3: Water Source Heat Map [35]

2.1.4 Calgary Energy Map

One of the early instances of Static Energy Mapping is the Energy Mapping Study of City of Calgary in 2008, carried out by Canadian Urban Institute. It aims at providing insights to achieve the goal of reducing 50% of Green House Gas (GHG) emissions by 2050 [1]. It depicts 1) how building design strategies and land use planning can influence the city level energy use intensity 2) the availability of alternative energy sources and the opportunities to combine building level sustainable design technology with the community level energy system design.

Calgary energy map first compares energy use intensity (the annual total demand for thermal energy of space heating cooling, hot water and electricity per unit area [1]) in GJ/ha between two development cases: "business as usual" case and "ultra-high efficiency" case (Figure 2.4). The comparison demonstrated a 34% reduction in energy use intensity from the former to the latter [1].

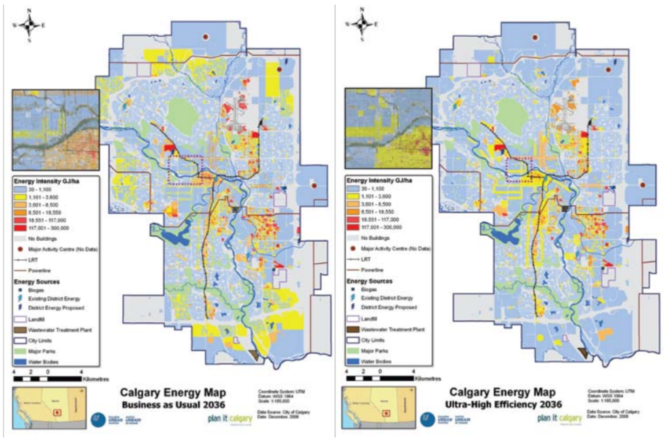


FIGURE 2.4: Calgary Energy Map (Business as Usual, Ultra-High Efficiency) [1]

It also shows alternative energy sources of district energy, solar hot water, solar air, energy sharing and PV installation on the map (Figure 2.5). By overlaying the alternative technology map and the "ultra-high efficiency" map, it highlights the opportunities of using alternative renewable energy sources and district energy system to further improve the energy performance of high energy demand areas after high performance building design was applied [1].

2.1.5 Energy Potential Mapping

Dobbelsteen et al. described a framework of Energy Potential Mapping (EPM) that aggregates information of energy supply, demand and infrastructure on the same map with demand and supply represented in the same unit of GJ or GJ/ha [12].

In 2010, a "Heat Mapping" study under the framework of EPM was launched by TU Delft aiming at visualizing heat demand and supply and infrastructure with the same

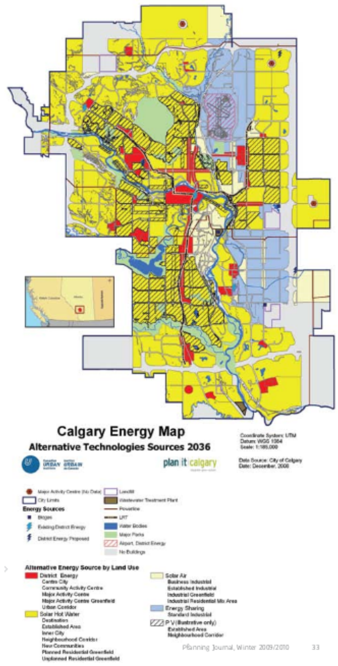


FIGURE 2.5: Calgary Energy Map Alternative Energy Source [1]

unit that facilitates easy comparison and facilitates the matching of supply and demand [12]. The map is presented with aggregated supply and demand in a 3D Heat Map. The absolute quantity of each type of demand and supply is represented with extruded height in the 3D map. Demand is represented with a transparent 3D feature, and each supply source is represented with solid 3D feature in a different color [12].

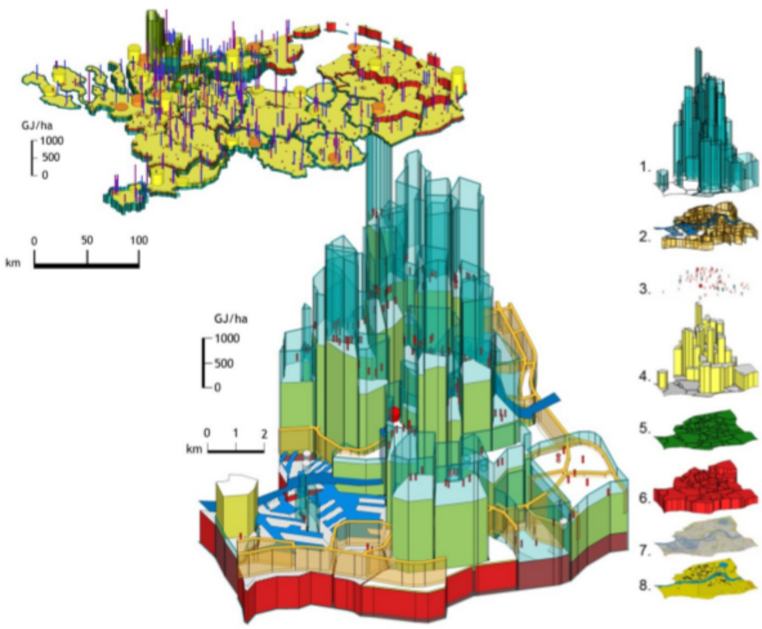


FIGURE 2.6: Heat Mapping of Netherlands and Rotterdam [12]

2.2 Dynamic Energy Map

Per definition of Dynamic Energy Map in the introduction, there are not instances that fully realized all the desired functions yet. In this section, some valuable attempts towards realizing and exploring the power of dynamic energy mapping will be discussed.

2.2.1 Lower Hill District Dynamic Mapping Project

In 2011 to 2012, the Dynamic Energy Map of the Lower Hill District, Pittsburgh, PA was created. It is designed to conduct feasibility analysis and comparison of alternative energy supply techniques of a district energy system [10, 15]. A geo-data base was created with ArcMap, ArcScene and Sketchup. In the database, each building, represented as a 3D feature, contains attributes of its building name, annual energy consumption, energy use intensity (EUI), and annual and monthly peak demand. The map is online accessible via GIS Cloud (Figure 2.7).

FIGURE 2.7: Online Accessible GIS-database with GIS Cloud [10, 15]

The feasibility analysis and temporal data display are separated from the geo-database and is performed in a excel screening tool. The tool takes input of energy cost rate, building type and size, development phase and central plant types and feature and produces a feasibility analysis and related temporal graphs (Figure 2.8) of annual hourly energy consumption for each building type and the aggregated demand of natural gas, cooling use electricity and total electricity.

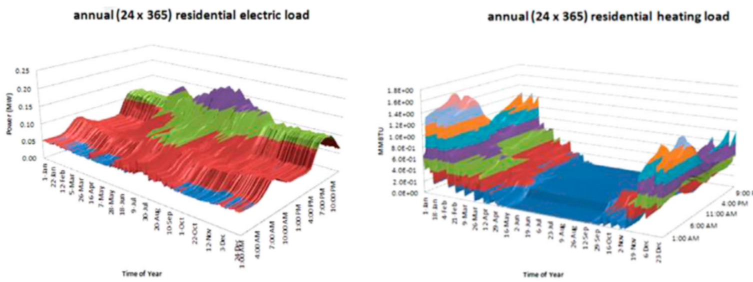


FIGURE 2.8: Heating Load and Electricity Load for Residencial Building [10]

2.2.2 Energy Mapping to Identify Opportunities for Future Networks Project (EMIOFN)

Another instance of energy demand dynamic map with high spatial resolution was found in the project "Energy Mapping to Identify Opportunities for Future Networks" [36]. The aim of the project is to "analyze the spatial and temporal distribution of energy consumption" and support decision making and design of energy network: more specifically, to identifiy opportunities of District Heating, CHP plant development and Building Design Improvement [36].

Energy Demand Maps of three different resolutions were created using QGIS: campus level, community level and city level. Energy data was retrieved from both metered data (used in campus level map) and HEM simulation (used in community and city level map). HEM is a tool for "mapping the possiblemapping the possible carbon and energy performance of a dwelling. It has pre-simulated results embedded as a data table in the tool and applies the appropriate system and context calculations to provide instant energy, carbon and cost results" [37].

For the campus level map, the heat demand density (heat demand over conditioned area) were depicted to identify "outliers": the buildings with high heat demand [38]. These outliers were potential buildings need to be improved in building insulation level or HVAC system efficiency. They claim a spatial map is sufficient for this outlier identification process (Figure 2.9). They also created a temporal spatial map of monthly heat consumption that is in the form of both small multiples (Figure 2.10) and non-interactive animated map (Figure 2.11). With the dynamic map, they identified two campus buildings with high heat demand through the whole year (anchor load building) and concluded that the two buildings could connect to a district heating system. They also created two animated maps with electricity and natural gas. By comparing these two animated maps, consistent high consumers for electricity and gas were identified as potential candidate building for a micro-CHP system [39].

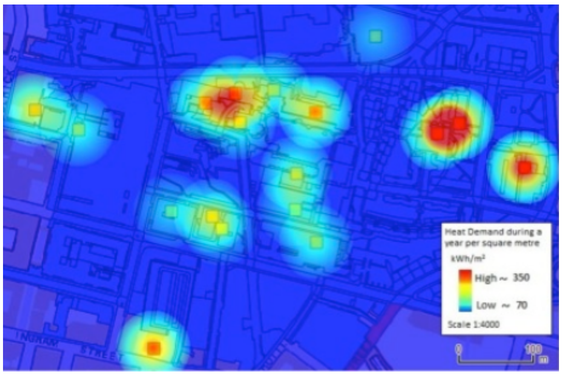


FIGURE 2.9: Campus Level Heat Demand Density Map [38]

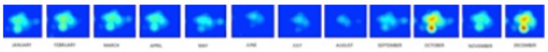


FIGURE 2.10: Campus Level Monthly Heat Demand Map in Small Multiples[38]

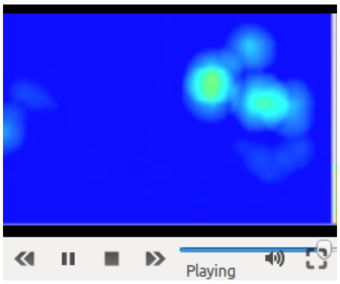


FIGURE 2.11: Campus Level Monthly Heat Demand Map in Animation[38]

The community level spatial and temporal GIS analysis undertook a similar process as the campus level except for the energy data is retrieved from HEM simulation. By comparing the four different building types: “Traditional Build, New Build, Council Estate, High Rise Flat”, they identified the consistent high gas and electricity demand of High Rise Flat buildings. They also discovered that the improvement of building design could adjust the heat to power ratio (HTP) and could make applying CHP option feasible [40].

2.3 Summary

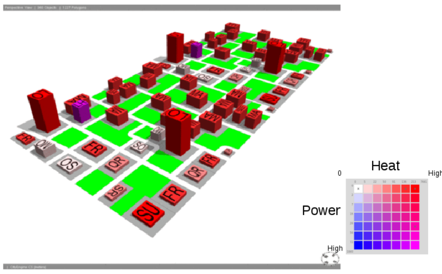
2.3.1 Demand Side Information

Table 2.1 summarizes the energy demand topics of the cases presented in this section. The demand information presented in all cases is heat demand except that the Calgary map has information of the total energy demand: the sum of heating cooling and electricity demand. The demand time resolution is year (represented as annual total or annual total density) or month (monthly peak or monthly total) for almost all instances, except that the Lower Hill District Project screening tool has hourly demand information in the screening tool.

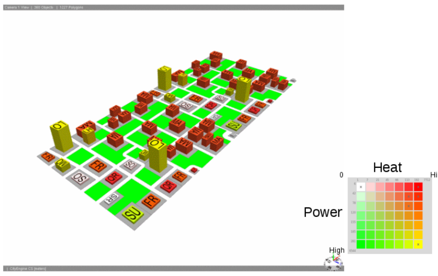
Table 2.1: Demand Side Input Information

Project	Demand Topic	Time	Unit
London Heat Map	heat demand	annual total density	kWh/m2 per year
National Heat Map	heat demand	annual total density	kWh/m2 per year
Water Source Heat Map	x	x	x
Calgary Map	sum of space heating, cooling, hot water and electricity	annual total density	GJ/ha per year
Dutch Heat Map	heat demand	annual total density	GJ/ha per year
Lower Hill District Map	heat demand and electricity demand	Geo-database: annual total density, annual total and monthly peak	kBtu/ft^2/$year$ for EUI, kBtu for annual total, Btu/hr for peak demand
		Screening tool: hourly	MW for electricity demand, MMBtu for heat demand
EMIOFN	heating and cooling demand	annual total density and monhly total	kWh/m2 per year

The information included in my dynamic energy map is similar to that of Calgary energy map: space heating, cooling, hot water and electricity demand are depicted on the map. Calgary map has a single layer of total demand, while my dynamic energy map provide single layers of heating, cooling and electricity demand over time, as well as two bivariate map layers: a bivariate layer of space heating and cooling demand and a bivariate layer of heating demand and electricity demand. The bivariate layer of space heating and cooling demand can help users identify energy recovery opportunities (Figure 2.12a). The bivariate layer of heat and power accompanied with the aggregated heating and electricity data plot can help users identify help the sizing of community district system CHP plant(Figure 2.12b). Data plot of heating, cooling and electricity of the community and single buildings in the community are also provided to anchor quantitative information (Figure 2.13).



(A) 3D bivariate layer of space heating and space cooling demand



(B) 3D bivariate layer of heating and electricity demand

FIGURE 2.12: Comparing Heating:Gas and Space Heating

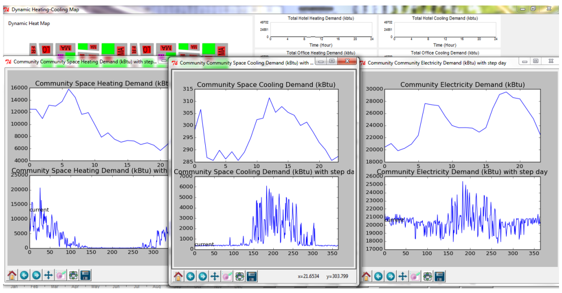


FIGURE 2.13: The example shows the plot of heating, cooling and electricity demand of the Large Office

Comparing with the static and dynamic map instances, which all use annual / monthly total / total density as the indicator for energy demand except that the screening tool in the Lower Hill District Project has hourly demand information. My dynamic energy map adopts the time resolution as the screening tool in the Lower Hill District Project. It contains hourly energy demand data for every single building and the community. Sizing of a district system requires peak thermal energy demand of the community. This variable is missing from all the existing static maps. My dynamic energy map shows the total heat and electricity demand as plot on the interface and the users can use this information to size a district energy system (Figure 4.19).

FIGURE 2.14: Plot of Heating, Cooling and Electricity

I chose to represent energy demand as absolute value rather than density value in order to provide quantitative information for the amount of energy that could be recovered within building groups or communities and to provide information for the total thermal energy demand in order to size system capacity of a CHP plant.

My dynamic energy map also provide different forms of energy data aggregation over the time dimension, such as total, peak and average demand over a year, a month a week or a day (Figure 2.15).

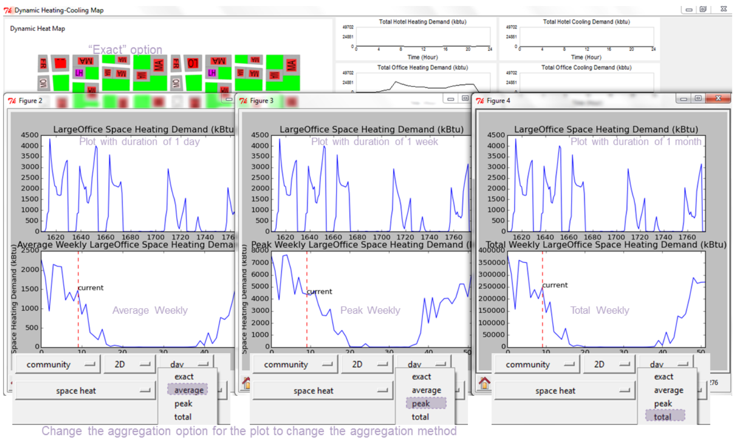


FIGURE 2.15: Plot of Different Energy Aggregation Method

2.3.2 Map Representation

Table 2.2 summarizes the data representation method used in the cases presented in this section.

TABLE 2.2: Map Representation of Related Works

Project	Geometry	Quantity representation
London Heat Map	point	graduated symbol size
National Heat Map	raster	discrete graduated color ramp (blue to red with red for high heat demand)
Water Source Heat Map	x	x
Calgary Map	polygon	discrete graduated color ramp (blue to red with red for high energy demand)
Dutch Heat Map	extruded polygon	height of polygon
Lower Hill District Map	Geo-database: 3D building and site	Bar Chart
	Screen Tool: no geometry associated	Screening Tool: 3D height graph
EMIOFN	raster	continuous graduated color (blue to red with red for high heat demand)

In London Heat Map, locations of potential heat consumers are aggregated to point features on each building centroid. The annual total heating energy demand (MWh per year) is represented with the graduated size of the point symbol (Figure 2.16).

In Calgary Energy Map, the total demand of heating, cooling, service hot water and electricity are represented as area density in GJ/ha. The demand layer is a polygon feature layer with energy demand density represented as a graduated color symbol from blue to red.

In National Heat Map and Water Source Heat Map, the heating demand in kWh/m^2 is depicted with a raster density map layer. The same approach of using the density raster layer to represent heating and electricity demand is adopted by the EMIOFN project. Raster density maps are helpful in removing clutter in small-scale maps that depicts large regions (Figure 2.17). For large-scale maps, the National Heat Map provides multiple views so that the raster heat demand density map can be visualize side by side with the satellite view to provide the urban environment context.

Dutch heat map uses the same density map approach but the density is not interpolated over space as in National Heat Map and EMIOFN. It is represented as the height of the building or region.

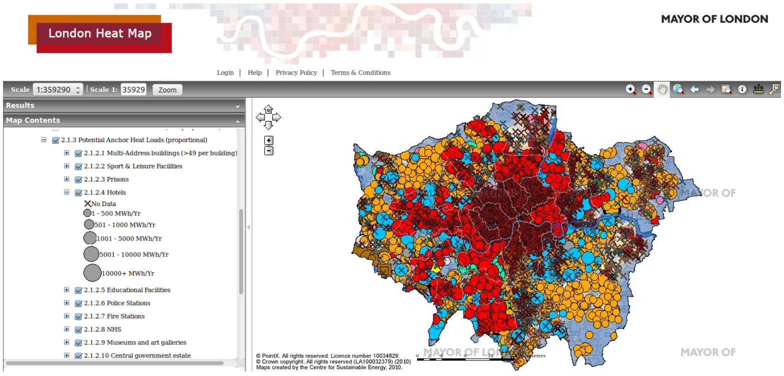


FIGURE 2.16: London Heat Map with Graduated Point Feature [32]

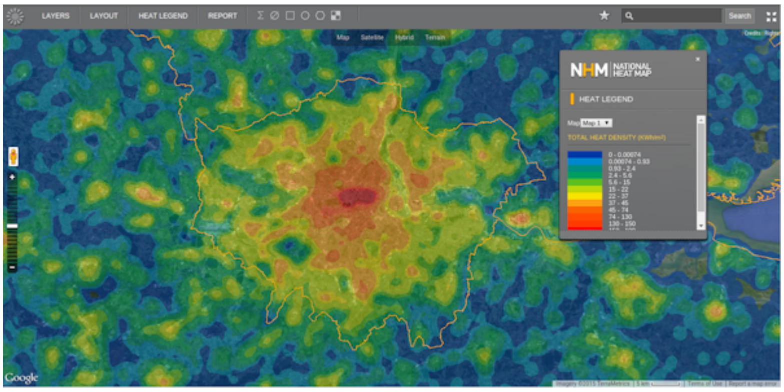


FIGURE 2.17: National Heat Map that depicts the region of London [32]

The Lower Hill District Map does not directly represent energy demand on the 3D map geometry, it uses an attribute table and bar chart to visualize the demand quantity.

My dynamic energy map does not took the raster density map approach because raster density map or graduated size symbol because the former creates a 3D geometry layer and the latter create too much shape distortion. Both approaches will impair my goal of representing a realistic urban environment since the current map only contains one map display window. These approaches could become valid in further development of my current map so that it provide two side-by-side window that shows the urban context and the energy demand layer in different display window as in the example of National Heat Map (Figure 2.18).

2.3.3 Techniques used

The Calgary Map, Dutch Heat Map and EMIOFN map are stand-alone maps produced with desktop GIS software. London Heat Map, National Heat Map, Water Source Heat Map and Lower Hill District project are on-line maps accessible through browsers.

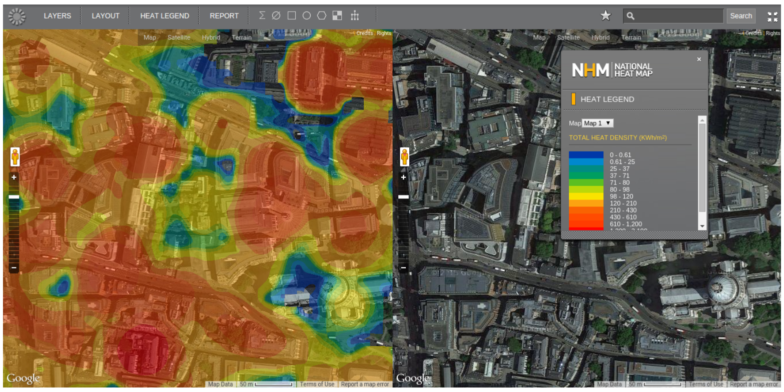


FIGURE 2.18: National Heat Map depicts the heating energy demand on the left and the urban environment context on the right [32]

With limited software survey of ArcGIS and CityEngine, existing GIS software are not capable of implementing an efficient dynamic energy map. The major weakness is in the energy data visualization and the high requirement of computational power. The limitations of existing tools are summarized in Section 3.2.4. The tool used in the implementation of the current dynamic energy map is Python [41] with the Tkinter package [42] for UI design and the pandas [43], NumPy [44], Matplotlib [45] and ggplot [46] for database functions and data plot creation. ImageMagick [47] is used in image formating and resizing. FFmpeg [48] is used in connecting image sequences to animations.

TABLE 2.3: Map Technology Summary Table

Project	Type		Software
London Heat Map	Static	web	ArcGIS WebApp
National Heat Map	Static	web	Google Map API
Water Source Heat Map	Static	web	Google Map API
Calgary Map	Static	stand-alone	?
Dutch Heat Map	Static	stand-alone	?
Lower Hill District Map	Dynamic	web	Map Creation: ArcScene, ArcMap, GIS Cloud Energy Simulation: EnergyPlus
EMIOFN	Dynamic	stand-alone	QGIS (Map Creation) HEM (Energy Simulation)

2.3.4 Building from the Lower Hill District Project

My current work builds directly on the Lower Hill District Project. As is mentioned in the introduction, the major functions of a dynamic energy map is: holding, visualizing and analyzing community level high spatial-temporal resolution energy demand and supply data and connecting to simulation engine for dynamic performance analysis.

In the GIS map of the Lower Hill District Project by Baird et al. [10], holding spatial-temporal (although with low temporal resolution) energy data and connecting to simulation software is realized by processing the energy simulation data with Microsoft excel and importing the csv file including "building name, total conditioned area annual, energy use intensity, annual and monthly peak demand". My dynamic energy map builds on this and makes the geo-database hold more high resolution energy data imported from EnergyPlus simulation, meaning the 8760 hourly energy data should be contained in the dynamic energy map.

The feasibility analysis of a district energy system is performed in a stand-alone Excel tool [10]. My further improvement is to aggregate part of the function of the screening tool, the calculation and display of aggregated total heating and electricity demand, into the dynamic energy map.

The spatial and temporal information are visualized separately in the Lower District Hill Project: the spatial information of 3D building geometry and location could be visually inspected in the GIS map but not the hourly energy consumption information; the temporal visualization of energy demand is done separately in the Excel screening tool as 3D graphs, but no spatial context is present and the spatial dimension is then lost. My improvement is to create a set of spatial-temporal energy data display system that can better convey the energy demand changes over space and time. I

Chapter 3

Methodology

3.1 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 [15] 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 [21].

   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 [21].

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 Prototype buildings of new construction which comply with ASHRAE 90.1-2013 Standard [17].

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 a co-generation system

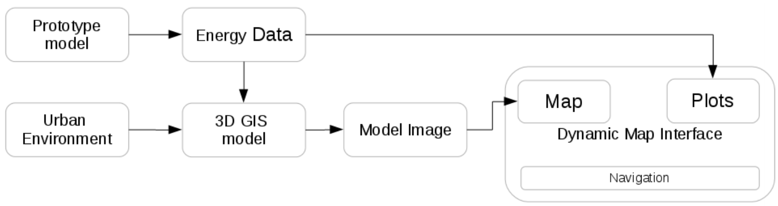


FIGURE 3.1: General Work Flow

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

3.2 Input

3.2.1 Prototype Models and Energy Data

In the Lower Hill District project, the Commercial Prototype Building Models (ASHRAE90.1-2013) [17] developed by the U.S. Department of Energy (DOE) were used to represent buildings in the community model in the district energy system feasibility analysis. This approach allows for a fast initial assessment of the district system [10].

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) [17]. There are 16 building types in the prototype models (Figure 3.1). The building types involved in the current project include: the Large Office (LO), the Medium Office (MO), Small Office (SO), Stand-alone Retail (SR), Strip Mall (SM), the Quick Service Restaurant (QR), Full Service Restaurant (FR), the Large Hotel (LH) and the 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 prototype buildings are shown in Table 3.1:

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 3.1: DOE Prototype Building General Information [2]

The prototype buildings comply with the ASHRAE Standard 90.1-2013. The HVAC system types are shown in Table 3.2. The major heating systems of the prototype buildings are gas furnace and boilers. Some are with packed terminal air conditioner as backup system. The two exceptions are the Small Office and the High-rise Apartment. The former uses an air-source heat pump for space heating with a gas furnace as backup. The latter uses a water source heat pump for space heating. The cooling system for most building types are packaged air conditioning unit. The Large Office, the Secondary School, the Hospital and Large Hotel use air or water-cooled chillers. The Small Office and the High-rise Apartment use water source heat pump for space cooling.

Table 3.2: Prototype 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

3.2.1.1 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 or in the condenser loop by evaporative cooling [49]:

- Air cooled unit: ambient air is blown through condensing coils and removes heat from the gas refrigerant.
- Water cooled chiller with cooling tower: A water-cooled chiller removes heat and reject the heat to the condenser water loop. The condenser water loop contains a cooling tower and the heat in the condenser water loop is rejected to the outside through evaporation [50].
- Water cooled 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" [49] (THR) in the condensing process equals to the "net refrigeration effect" [49](RE, the hourly cooling demand), plus the compressor input, it can be represented with the following equation [49]:

$$THR = RE * f \tag{3.1}$$

f is the "Heat Rejection Factor" and it is typically between 1.15 and 1.25 [49]. The water-based system has heat rejection factor closer to 1.15 and the air-based system closer to 1.25 [49].

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 3.1) is an indicator for heat rejection that could be recovered and shared within a single building or a building group. The heat rejection that could be captured and reused by the building that produces reject heat or by nearby buildings is very complicated and involves the detailed configurations of the cooling system, cooling energy transmission system and the energy recovery system. In my dynamic energy map for the current stage, for demonstration purpose, a simplified assumptions is made that 100% of the cooling reject heat can be recovered. Thus the researcher use THR as an approximation for recoverable cooling produced reject heat and is used in the calculation of energy recovery potential (Section 3.2).

From Table 3.4, the Small Office, the Medium Office, the Large Office, the Outpatient Healthcare, the Hospital, the Small Hotel and the 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. The researcher thus use the EnergyPlus simulation output parameters “heating:electricity” and “heating:gas” to represent the space heating demand of reference buildings.

TABLE 3.4: Annual Total Heating Demand by Fuel Type [2]

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

Electricity is the only fuel used for space cooling [2], thus the EnergyPlus output parameter “cooling:electricity” is used to represent space cooling demand. According to the suggested heat rejection factor [49], the heat recovery potential will be calculated with $f = 1.15$ for the Large Office, the Hospital and the High-rise Apartment, and $f = 1.25$

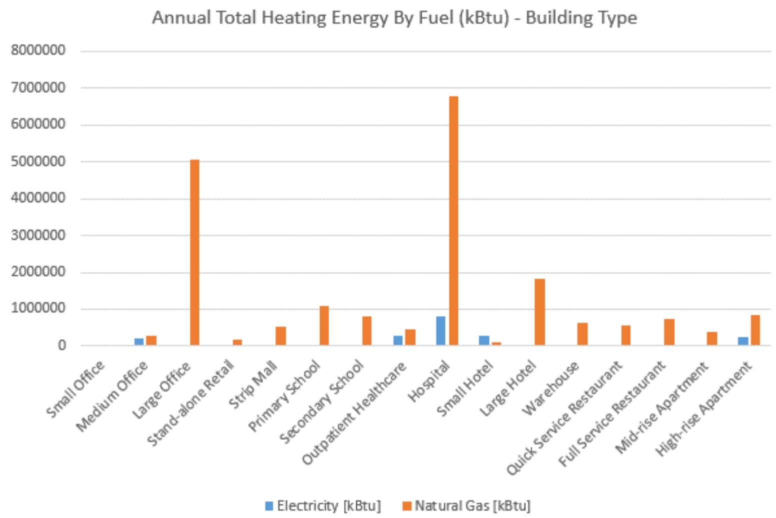


FIGURE 3.2: Heating Fuel

for the remaining building types:

$$\text{Heat Recovery Potential} = \text{cooling:electricity} \times f \tag{3.2}$$

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 all 16 DOE Commercial prototype buildings.

3.2.1.2 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 [10] 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 3.2.1.1 . It contains the space heating demand and the service hot water demand. From the summary files of prototype models, one can observe that the Small Office, Strip Mall, Warehouse and Mid-rise Apartment use electricity to produce service hot water; the Medium Office, the Large Office, Stand-alone Retail, the Outpatient Healthcare, the Small Hotel, the Quick Service Restaurant and the High-rise Apartment use gas for service hot water; Primary School, the Secondary School, the Hospital, the Large Hotel and Full Service Restaurant use both electricity and gas for service hot water (Table 3.5). 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 3.5: 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

3.2.2 Simulation Data Analysis of the prototype models

The output of EnergyPlus simulation of 16 prototype 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 includes "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 3.6:

Table 3.6: 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

3.2.2.1 Single Output

Analyzing the EnergyPlus [51] simulation result of the output above provides a basic understanding of the energy profile data distribution involved in the current project. This can be used as a basis to compare with the additional analysis one can perform in a dynamic energy map described in the following sections.

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

The hourly gas heating demand of the prototype buildings ranges from 0 to 8000 kBtu/hr. The majority (75%) of all hourly consumption is below 1000 kBtu/hr. All building types have a large number of outliers above the 75% quartile. This indicates that the gas heating demand of all building types are severely right skewed which means the median is much smaller then the mean of the distribution and the data set has many extremely large values. The Hospital has the highest median gas heating demand of about 800 kBtu/hr. The Large Hotel has the second larges hourly gas heating demand.

This indicates that the Hospital and the Large Hotel has year-round high heating demand and they can act as anchor load buildings in a district energy system. In terms of peak demand, The Large Office and the Secondary School have the highest peak hourly gas heating demand (Figure 3.3).

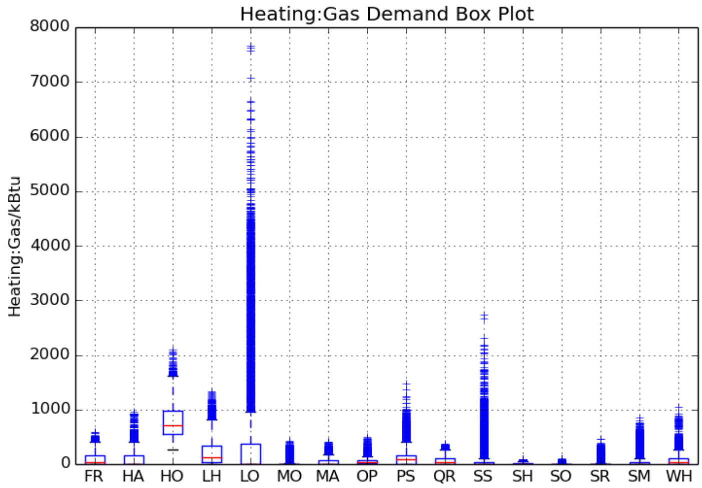


FIGURE 3.3: Heating:Gas Box Plot

The hourly hot water demand of the prototype buildings ranges from 0 to 600 kBtu/hr, about 1/12 of the range of space heating gas demand. Most buildings have median hot water hourly demand below 150 kBtu/hr. Primary School and the Secondary School has a large number of outliers above the 75% quartile and the hot water demand of these two types of buildings are severely right skewed. This means these two building types have a lot of large values in their hot water demand profile. The High-rise Apartment and the Large Hotel have the largest median hot water demand of about 150 kBtu/hr, indicating that these two building types have year round high hot water demand and they may act as anchor load buildings in a district energy system that distribute hot water. The First Service Restaurant, the Hospital, the Large Office, the Mid-rise Apartment and the Small hotel all have a median service hot water demand of about 50 kBtu/hr. The remaining building types have almost zero median hot water demand. The Large Hotel and the Secondary School has the highest peak demand for service hot water. (Figure 3.4).

From Table 3.4, the Small Office, the Medium Office, the Large Office, the Outpatient Healthcare, the Hospital, the Small Hotel and the High-rise Apartment use electricity

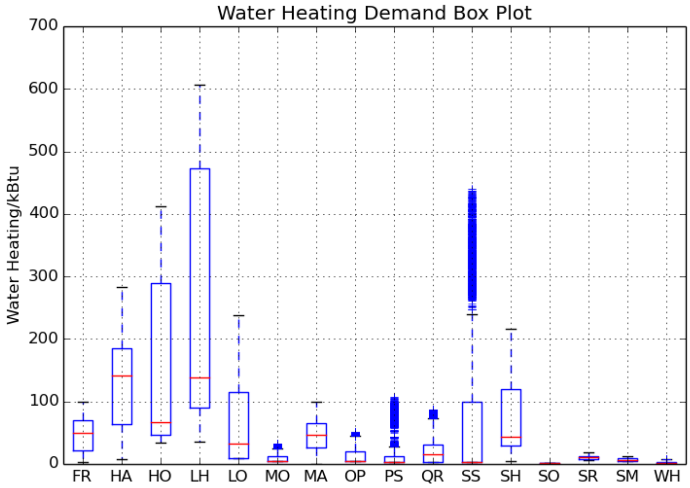
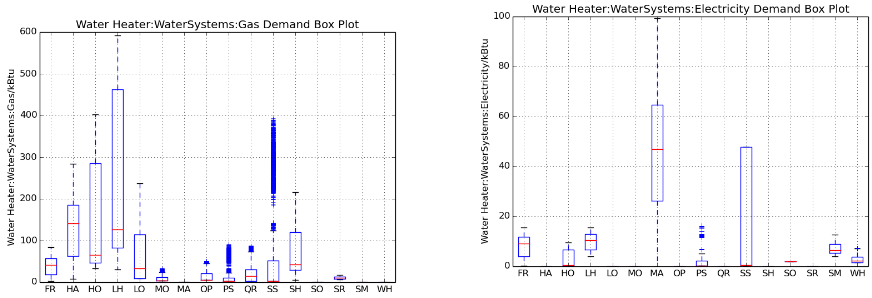


FIGURE 3.4: Service Hot Water Box Plot



(A) Gas Water Heating Box Plot

(B) Electricity Water Heating Box Plot

FIGURE 3.5: Comparing Heating:Gas and Space Heating

and natural gas for space heating. The hourly electricity heating demand of these buildings ranges from about 0 to 630 kBtu/hr. Almost all of them have nearly zero median electricity heating demand, except the median demand for the Outpatient Healthcare is around 30 kBtu/hr. This means the electricity space heating equipment only operates in heating seasons. Almost all building types have a large number of outliers above the 75% quartile except for the Hospital. The Medium Office has the highest hourly electricity heating peak demand and the Outpatient Healthcare and the Small Hotel have the second largest hourly electricity heating peak demand (Figure 3.6).

The hourly cooling demand among the prototype building types ranges from 0 to 2000 kBtu/hr, which is about 25% of that of the peak gas heating demand. The Hospital has the largest median cooling demand of about 150 kBtu/hr. All building types have a large

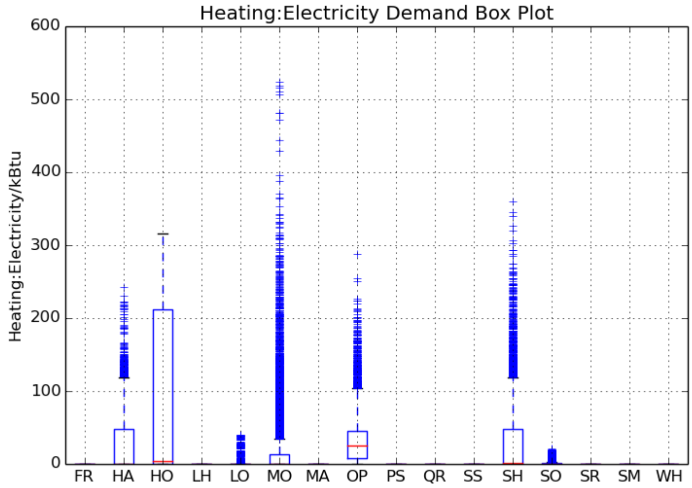


Figure 3.6: Heating:Electricity Box Plot

number of outliers above the 75% quartile, indicating a severe right skew for their hourly cooling demand distribution. This indicates there are a lot large values in their demand profile. 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 1900 kBtu/hr and the Secondary School has the second largest peak demand of about 1500 kBtu/hr. There are five building types with non-zero median hourly cooling demand: the Hospital, the Large Office, the Outpatient Health Care, the Large Hotel and the Small Hotel. This means they need space cooling for at least 50% of the year. The constant cooling demand creates opportunities for energy recovery of reject heat produced by space cooling (Figure 3.7).

The hourly electricity demand of prototype buildings ranges from 0 to 8000 kBtu/hr, which is about the same as that of the peak gas heating demand. Comparing with other output variables, the electricity demand distribution has fewer outliers in general. This indicates that all building types have consistent electricity demand all year round. There are not as many extremely large demand values in the electricity demand profile of any building type. The Large Office has the largest median hourly electricity demand (about 3400 kBtu/hr). The Hospital has the second largest median hourly electricity demand (about 2000 kBtu/hr). The Large Office has the largest electricity hourly peak demand.

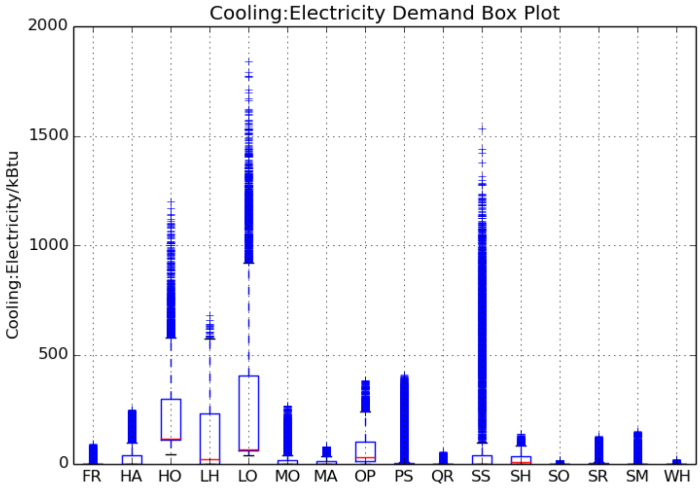


FIGURE 3.7: Cooling:Electricity Box Plot

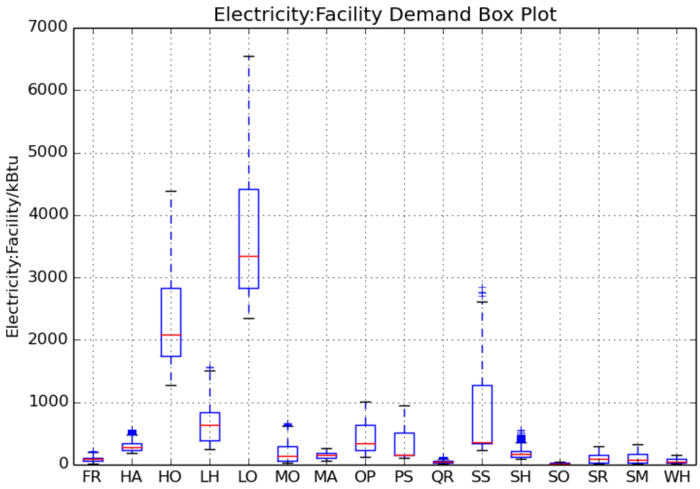
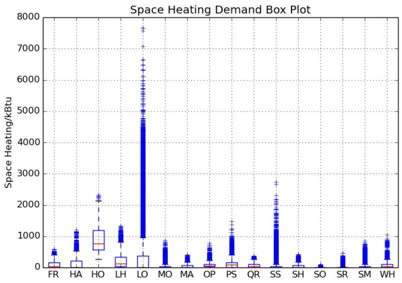


FIGURE 3.8: Electricity:Facility Box Plot

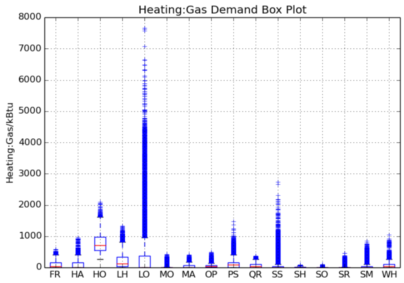
3.2.2.2 Space Heating Demand vs. Space Cooling Demand

The hourly space heating demand of the prototype buildings closely follows the distribution of gas heating demand, with minor demand increase in the Hospital, the Medium Office and the Outpatient Health Care (Figure 3.10a).

Comparing the space heating (Heating:Gas and Heating:Electricity) with space cooling (Cooling:Electricity), one can see that the heating peak demand is larger than the cooling peak demand for all building types. The Hospital, the Large Hotel and the Outpatient



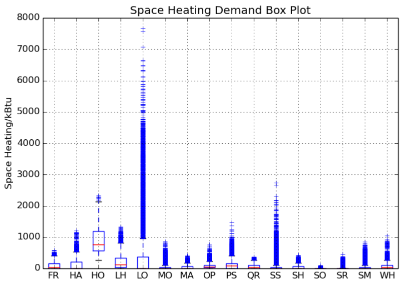
(A) Space Heating Demand Box Plot



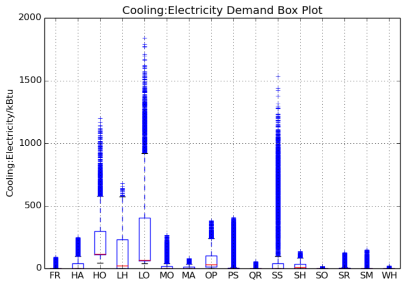
(B) Heating:Gas Box Plot

FIGURE 3.9: Comparing Heating:Gas and Space Heating

Health Care have both the highest median space heating and space cooling demand, indicating a potential for single building level energy recovery.



(A) Space Heating Demand Box Plot

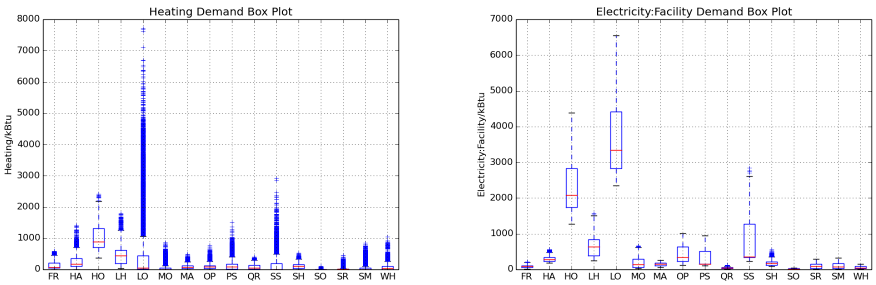


(B) Cooling:Electricity Box Plot

FIGURE 3.10: Comparing Space Heating and Space Cooling Demand

3.2.2.3 Heating Demand vs. Electricity Demand

Comparing the heat and power demand of each prototype 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 [52]. From Figure 3.12, one can see that the range of HTPR is from 0 to 25. The building with highest median of HTPR is the Quick Service Restaurant (about 1.5). The remaining building types have a median HTPR below one. Increase the number of buildings with high HTPR ratio is helpful in increasing the total HTPR of the community. This allows for 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 that shifts the occurring time of the peak of heat demand and electricity demand.



(A) Heating Demand Box Plot (B) Electricity Demand Box Plot

FIGURE 3.11: Comparing Heating and Electricity Demand

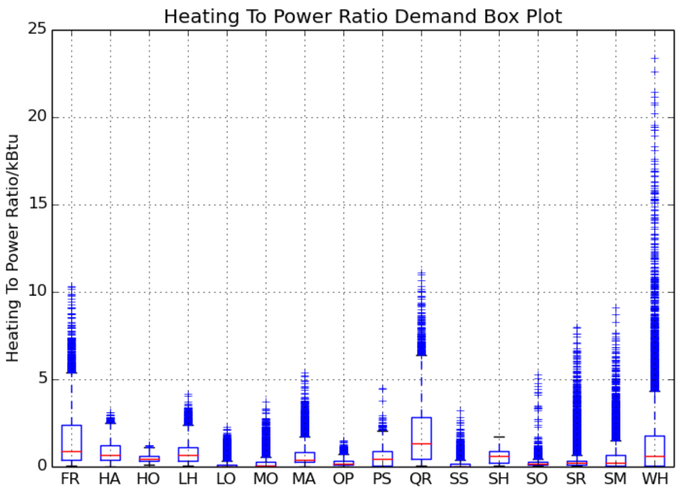


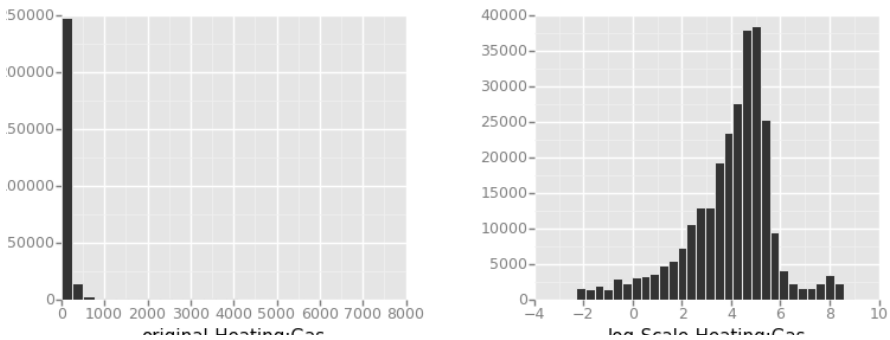
FIGURE 3.12: Heat to Power Ratio Box Plot

3.2.2.4 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 the researcher paired the histogram of the original data with a histogram with natural log scaling.

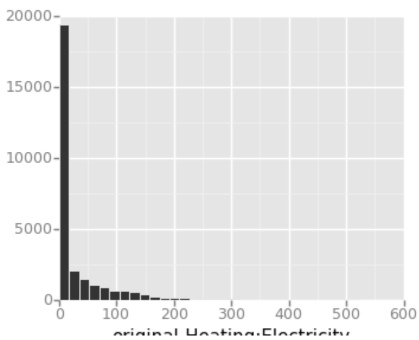
The difference in data distribution might influence the data classification and energy data color-encoding, which then influences the map display design. For example, as is explained in Section 4.2, the continuous function from the energy demand to some color in a color ramp seems to be more efficient in conveying the energy demand changing pattern over time. In order to create such a mapping with enough color or symbol variation, a transform function that reduces the difference between the max and the min in the Probability Density Function (PDF) of a distribution is important. Log scaling could be one possible transformation function and is used in Section 4.2 for the creation of the non-interactive gas heating demand animated map. A closer look at how different energy data distribution can be better visually inspected could be one of the topics for the next stage of the project.

- Heating:

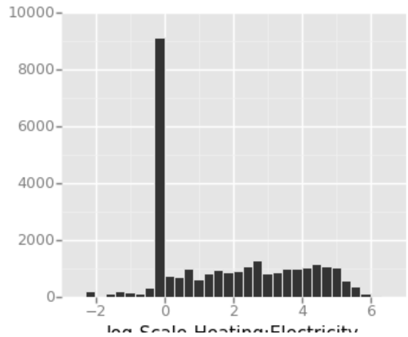


(A) Gas Heating Demand (B) Gas Heating Demand in Log Scale

FIGURE 3.13: Gas Heating Demand in Log Scale

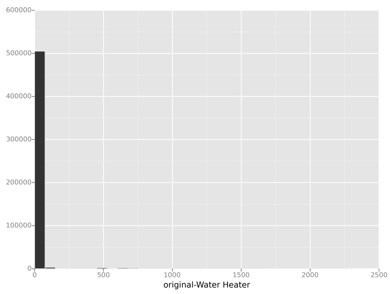


(A) Electricity Heating Demand

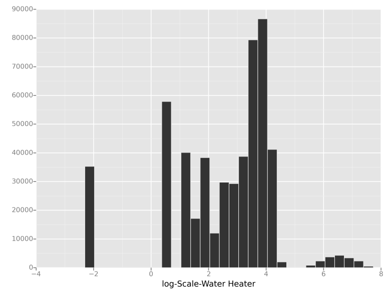


(B) Electricity Heating Demand in Log Scale

FIGURE 3.14: Electricity Heating Demand in Log Scale

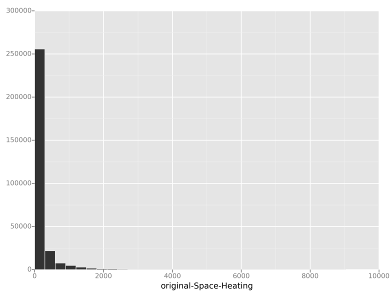


(A) Service Hot Water Demand

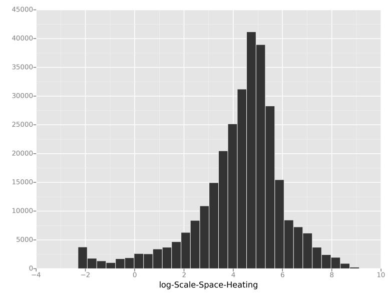


(B) Service Hot Water Demand in Log Scale

FIGURE 3.15: Service Hot Water Demand in Log Scale



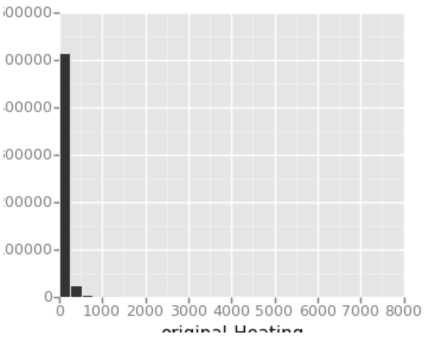
(A) Space Heating Demand



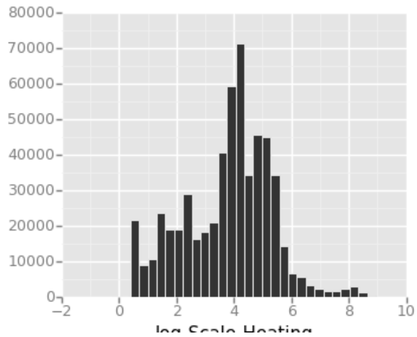
(B) Space Heating Demand in Log Scale

FIGURE 3.16: Space Heating Demand in Log Scale

- Cooling

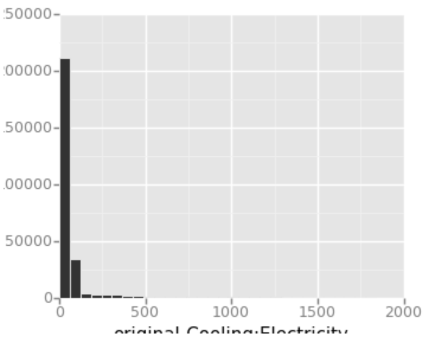


(A) Heating Demand

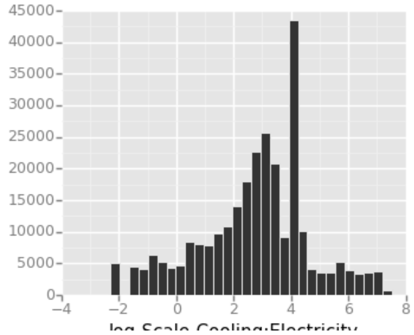


(B) Heating Demand in Log Scale

Figure 3.17: Heating Demand in Log Scale



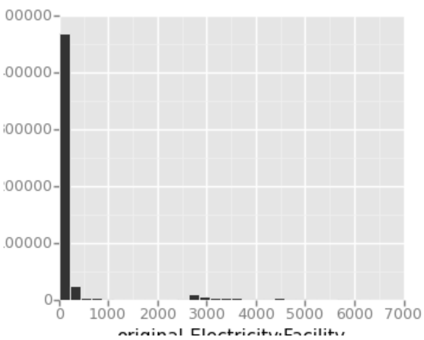
(A) Electricity Cooling Demand



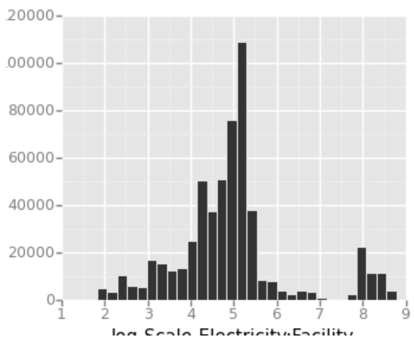
(B) Electricity Cooling Demand in Log Scale

Figure 3.18: Electricity Cooling Demand in Log Scale

- Electricity



(A) Electricity Demand



(B) Electricity Demand in Log Scale

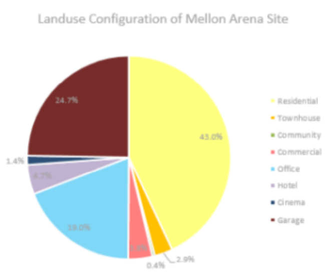
Figure 3.19: Electricity Demand in Log Scale

3.2.3 3D GIS Model Geometry

The conceptual community model is constructed in CityEngine [14]. CityEngine is a software developed by Esri [53]. It can aggregate geographic information into buildings and is capable of smoothly transition models to ArcGIS[54], 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 A.

Although the urban environment in this study is a conceptual setting, I still want it to reflect the topological and density pattern in a real urban environment. To construct the model, the researcher first extracted the topological pattern from an existing urban design project, the Lower Hill District Project [10] (Figure 3.20a. 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) Lower Hill District Project Site Plan View



(B) Lower Hill District Site Land use Configuration

The 16 building types in DOE commercial prototype models do not perfectly correspond to those in the Lower Hill District Site. In order to adapt the topological pattern of the Lower Hill District Project, a mapping (function) from building types of Lower Hill District Site to building types of DOE models is created as is shown in Table 3.7.

The four major building types involved in the current project are residential, commercial, office and hotel. Their topological pattern is represented in Figure 3.21. The conceptual

Lower Hill District 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%	Strip Mall
	25%	Stand-alone Retail

TABLE 3.7: Mapping of Lower Hill District to Building Types of DOE prototype model

model construction follows the building type topological pattern and the urban density as the Lower Hill District Project (Figure 3.22)

After the land use is assigned (Figure 3.22), 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 prototype buildings. The building geometry is simplified in order to highlight the color of each building that encodes its energy demand.

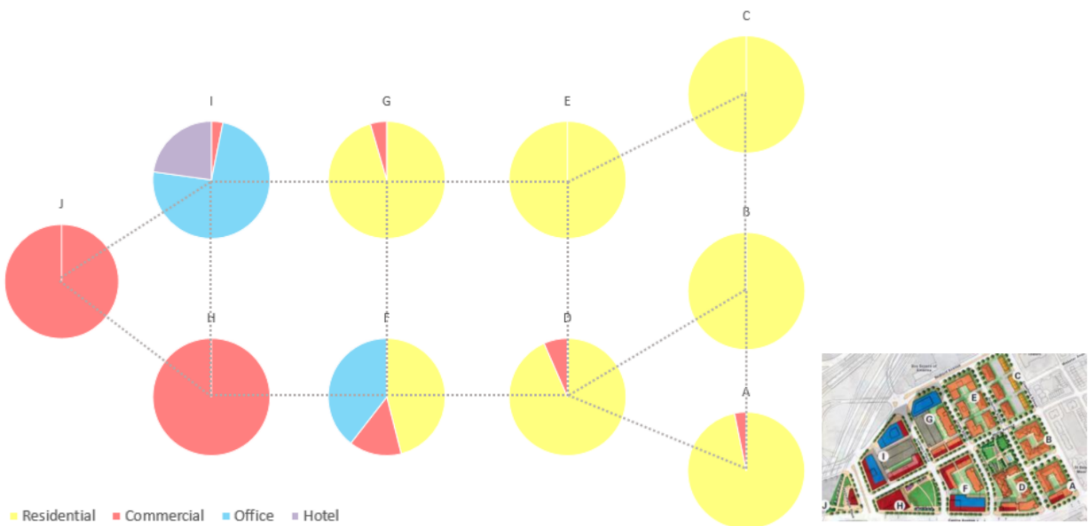


FIGURE 3.21: Building Type Topological Pattern, Lower Hill District

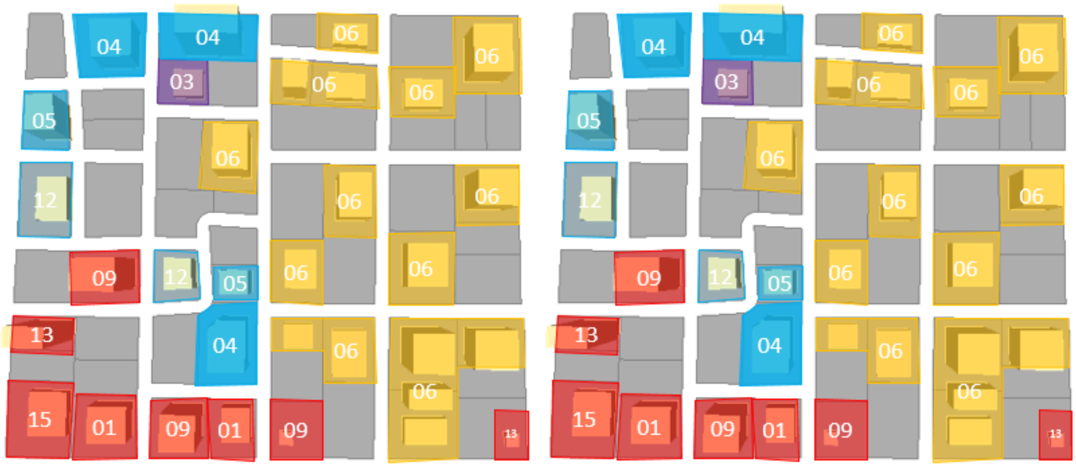


FIGURE 3.22: Site Plan of Conceptual Model
(01: Full Service Restaurant, 03: Large Hotel, 04: Large Office, 05: Medium Office, 06: Midrise Apartment, 09: Quick Service Restaurant, 12: Small Office, 13: Stand-alone Retail, 15: Strip Mall)

3.2.4 Aggregating The hourly Energy Data to 3D GIS Model

3.2.4.1 Comparing Different Approaches

I have experimented with three approaches for aggregating energy profile data into the conceptual model constructed in CityEngine were tested.

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 C

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

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 first approach has the advantage of approach a ready-to-use data classification method and map symbol templates that facilitates choropleth map design and the "time-slider" function for creating a time-wise navigation and animated map. Figure 3.23 shows the interface slider and the dynamic map of heating energy demand for the conceptual model using ArcGIS.

There are several problems with this approach:

- Its high requirement of computational power makes it infeasible to model or view on a typical PC.

  The researcher 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, only one month of data could be imported. 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.

- The time dimension only exists inside the map file.

  This means even if one produced a dynamic energy map, one cannot share it without packing all related files and send to others. This requires the viewer 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 a time legend, the timing and duration of the dynamic changes are not shown.

- For 3D GIS model, it does not contain a proper function to extract single frames of map images, making it impossible to create an exterior interface that deals with 3D maps images.

The second and third approach, on the contrary, provide more flexibility but also requires much user-end work including: pre-processing of energy profile data, implementing data classification method and creating the bivariate color ramp. An interface is also needed for visualizing the image sequence. Comparing these two approaches that does not involve ArcGIS, since CityEngine does not provide the bivariate color ramp, the color encoding cannot be directly computed inside CityEngine, so the researcher chose the method of processing the color encoding outside of CityEngine and writing the generated color encoding representation into CityEngine rule file for the final energy data aggregation method.

FIGURE 3.23: ArcGIS Time Slider for Temperal Data Display

Due to limited time, the experimental GIS software uses only ArcGIS and CityEngine. There might be better alternatives to achieve a dynamic map with more elegance and also to put the stand-alone map on-line to facilitate easy sharing. Finding a better alternative software to implement a dynamic map could be part of the work of the next stage of the project. Resch et al. evaluated some existing web-3D and 4D visualization technologies [55] and found WebGL to be competitive because of its high performance, portability, spatial coordination support with three.js framework and no requirement of plug-in etc [55].

3.2.4.2 Data Classification

This researcher developed a function to translate energy data to its color representation in order to visualize energy data in the map. A common approach is to create a series of graduated colors or symbols and to classify the data into a few groups, 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 researcher conducted a brief survey of the commonly used GIS software for commonly applied data classification methods. The software surveyed in the study include: ArcGIS [56], GRASS GIS [57], gvGIS [58], 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 the researcher chose to implement the "Equal Interval" and "Quantile" method were selected for 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 3.8: Data Classification Method (o: yes, x: no)

From the distribution of energy data in Chapter 3, a severe right skew was observed 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 the low-energy demand end. For example, in the distribution shown in Figure 3.13a, over 84% of the data points are between 0 to 1000. If using equal interval with 8 classes, all 84% of the data will be classified into the first group. This means the difference in the majority of the energy demand between buildings are not effectively shown. 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 (Figure 4.14). This method makes sure every class has the same number of points in it which ensures a balanced color display in each frame of the dynamic energy map. Since the heating and cooling demand are seasonal for most building types, there are a great portion (50%) of hours in a year with zero heating or cooling demand. If calculated directly, the "Quantile" method will output several classes with their members all being zero, leading to the effect of representing the same value zero with different colors or symbols. Thus zero is eliminated in calculation of break points.

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.

3.3 Output Map Images

After the energy information was aggregated into the CityEngine model, map images are could be generated. The map images are extracted as snapshots from CityEngine with Python script by iterative setting the time step and extracting a 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 were extracted and named according to their time stamp ("imgxxxx.png" represents the energy demand for the xxxx-th hour)

3.4 Interface Specification

As is addressed in Section 3.2.4, an interface is needed to combine the map image sequence with data plot and to provide the ability to visualize and analyze more complicated spatial-temporal data. In this section the researcher provides some abstract specification of the functions of the interface are offered, in Chapter 4 a more detailed illustration of the design and application of the interface is given.

3.4.1 User Definition

First the researcher 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 about 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 a basic understanding of building energy performance attributes 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.

3.4.2 Function Specification

The major 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 functions of the dynamic energy map in the current study include:

1). Help 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.

2). Help 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.

3.4.3 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.

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.

Chapter 4

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 is presented. For the non-interactive animation, the advantages and disadvantages between different symbol or color representation on the effectiveness of conveying information was briefly discussed.

Next a detailed documentation of the dynamic energy map interface is presented. The layout and functions of each components of the interface is explained and the design of each component based on literature studies of dynamic map design is discussed. The use of dynamic energy map to identify energy recovery opportunities and to help design and size a district energy system is demonstrated.

4.1 Overview

Dorling and Openshaw pointed out that a 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 [59]. In order to better conduct a space-time visualization of the space-time energy demand information in the dynamic energy map,literature studies on space-time map visualization were used to design the dynamic energy map.

Brownrigg mentions 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) a sequence of snapshots displayed over time (animated map) 3) small-multiples of snapshots of changing states [60].

Based on the classification above, method 1) and 2) were applied to represent time for the dynamic energy map. The dynamic plot of temporal time series uses method 1) to anchor the quantitative information. The sequential map image display is using method 2). The researcher did not use 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 [60] 2) the subtle changes are easier to be noticed in the form of animation than with small-multiples [60]. Both drawbacks of small-multiple method will impair the ability to convey the rapid temporal changes of community energy behavior, hence is not suitable for the current project.

4.2 (Non-interactive) Map Animation

Map animation was introduced to cartography in 1930s [61]. 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 [59]. Animated maps are proven to be more powerful in conveying the spatial-temporal pattern than static maps [62].

The level of user control of playback behavior of animated maps is debatable. Providing the full freedom of adjusting the playback can enhance pattern understanding [63], but it might also reduce time animation to still images and impair its ability in conveying temporal changes [64]. In the current dynamic map project. The researcher observed that the non-interactive map animation is especially helpful in conveying the dynamic energy changing and the non-coincident peak arriving time of different buildings in the community. Resch et al. suggest that the interface for general public should "ensure that the amount of information shown to the users at any given time, and its complexity, are reduced" [55]. The non-interactive animated map could be one of the potential choices for an interface of a dynamic energy map with general public as the target user group.

For this project a continuous color encoding method was used in the creation of non-interactive animation of a univariate gas heating energy demand map. Similar to the National Heat Map, the Calgary Map and the EMIOFN project (Table 2.2) discussed in Section 2.3.2, a red to blue color ramp is used in the map display. Different from the cases above, the current project chose to represent high heat demand with blue and low heat demand with red as a result of a limited survey of potential users. Each color within this red-to-blue color scheme is represented as a real number between 0 and 1 with 0 representing pure red and 1 representing pure blue.

The first approach to calculate the corresponding color for each heating energy value is to calculate the normalized distance between the current value and the maximum value (Equation 4.1).

$$\frac{E(t) - E_{max}}{E_{max}} \tag{4.1}$$

$E(t)$ is the energy consumption for the current time spot t, E_{max} is the maximum energy consumption over the year. The problem for this approach is that the color changing is not visible enough as a result of a extremely right skewed energy data (with each data point representing the hourly energy consumption of a certain building in the community at a certain hour of a year) distribution (Figure 4.1).

By directly applying this normalized color scheme, the color distribution on a map will be very un-even, with most of the buildings colored with the red color for most of the time.

Kolter and Ferreira discovered that the annual total energy consumption of the 6500 buildings in Cambridge MA area follows a "log-normal" distribution [65]. By applying similar log scaling for the hourly heating energy data of the community, the researcher

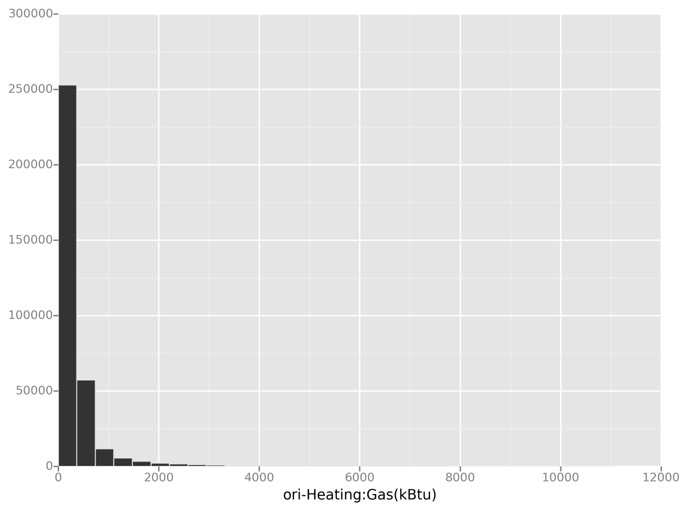


FIGURE 4.1: A histogram of hourly energy consumption per building, for the 68 buildings in the community

found that the hourly heating energy distribution also roughly follows a normal distribution (Figure 4.2). the researcher apply log scaling to flatten the distribution and calculate the color from energy $(E(t))$ as follows:

$$\frac{\ln(E(t)) - \ln(E_{max})}{\ln(E_{max})} \tag{4.2}$$

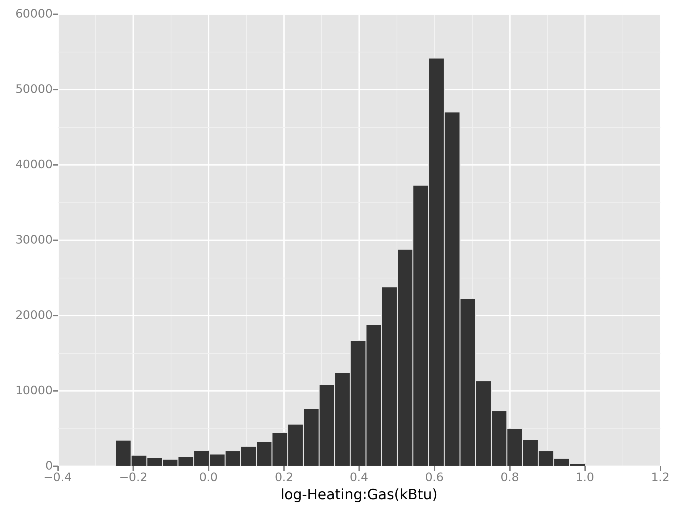


FIGURE 4.2: Heating Demand of Conceptual City

Figure 4.3 is one snapshot of the conceptual urban environment model under the log scaled calculation method in Equation 4.2.

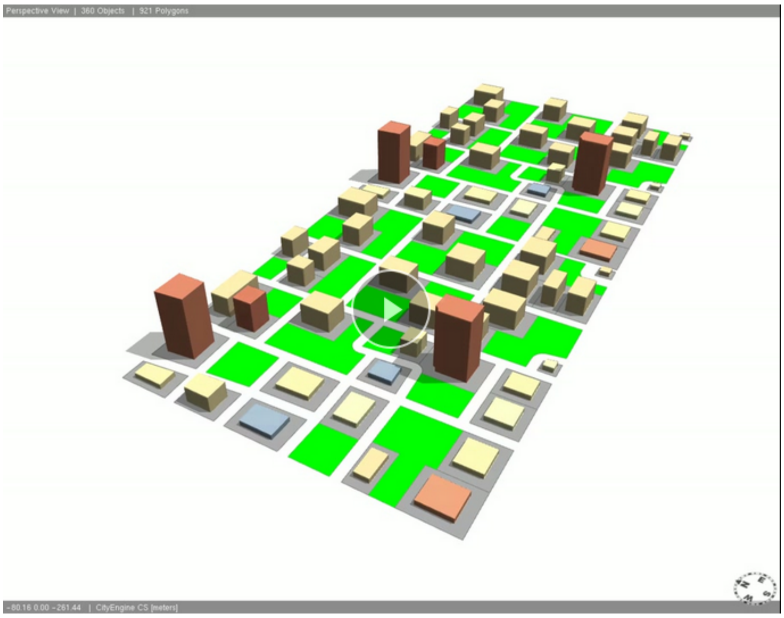


FIGURE 4.3: Animated demonstration of the log-scaled dynamic energy heating demand map
Click here to go to the animation link.

TABLE 4.1: Heating-Cooling Breakpoints in the Interface

heating		cooling	
kBtu	Ton	kBtu	Ton
5	60	2	24
22	264	7	84
50	600	15	180
91	1092	26	312
136	1632	56	672
213	2556	72	864

In the dynamic energy map interface design, the researcher applied a discrete color encoding with a seven-class bivariate choropleth representation (Table 4.1). The break points are calculated purely with the Quantile method in Section 3.2.4.2. 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: the animation with continuous color encoding depicts only one variable (gas heating) while the animation with discrete color encoding depicts two variables (space heating and cooling), the researcher 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.

4.3 Interactive Dynamic Map Interface

4.3.1 General Layout

The general layout of the dynamic map interface is displayed in Figure 4.4. It contains the following major sections :

(A) A snapshot of the dynamic energy map interface

(B) Dynamic Map Interface Layout

FIGURE 4.4: Dynamic Map Interface Layout

- A main map display on the upper left that shows the 2D or 3D version 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 defines the two-letter 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.

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

4.3.2 Main Display Window

As is mentioned in [60], the choice of 2D representation vs. 3D representation is one of the debated decisions in the world of cartographic data visualization [60]. 2D maps are 1) easier to navigate and 2) the operation of selecting an element or a region is easier to perform in a 2D map. Another important advantage of 2D map is that it has better theory support [55]: Jacques Bertin defined the seven visual variables in the graphic sign-system and their construction rules to effectively convey geographic information [66]. However the principles and variables of 3D or 4D maps (space-time map) are not thoroughly investigated [55]. 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" [55]. Regarding this, a 3D map is rich in geometry representation and can provide realistic scenes. The realistic scene is important in conveying information to not only researchers but also the general public. The difference in surrounding building height and their exterior reflection properties could influence the exterior shading of a building, so the height and density distribution of a community could influence its total energy demand. The correlation of 3D community configurations with difference in building height, density and exterior surface properties on the total community level energy performance could also be identified with a 3D display. The current project does not use the whole-community energy simulation and this capability of the 3D display is not demonstrated. Integration with whole-community simulation thus could be one of the later development of the current project. However, the 3D display 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 [67]. For an energy map, variables such as geothermal energy potential, biomass potential could be represented as 2D layers while solar energy potential might be more suitable to be visualized in 3D layers since its performance is influenced by exterior shading in an urban environment.

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, the 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 4.5).

4.3.3 Bivariate Map Legend

4.3.3.1 Symbol Chosen

The major reason 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 extruding

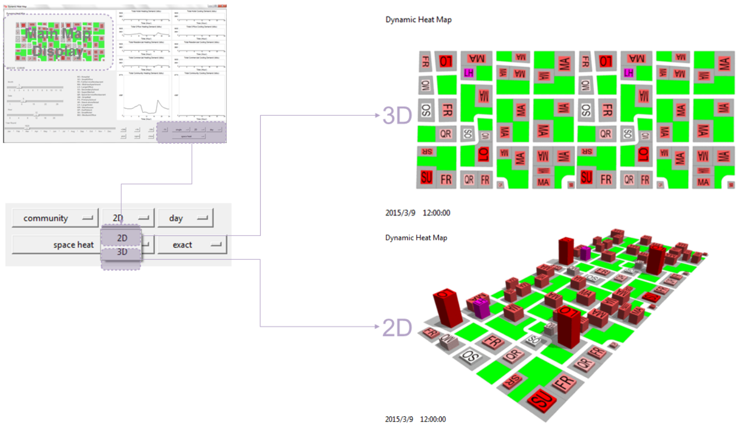


FIGURE 4.5: The current interface provides the choices of viewing 2D and 3D map display by toggling the 2D/3D option menu

the building or region by a corresponding height encoding its energy demand or supply [12]. This approach provides an easy way of aggregating energy demand and supply by adding up geometry height. For this project this approach was not chosen for the map design because it creates shape distortion and will impair the 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 case is encountered in the current project: bivariate map design that visualizes the correlation of two variables on a same map. Elmer points out the challenge of the bivariate map design as a result of its increased information density. He presented eight possible types of representation for bivariate maps (Figure 4.6): "shaded cartographer, rectangle map, bar chart, value by alpha, choropleth with graduated symbol, bivariate choropleth, spoke glyph and shaded texture" [68]. In order to incorporate the bivariate map symbols to the current 3D model without introducing too much shape distortion, the researcher did not choose the representation with dimensional changes, i.e. the changing of building height, width, depth or the size changing of building centroid are not chosen in the map design of the current project. The choices are the ones that involves color or texture, i.e. "bivariate choropleth, value by alpha and shaded texture" (Figure 4.6). Among these three choices, bivariate choropleth representation has the highest accuracy rate [68], hence the researcher chose 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

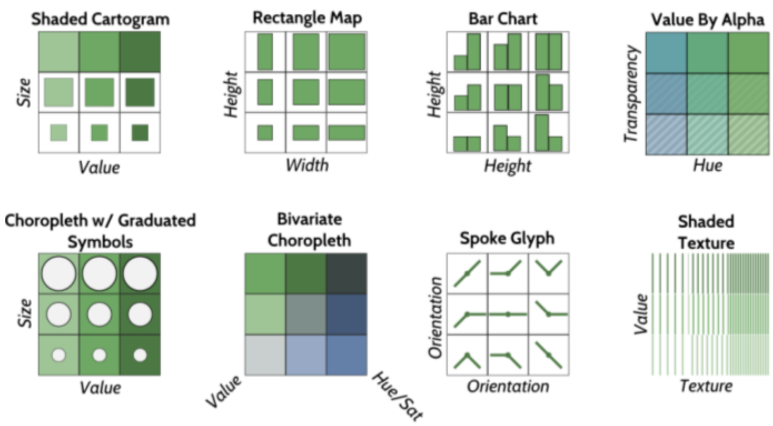


FIGURE 4.6: The eight bivariate map display approaches tested in Elmer's [68] study

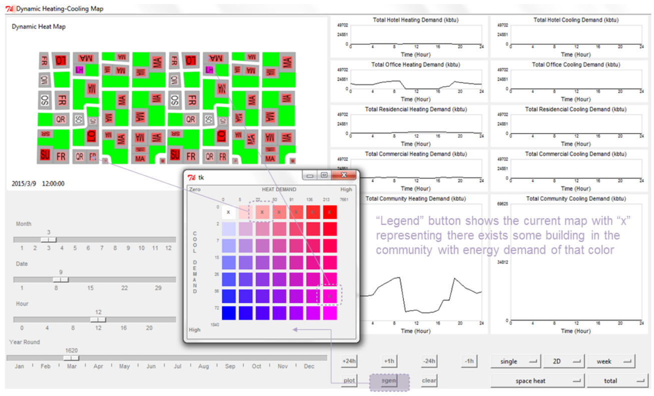


FIGURE 4.7: The seven-class-bivariate choropleth legend is used in the dynamic energy map interface design with red representing high space heating demand, blue representing high space cooling demand. "x" in the legend corresponds to colors appear in the current map display window

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 4.7. How to use the legend to identify the buildings or building groups that have large energy recovery potential is demonstrated in Section 4.4.1.

4.3.4 Time Sliders and Navigation Buttons

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

Harrower and Fabrikant classify time into two types: linear and cyclic [61]. The former represents the periodical changes and the latter represents the linear changes of spatial temporal variables. To address this, the design of the current interface includes 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 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 the "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 form 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 viewers pull the "date" slider, they can compare the different energy demand of this hour (12:00:00) throughout the whole month. With the 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.

4.3.5 Data Plot

4.3.5.1 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 plots are directly shown on the right of the interface. They depict the energy demand of the four major building types (Hotel, Office, Residential and Commercial buildings) and the community.

Space heating and cooling energy demand is displayed in Figure 4.4. 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 4.8). 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 4.9).

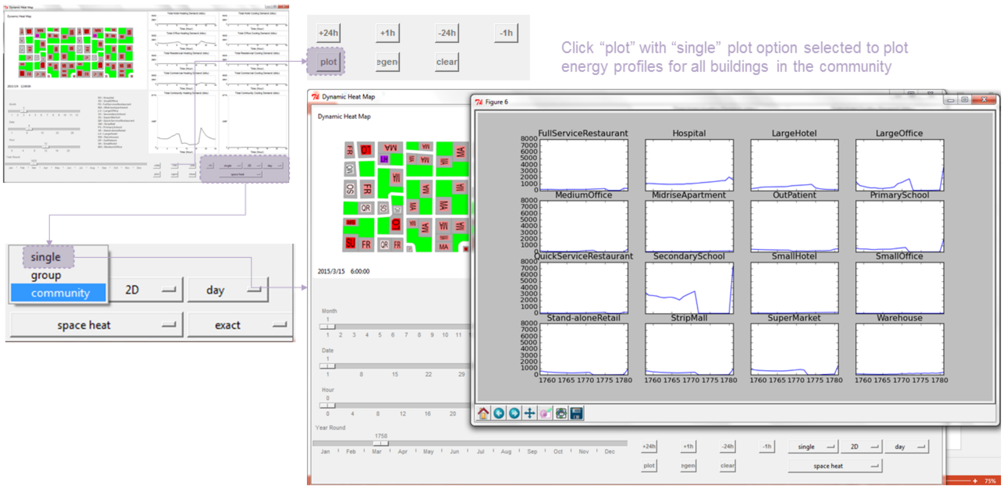


FIGURE 4.8: The plot shows the space heating energy demand plot of each of the 16 benchmark buildings

3) **By clicking on the building footprint in the 2D map display.**

A building is "selected" if the user clicks on its foot print. Each new click of a building footprint 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 footprint, a data plot will be created for the building the viewer just clicked on (Figure 4.10). If "group" is chosen in the option menu, each click of a building's footprint will create a data plot for the current selection set (Figure 4.11). This function is important in assessing the building group level energy recovery potential. Users can assess the energy recovery potential of the building or building group that rejects heat. They can also assess the space heating demand of the group of surrounding buildings of the reject heat

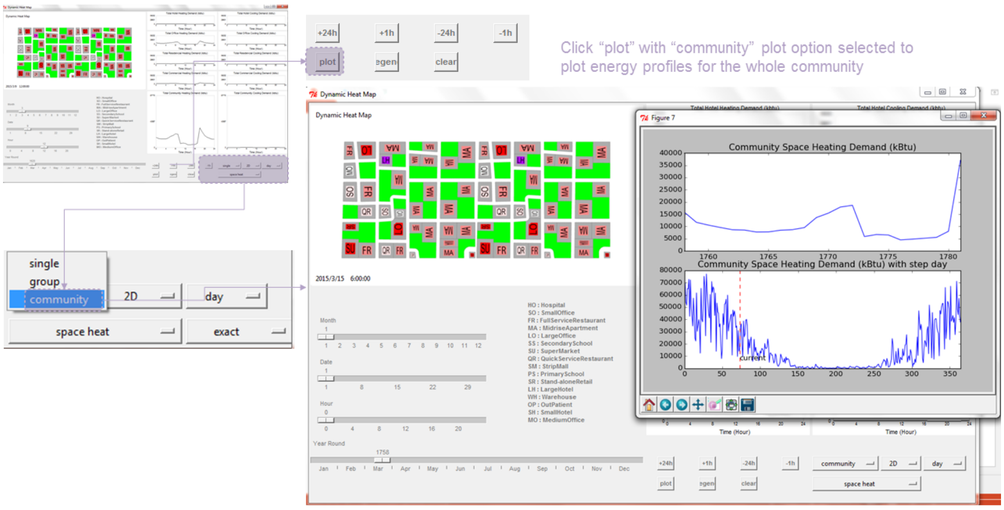


FIGURE 4.9: The plot shows the aggregated space heating energy demand for the whole community

producers. By comparing these two graphs the users can assess the effectiveness of energy recovery strategy in reducing the space heating demand of the group of buildings. A demonstration of presented in Section 4.4.1

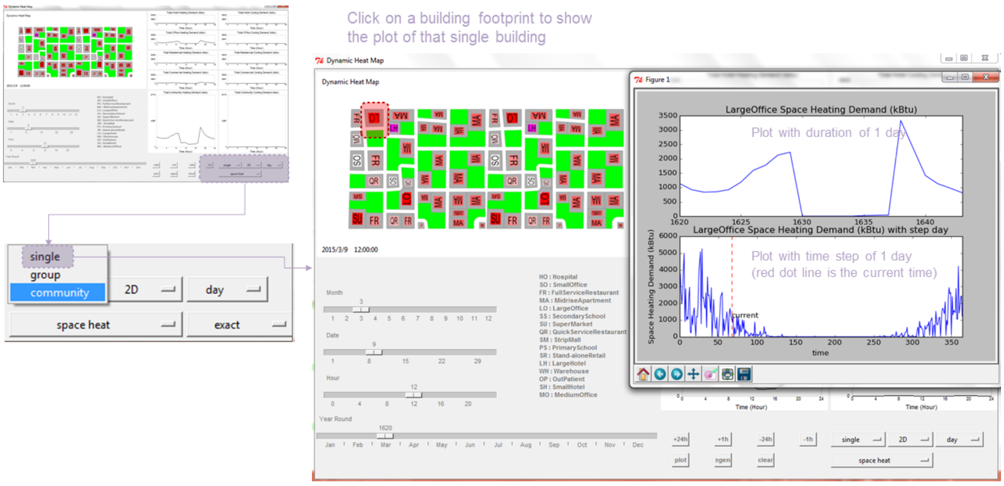


FIGURE 4.10: Click on a building foot print shows the energy plot of this building

4.3.5.2 Providing Temporal Context in Data Plot

Brownrigg suggested that it is necessary to provide a 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.” [60].

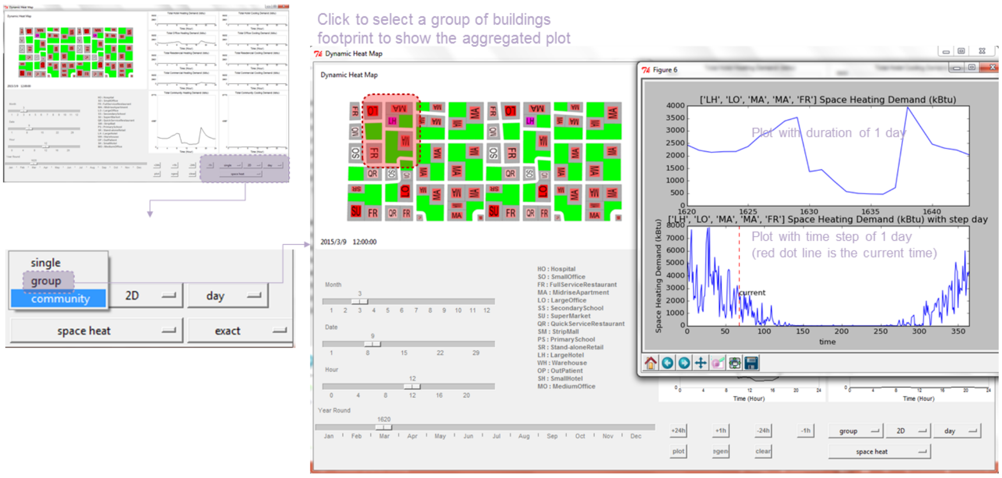


FIGURE 4.11: Click on a building footprint shows the energy plot for the selected building group

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 4.13, 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, the viewers are provided with a general understanding of whether the changing of energy demand behavior is drastic or subtle and whether

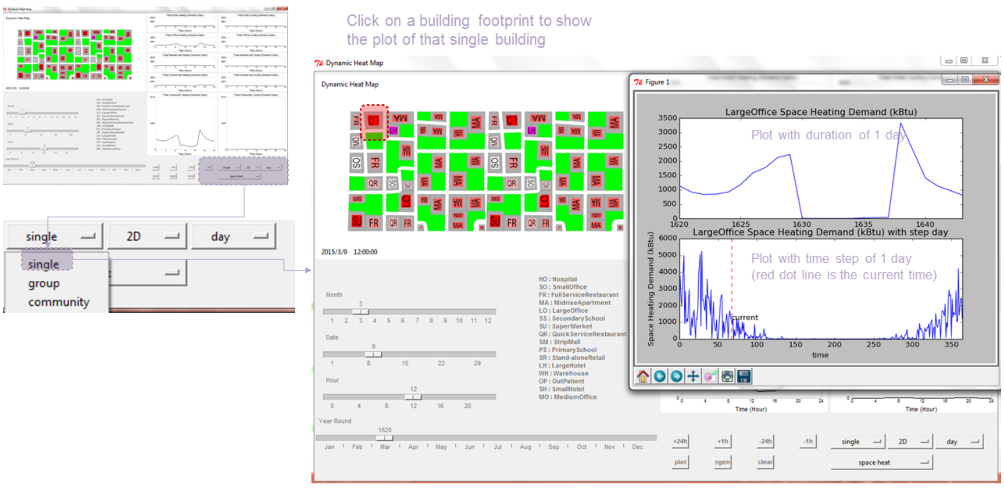


FIGURE 4.12: The data plot presents the longitude and latitude comparison of energy demand, the top plot presents a temporal context of the energy demand of the next 24h, the bottom plot presents the time context of the demand of the same hour throughout the 365 days of the year

FIGURE 4.13: 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

a drastic change is coming and whether the current demand is high, low or moderate comparing to the overall distribution over time and space.

4.4 Use Case Demonstrations

4.4.1 Use Case I: Identification of Energy Recovery Opportunity

In this section, the researcher 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 3.2.1.1, the ammount of cooling-induced reject heat is positively corelated to the cooling demand. Thus a building with high cooling demand will also have a large amount of reject heat. The reject heat from this building or group of buildings could possibly be recovered for use within the building such as pre-heating water or outside air or be transmitted to other buildings that have 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 researcher 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 4.14) . Red represents high heating demand and blue represents high cooling demand. The closer the color cell is to the top, the lower cooling demand. The closer the color cell is to the left, the lower heating demand. The cells on the diagonal line (purple colored cells) represent buildings that have relatively similar 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” [56] for demonstration.

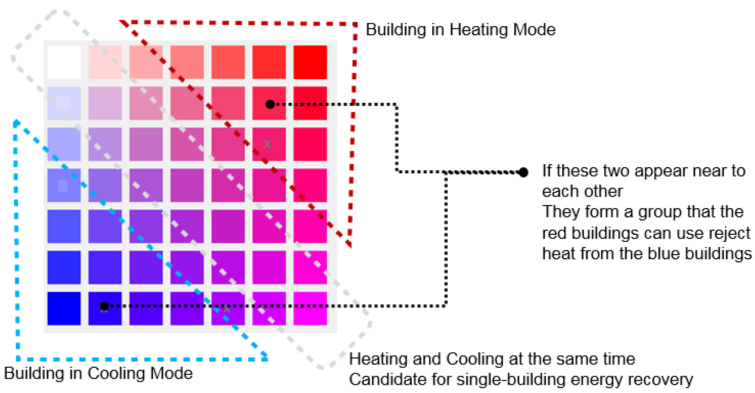


FIGURE 4.14: The bivariate color ramp displays two variables at the same time: space heating and space cooling. It better displays the co-relation between these two variables and thus helps users to identify energy recovery opportunities

With the dynamic energy map, the 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, users can identify the potential reject heat suppliers and consumers over time (Figure 4.15).

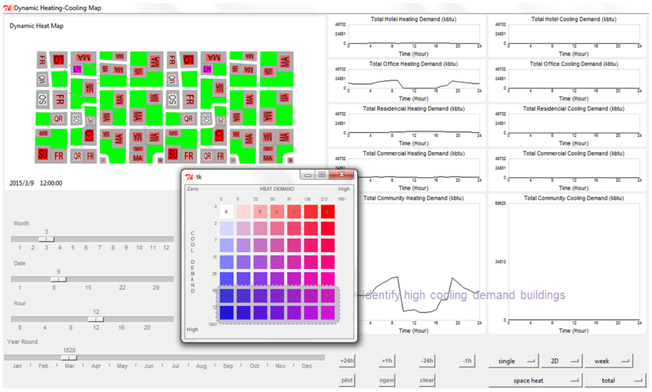


Figure 4.15: In the demonstration, buildings with a high cooling demand have colors on the bottom rows of the legend, thus Large Hotel and Large Office are identified as potential reject heat energy suppliers

Users can then calculate the "energy recovery potential" in the dynamic energy map with a specified time duration and step. In the example of Figure 4.16, users identify the Large Office and the Large Hotel as reject heat suppliers and calculated their aggregated energy recovery potential for the 16th week of the year in the graph on the left. Then they calculated the space heating energy demand of the group of surrounding buildings of reject heat suppliers: two First Service Restaurants, two Midrise Apartment and one Small Hotel.

By comparing the two graphs, users can see that the peak of the energy recovery potential is about four times of the peak of the space heating demand of the group of surrounding buildings. They can also observe that there are two peaks for space heating demand of the surrounding building group but only one peak for the energy recovery potential. There are some difference in the weekly pattern of the reject heat supply and the space heating demand: the last two days of the week has very little reject heat but the space heating demand is relatively high. We can also see that the peak of reject heat does not occur at the same time with the space heating demand peak: in the 2800th hour, reject heat (in the graph on the left) reaches its peak while space heating demand on the right is zero. With the dynamic energy map, users can identify complicated non-coincidence in the supply and demand of reject heat. This information could help users design more detailed heat recovery strategies and assess the capacity of thermal energy storage devices.

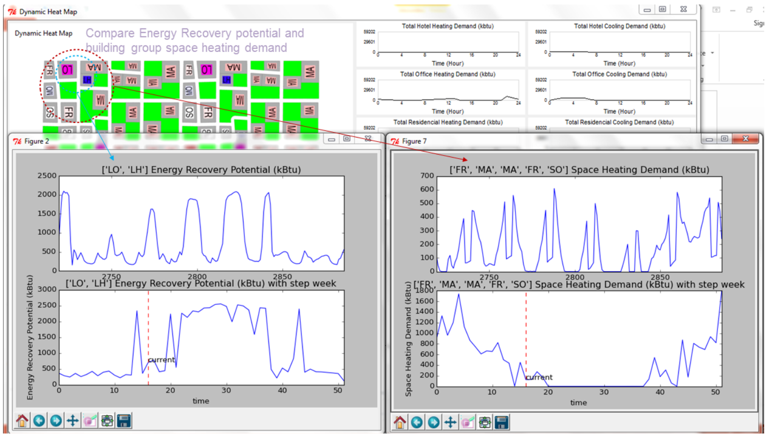


FIGURE 4.16: The users can calculate the energy recovery potential of the group of reject heat suppliers (Large Office and Large Hotel). They can also calculate the total heat demand of the surrounding buildings with space heating demand (two FirstService Resturant, two Midrise Apartment and one Small Office).

4.4.2 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

- Identify anchor load buildings

  To achieve this function, the map should be able to make the building with persistant high heating or cooling demand stand out. Thus the color scheme 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 the quantile classification method.

  Although with the box plot of heating demand (Figure 3.10a), the buildings with high consistently high heating demand through its high median and 25 percentile, 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) the Large Office, the Large Hotel and the Midrise

Apartment forms a high heat demand region, these could be potential locations for making a connection to a district system.

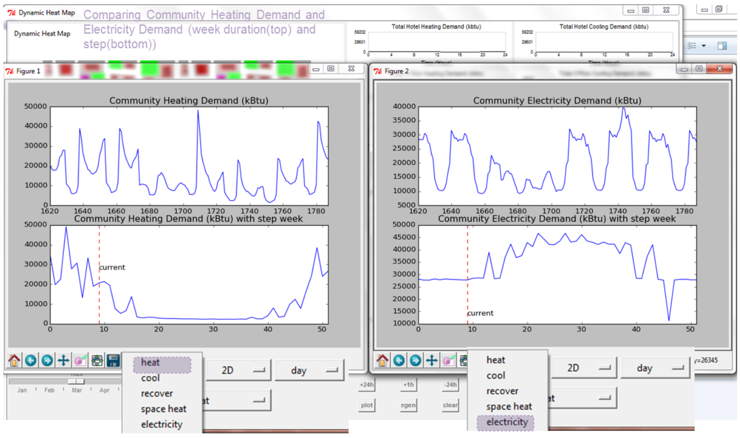


FIGURE 4.17: In this example, the users compare the week-wise heating and electricity demand

- Size a CHP plant

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 4.19. The dynamic plot on the right of the interface depicts the heating and electricity demand of the four building sectors and the community .

The user can also inspect heating energy and power demand of he community with different time span and different aggregation method. For example, they can compare the heating and power demand for a week and see if the demand align. In Figure 4.19, users can see the peak heating demand for the ninth week is about the same level as the peak demand for the electricity. However, their weekly behavior is different: the heating demand for the second half of the week are relatively low but the electricity demand is relatively high. The lower graph also shows that the annual peak demand of electricity occurs during the time when the community has the lowest heating demand. This poses the challenge for the district energy system with Co-generation local plant and the necessity for thermal energy storage devices in a district energy system.

- Local load balancing

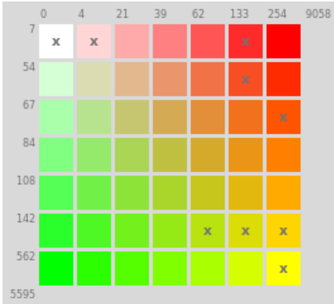


FIGURE 4.18: Legend for Heat and Power Map

FIGURE 4.19: In this example, the users compare the week-wise heating and electricity demand

Apart from the information for the minimum and maximum value of the heating and electricity demand of the community, more specific heating and electricity demand of single buildings and building groups are also available. This could be used to design micro-scale CHP equipment or to locate thermal energy storage devices and to size their storage capacity. For the micro-scale CHP equipment design, a load balancing in the level of a building group could make the micro-scale CHP equipment operate in its high efficiency output for a longer period.

To achieve this, the program enable users to select a subset of the existing buildings and creates the aggregated heating load plot for 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 sequentially but not simultaneously. Then they can check the building demand profile by clicking on the building footprint in the 2D map (Figure 4.20).

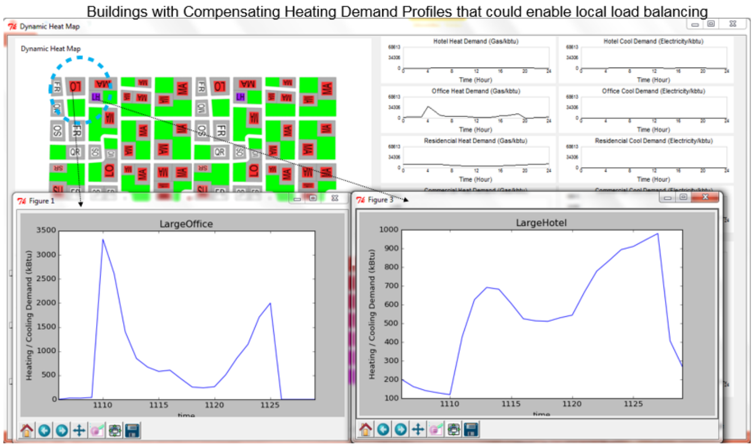


FIGURE 4.20: Users can check the building energy demand (thermal or electricity) by clicking on the building foot print in the 2D map and the interface will show the plot of the energy demand profile within a period (the example is showing the demand for a 24h hour period)

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 prototype buildings and see if there are some building types that have demand complimentary (so they have a rough idea of what is a "good building combination" (Figure 4.21) at this time that could be a candidate for load balancing) and they will look at the map and search for this "good combination".

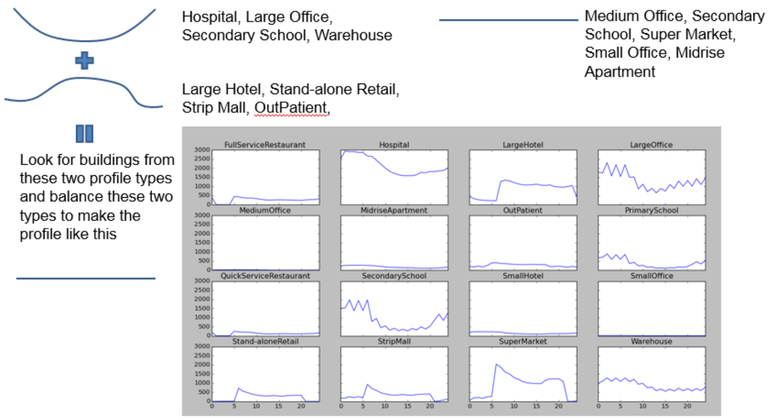


FIGURE 4.21: Users can plot all building energy demand profile (heating gas demand for the example) and search for "good cobimations" that have compensate load profile

After the qualitative experimentation, users can select a group of building by clicking on the building footprint and the program will output a graph of aggregated load

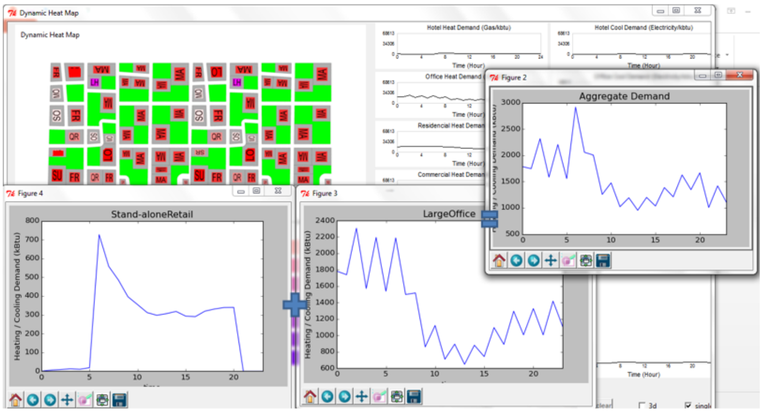


FIGURE 4.22: In this example, users selected the Stand-alone Retail and the Large Office and plots of each single building and the aggregated demand of the two buildings are displayed

Chapter 5

Findings and Discussion

5.1 Summary of contribution

The document presents an approach of implementing a dynamic energy map with a focus on visualization of high spatial-temporal energy demand data of single buildings, building groups and the whole community.

The project is developed based on the Lower Hill District Project [10] and improved it by aggregating energy demand profile to each building with higher temporal resolution, and by creating a dynamic energy map interface that combines the visualization of high resolution spatial temporal energy data in the form of a series of time-indexed choropleth map images with color-coded energy consumption. It also provides energy data aggregation method over space and time.

In order to visualize the energy demand data to better convey the dynamic energy demand changing, a detailed analysis of the input demand data profile of each building type and the aggregated community was conducted in Section 3.2.2. From this analysis, the researcher observed a great variation in the demand profile distribution between different building types and a strong skew of the energy demand profile of the whole community. Log scaling and data classification with the quantile method were adopted to cope with this skewed data distribution in the design of the conversion from energy demand to their color encoding.

An interface is designed to visualize the 2D/3D map images that encodes energy demand information with a bivariate choropleth legend. A series of data plot functions accompany the map image display to provide quantitative information. The data plot provides different level of temporal and spatial aggregation that suits more generic purpose of data analysis and visualization so that it suits the need of the target user group: researchers in energy related fields who have different research interests and focuses.

Through the dynamic energy map, many detailed spatial temporal energy demand pattern can be revealed:

- The daily peak energy demand arrival time is different for different building types: in the example in Figure 5.1, the Large Office has the highest peak heat demand, it occurs during the day time. The peak demand of the Primary School, the Medium Office and the Stand-alone Retail have high heat demand during the day time and have zero demand in the early morning and late evening. The Full Service Restaurant and OutPatient Healthcare have stable high heat demand throughout the day.

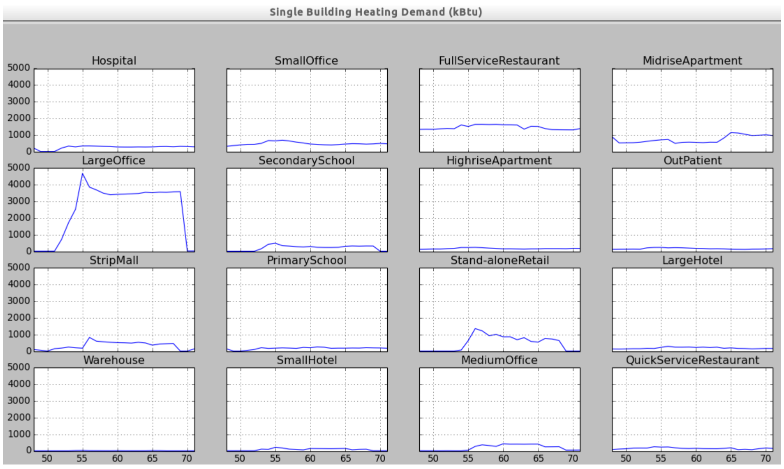


FIGURE 5.1: Space heating demand on 1/1/2015 of the 16 prototype buildings

- The weekly demand pattern is different between different building types. In the example of Figure 5.2, the Large Office, the Primary School, the Stand-alone Retail have strong weekday-weekend difference, while the rest of the building types have stable demand throughout the week.

- In the use case study of identification of energy recovery opportunities, users could see the quantity of reject heat production and space heating demand of the group

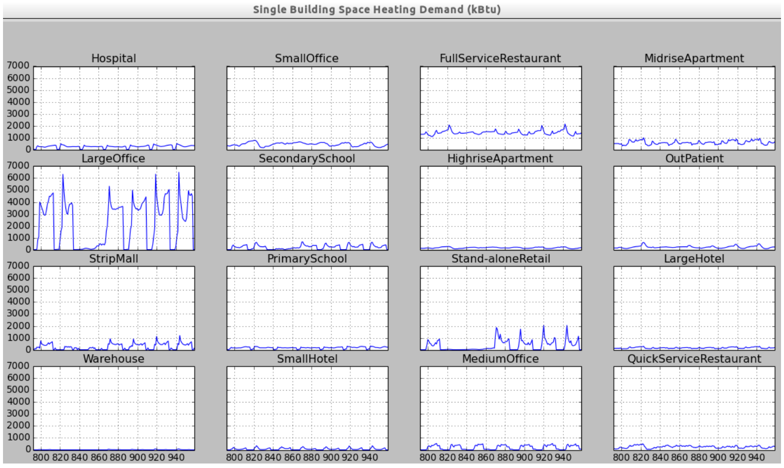


FIGURE 5.2: Space heating demand from 2/3/2015 to 2/10/2015 of the 16 prototype buildings

of buildings. They can observe the weekly pattern of the reject heat supply and the space heating demand are not co-incident: reject heat production in weekends is low while space heating demand in weekends is high (Section 4.4.1).

- In the use case study of CHP sizing, users can observe that the heating and electricity demand for the community have very different weekly demand behavior: electricity demand has strong weekday-weekend pattern with weekday having high demand and weekend having low demand, while heating demand does not have as strong a weekday-weekend pattern. (Section 4.4.2).

5.2 Limitations and Further Development

The current project presented an initial implementation of a dynamic energy map with the focus on spatial-temporal energy profile visualization. Due to limited time and resources, there are many improvement to be realized in the next stage development:

- Input data

  Urban level simulation software is not used in the energy profile generation. This leads to simplified assumptions of the influence of micro-climate in an urban environment on energy demand of buildings and the whole community. The building height and urban density could influence the exterior shading and could influence buildings' heating cooling and electricity demand: Ratti et al. analyzed the urban texture including surface-to-volume ratio (the total surface area over the total building volume), the ratio of passive zone ("quantify the potential of each part of a building to use daylight, sunlight and natural ventilation" [69]) to non-passive zone, and self-shading on the urban level energy demand with DEM models and LT simulation method in London, Toulouse and Berlin [69]. They discovered that the high ratio of passive zone has a strong positive effect on urban level energy demand reduction. Steemers discovered that in an 400×400 region of London, doubling urban density results in a 25% increase with the plot ratio ranging from 1.25:1 to 5:1 [70]. The energy impact of urban environment configurations including urban density and the spatial distribution of building height could potentially be conveyed with the dynamic energy map with 3D map sequences. However as a result of the stand-alone assumption in commercial prototype building models, this layer of information is not demonstrated in the dynamic energy map in the current project.

The current project focuses mainly on the energy demand information of heating cooling and electricity. The only energy supply parameter included is the cooling-induced reject heat. One of the major goal of energy mapping is to present detailed information of energy supply and energy demand and suggest possible connections that better matches the demand and supply. In order to fully realize the function of an energy map, adding high space-time resolution supply side information is crutial. In the further development of the project, supply side information, especially renewable energy supply assessment should be added to the dynamic energy map and the "opportunity region" where supply well meets the demand will also be calculated and depicted on the map. Different from the static map, the temporal changing of the size and location of the focus area will also be depicted on the next version of the dynamic energy map. The newly added layers of various energy supply and opportunity region could pose new challenges of map design and data visualization as a result of the potential overflow of information. Further investment of proper spatial-temporal data visualization method could also become another topic of the next stage development of the project.

The matching of energy demand and supply include not only matching in energy quantity but also energy quality in terms of exergy [12]. The current map interface does not contain exergy information. Further development could add exergy information in order to facilitate the design of energy cascading and the design of a "net-zero exergy district" [71].

- Visualization

  In the data classification step, the break point is acquired with quantile classification method as is discussed in Section 3.2.4.2. Further analysis of building science context based break point selection, such as critical value for mechanical equipment sizing or minimum recoverable heat considering transmission loss etc., should be taken into consideration in the next stage development of the project.

- Data Sharing

  As is envisioned in the study of Baird et al. , an on-line platform is needed to facilitate data access, model sharing and advanced analysis of a dynamic energy map [10]. The current implementation of the dynamic energy map is a stand-alone tool. Bringing the current stand-alone map to an online platform could be one of the topics of the next stage development.

- Technical issue

  As a result of the dependence on an existing modeling software, CityEngine, for image generation, user could not create community design and compare design alternatives on the current interface; user control over data classification and legend selection are not realized either. To solve this problem, a 3D model importing and rendering function should be added to the current map to facilitate the performance-based geo-design method in the community energy planning.

- Analytical ability

  The primary focus of the project at the current stage is on energy demand data visualization, thus the decision support routines including district system specification, the financial assessment and additional land use constraints are not added to the current interface. Equipping the current dynamic energy map with the analysis abilities above could be one of the topics of the next stage development.

  In the use case of identification of the energy recovery opportunity, the calculation of energy recovery potential has a simplified assumption that all reject heat could be recovered. In the further development of the project, the research would add more detailed analysis of reject heat taken detailed system configuration into account.

Another analytical ability is to calculate the "opportunity region" where there is a high potential of the better matching of the supply and the demand. Since the demand and supply changes over time, the "opportunity region" will also change over both space and time. For a dynamic energy map, the change of the location and service area of the "opportunity region" could also be depicted. This information could help planners create time-of-use strategies that adapts to the spatial-temporal changing of region with better matching of supply and demand.

Another crucial feature to be developed in the next stage is the generic analytical functions of space-time data. Although visualization of space-time energy profile on the community map facilitates the recognition of the general pattern of energy demand and supply, more accurate description and validation of the pattern discovered from the process of visualization needs to be tested against more rigorous mathematical analysis of space-time data. For example, the buildings with large demand variations can pose challenges to the district system design because they'll require the capacity of the district system to be large enough to meet their peak demand, causing the district local plant to run on its non-optimal output for a longer period. If these types of buildings are paired with buildings with complimentary energy demand (Figure 4.21), the total demand variation of the group of buildings would be reduced. However to define what is "complimentary" demand is not easy, especially when all buildings have different energy demand profile. A brute force approach that tries out all possible combinations of building demand profiles and check if they reduce the aggregated demand is not feasible because the time spent to solve the problem grow exponentially with the number of distinct building profiles. For the current dynamic map model, with 68 buildings and 9 different building energy demand profiles involved, the total number of trials could be about $2^9 = 512$. For the current community model, if all buildings have their own demand profile, the total number of trials will be 2^{68}, about 3×10^{20}. Obviously this method will not feasible for large communities. In this case, k-mean clustering method [72] can be used to classify the building energy demand profiles into groups with similar demand behavior and reduce the distinct building profile type to a manageable amount. Adding such advanced data analysis functions could provide more informative land use design suggestions to improve the overall community energy performance.

Chapter 6

Conclusion

6.1 Future Opportunities

Along the path of community energy planning and the increasing development of energy mapping approaches that assist community level sustainable design, the current project demonstrated some possible approaches to add the time dimension and reflect the time-of-use energy demand behavior in a community energy map.

Due to increased data complexity, the visualization of a dynamic energy map poses more challenges [59]. Creating an effective visualization to convey the complicated energy demand changing of buildings and the whole community becomes one of the problems the project aims to solve.

The researcher has experimented with the continuous and discrete method of converting energy data to its color encoding and identified the evaluation of the two methods to be one of the next stage development in the visualization section of the current dynamic energy map. In the map display design, considering the demonstration purpose, the color encoding and the data classification ensures the buildings with high energy demand stand out with vibrant color and that the color distribution on each frame of the dynamic energy map is relatively even.

Visualization can assist understanding of the general pattern of the space-time energy data, but mathematical description and identification of patterns is still necessary to provide quantitative insight and to validate the pattern recognized in the process of visualization. The lack of data analysis functions pushes the pattern recognition task entirely to the visualization, which itself lack established standards as is addressed in the study of Resch et al. [55]. Thus the researcher also identifies the necessity to equip the current dynamic energy map with more advanced space-time data analysis functions to be one of the focus of next stage development.

By providing additional plotting tools that present exact and aggregated demand profile over space and time, the project asserts that the dynamic energy map could reveal the thermal energy and electricity demand changing behavior over time:

- the non-coincident peak arrival time of a certain energy end use between different building types,
- the different daily, weekly and monthly demand profile or their aggregated forms such as average, peak and total demand between different building types,
- the non-coincident demand peak of different building energy end uses including heating, cooling and electricity on the level of a single building, a building group or the community.

These detailed information are not shown in the static energy maps because the demand side variables depicted in a static energy map are either annual / monthly total or annual / monthly total density as is summarized in Section 2.3.1.

One of the design support function of static maps is to highlight the "opportunity regions" which have a high opportunity of better match of the energy demand and supply. As a result of the temporal changes of both energy demand and supply, the location and service area of the opportunity regions also change over time. This aspect of changing cannot be revealed in a static energy map because the time information is not included. In the next stage, the current dynamic energy map will add the time-dependent demand information and the opportunity region calculation functions. With these functions, planners can visualize the dynamic changes of the opportunity regions over space and time. With this information, planners can consider more time-specific energy system design and management strategies.

Comparing with the statistical analysis conducted in Section 3.2.2, the dynamic energy map not only reveals the frequency count of energy demand data, but also their timing.

6.2 Insight of Dynamic Energy Map

The current project realized the following functions of a dynamic energy map:

- holding energy demand and supply data with high spatial-temporal resolution,
- visualizing energy demand data with high spatial-temporal resolution with a general display of map image series,
- providing basic data analysis tools,

Apart from these functions, the dynamic energy map should ideally be connected to an urban-scale energy simulation tool to generate more holistic and realistic energy demand input data. In addition to the quantity of energy demand and supply, it should also record the energy quality information to facilitate the design of energy cascading and net-zero exergy districts. With the development of the 3D and space-time map design theory, the visualization design should be more efficient in conveying energy demand and supply information. Advanced space-time data analytical capabilities could assist more complicated pattern recognition and decision support for more detailed community level energy supply system design.

Appendix A

Implementing Dynamic Energy Map in CityEngine

A.1 General Introduction

The following document records the method of using CityEngine to visualize the dynamic energy (heating energy in kwh for this document) changes with a slider bar embeded in the CityEngine software. To be more specific, users will be able to navigate through the 8760 hour of a year with a time slider and see the color-coded energy consumption data for all buildings in the community model for the hour the slider cursor is at. The detailed rule file is included in Appendix B.

The general process is as follows.

Step 1 Create an urban environment layout by finding a base map if it is a real site or by generating a random urban environment layout if it is a conceptual setting.

Step 2 Add attributes of “landuse” and “time” to the building lot.

Step 3 Write a rule file with energy consumption data (or the color representation of each energy consumption data) for each building type held in the form of string lists in the rule file and then apply the rule files to the building lot.

Step 4 Finally set the attribute of “landuse” and “time” in the rule file to be driven by the value of the building lot object attribute “landuse” and “time”.

The "time" attribute is used to index into the string list of energy profile (in rule files) for each building type. For example, when the "time" attribute of all building lots are set to 10, all buildings in the community model will change its color to the color representing its heating energy consumption in the 10th hour (zero-indexing) of the year.

Each step will be explained in more details in the following session.

A.2 Explaining Each Steps

1) Create a Urban Environment Layout

   If one is working with a real project, an OSM Map [73] will be a good choice for a base map. The OSM file contains many useful attribute such as street center line, building name, elevation etc. It is of XML format and is easy to manipulate as text files, which makes it easier to work with and less bulky comparing to ArcGIS gdb files. Figure A.1 is an example of the CMU Campus OSM Map.

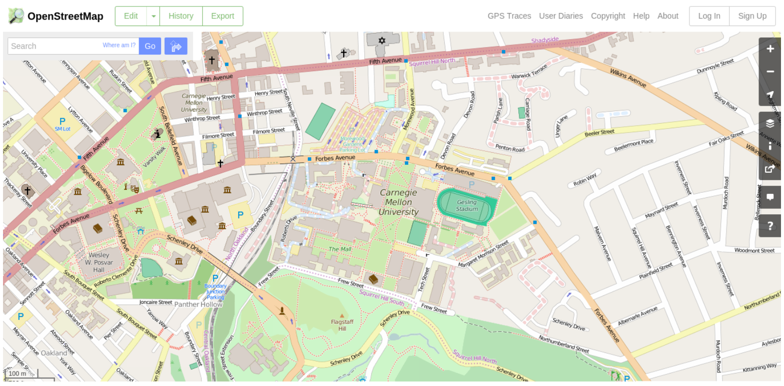


FIGURE A.1: CMU OSM Map [73]

   If it is a conceptual setting, then one could create an urban environment setting by generating a random city of proper size using "grow street" function with some clean-ups (Figure A.2).

2) Add Attributes to Building Lots

   To implement the function of a time slider-bar that navigates and shows energy consumption for each building in each hour of the year, two additional attributes are needed: 1) "time" attribute of type float (ideally the researcher would like it to be integer but there is no integer types in object attribute) ranges from 0 to 8760 (not

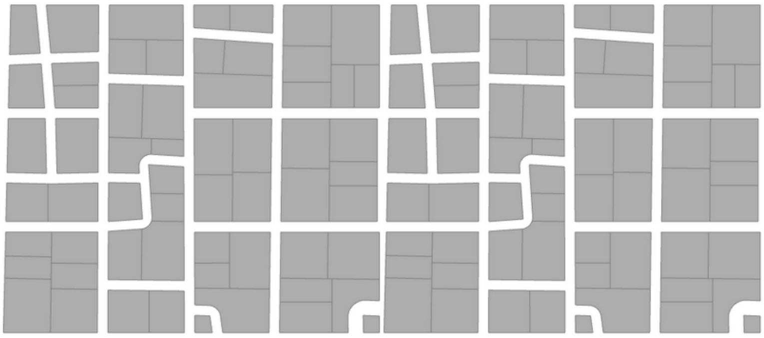


FIGURE A.2: Conceptual City Generated with CityEngine

inclusive) that represents the hour of a year and 2) "landuse" attribute of type float (since no integer type is available) that represents the land use type of the lot.

Adding these two attribute could be done either inside an OSM base map or inside CityEngine.

The typical way to add a building attribute can be done by selecting all building lots and right click one of the Object attributes and select "Add Object Attribute" to add new attributes.

If an OSM base map is available with building footprint information, adding attributes can be achieved within OSM maps by one searching for `"<tag k="building" v="yes"/>"` and add two new tags after this line:

`"<tag k="time" v="0">"`

`"<tag k="landuse" v="0">"`

3) Importing Geo-referenced Image (Optional)

If one is working on a real project, one can add an geo-referenced terrain image to make the model more realistic. In the following example, the terrain geo-tiff was retieved from PASDA website [74] according to the "Allegheny County Imagery 2013 - Tile Index". The image showing the area of interest is clipped in ArcMap and imported as a geo-referenced image (.tif) to CityEngine (Figure A.3).

After importing geo-referenced image, OSM map could be imported and a working base was formed (Figure A.4).

4) Writing Rule File for Building Generation

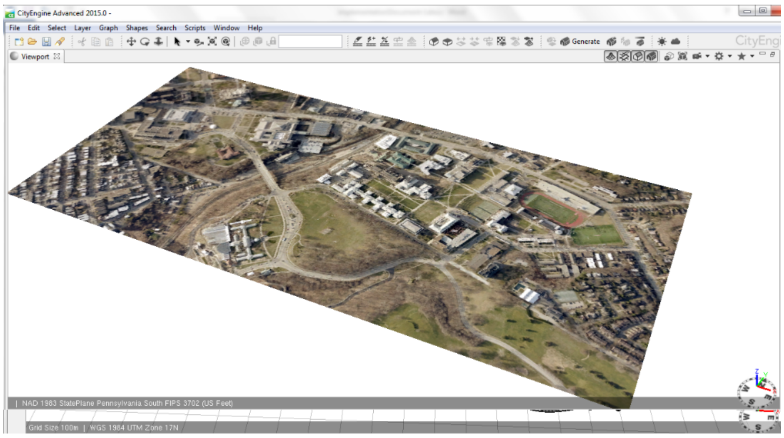


Figure A.3: Example of Geo-referenced Image in CityEngine

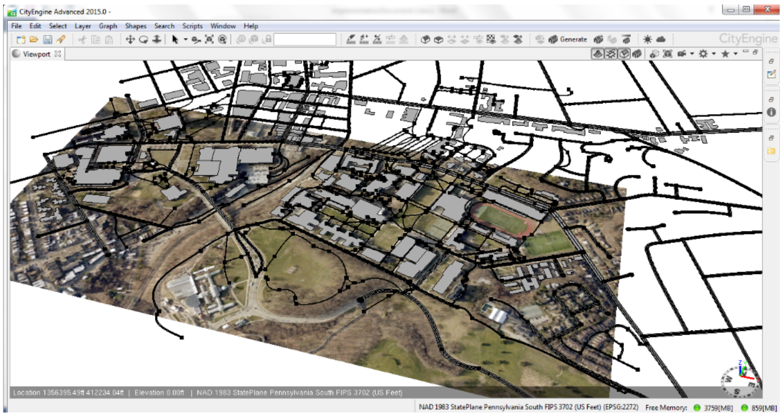


Figure A.4: Geo-tif with OSM Map

The researcher used “time” as the index into the string array that holds the hourly heating energy consumption data. By setting the rule attribute “time” to some t, one will be able to retrieve the energy consumption information at hour “t” from the energy string list.

When implementing the dynamic energy map inside CityEngine, one should decide a proper color scheme for encoding the energy consumption data. No building-science specific breakpoints were specified at the current stage of the project. The researcher used the continues red-to-blue color ramp in the stand-alone CityEngine based dynamic energy map implementation.

5) Deciding Data Encoding

The detailed discreption of the method is in Section 4.2.

6) Associating Rule Attribute with Object Attribute

How to globally set all "time" attribute for each rule file is a key problem to solve to implement the time-navigation inside CityEngine. Writing a python code for processing all the rule files as pure text files and apply rule files to its corresponding lot at each given "time" could be one solution, but there are two drawbacks 1) it is time and space consuming because as many as 8760 rule files needs to be generated 2) the "slider-bar" feature associated with the object attribute will not be available if implemented this way.

The researcher used object attribute (building lot) to drive the change of "time" for rule files for each building. The way to create the connection between object attribute "time" and the building attribute defined in rule files is by setting the source of "time" attribute (in rule file) by the building lot "time" attribute using "Connection Editor" [75].

After the connection is established, one will select all buildings of interest in the community model and change the object attribute "time" of all selected building lots to visually inspect the color-coded energy consumption of all selected buildings. The Campus example is depicted in Figure A.5 and the community example is depicted in (Figure A.7)

FIGURE A.5: Slider in Campus Example

7) Sharing the Map

This is not achievable with CityEngine itself. The sharing of CityEngine models is through publishing a "web scene" or through sharing a "rule package". The first approach only shares the building geometry, not the building lots and the building

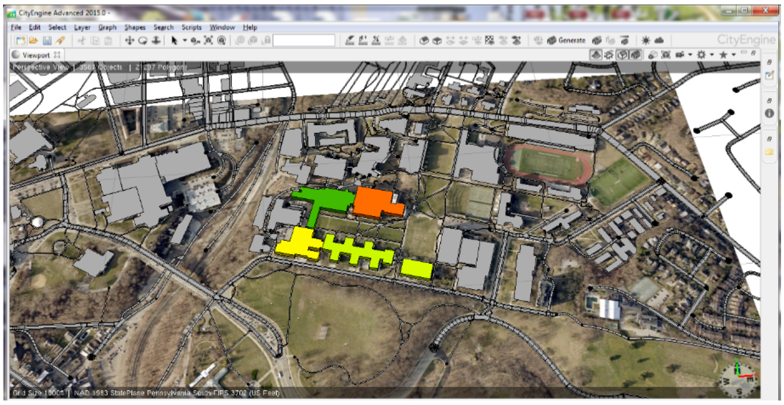
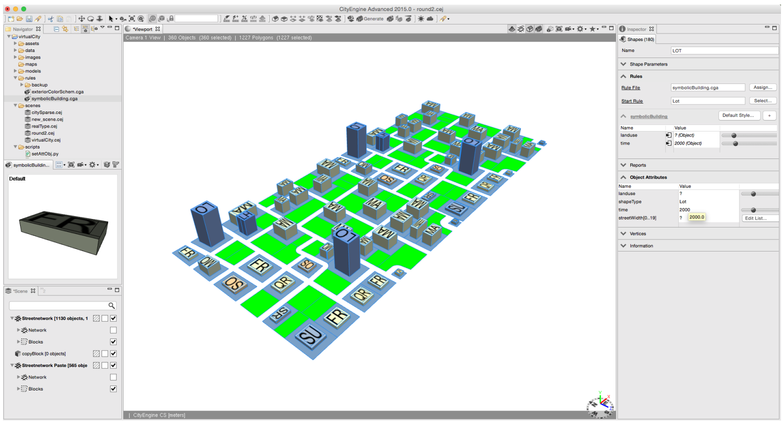
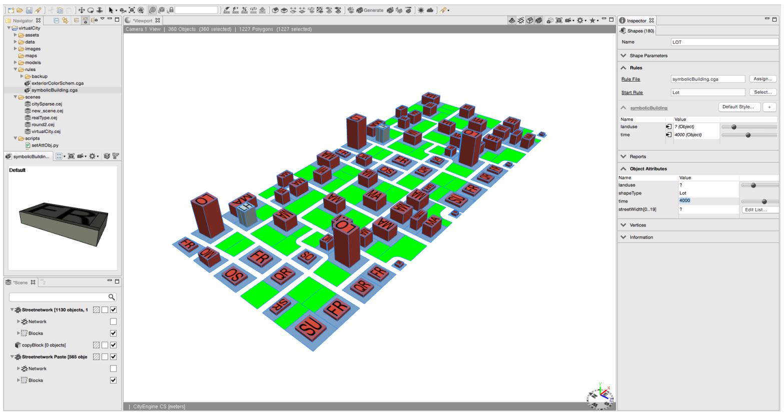


Figure A.6: Finished Campus Example



(a) Conceptual Community Setting Slider Winter



(b) Conceptual Community Setting Slider Summer

Figure A.7: Comceptual Community Setting Slider

lot attribute function. Since the dynamic map operates on setting the building lot object attribute, when shared with "publishing web scene", the time dimension is lost. The other approach is through sharing the "rule package", since the building energy demand data are included in the rule file, by sharing the model and the rule package, all functions of the dynamic energy map one implemented inside CityEngine can be retained. The drawback is that it requires the viewers of the dynamic energy map to 1) have CityEngine software, which is not free 2) have sufficient knowledge of the CityEngine software.

Another way to share the dynamic map implemented in this way is through a streamed animation or video. More details on animated maps is explained in Section 4.2.

Appendix B

Rule File for Implementing Dynamic Energy Map in CityEngine

The session records the version of rule file that implements dynamic energy map within CityEngine.

```
/**
 * File:    symbolicBuilding.cga
 * Created: 31 May 2015 21:47:21 GMT
 * Author:  yujiex
 */

version "2015.0"

//creating an attribute to receive the corresponding value
//from the object attribute, initial value are not important
attr landuse = 1
@Range(0, 8759)
attr time = 0

//Hourly Energy Information, x_01 holds the first 4380 hour
//energy data, x_02 holds the second 4380 hour energy data
//The lists are truncated here and not all data are shown
FullServiceRest_01 = "122;0;0;0;0;139;129;115;109;108;98;8       ..."
FullServiceRest_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0        ..."
hospital_01 = "778;911;881;878;849;848;779;764;694;619;551   ..."
hospital_02 = "110;106;96;92;93;126;144;181;194;219;228;23   ..."
LargeHotel_01 = "304;236;217;201;239;279;366;956;1172;986    ..."
LargeHotel_02 = "230;216;227;226;196;233;274;267;268;362;2   ..."
LargeOffice_01 = "1005;990;1279;865;1216;853;1221;841;986    ..."
LargeOffice_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0    ..."
MediumOffice_01 = "121;113;151;116;153;117;155;116;134;88    ..."
MediumOffice_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0   ..."
MidriseAppartment_01 = "154;183;182;183;182;180;177;173;16   ..."
MidriseAppartment_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0      ..."
OutPatient_01 = "76;64;83;68;92;160;164;141;132;123;115;11   ..."
OutPatient_02 = "6;5;5;5;8;12;17;26;27;28;40;33;43;35;45;3   ..."
PrimarySchool_01 = "200;207;262;174;250;174;254;107;127;69   ..."
PrimarySchool_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0      ..."
QuickServiceRest_01 = "68;0;21;34;38;78;69;64;62;57;49;40    ..."
QuickServiceRest_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0   ..."
SecondSchool_01 = "442;446;577;401;567;404;578;230;279;130   ..."
SecondSchool_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0   ..."
SmallHotel_01 = "70;85;87;89;91;91;87;79;60;53;50;46;43;38   ..."
SmallHotel_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0   ..."
SmallOffice_01 = "13;12;12;11;13;11;13;11;13;9;10;6;7;5;5    ..."
SmallOffice_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0    ..."
StandaloneRetail_01 = "47;60;66;68;66;62;266;200;172;137;1   ..."
StandaloneRetail_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0    ..."
StripMall_01 = "52;53;76;60;78;56;274;206;176;139;121;105     ..."
StripMall_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0     ..."
SuperMarket_01 = "177;250;181;294;264;190;885;774;558;515     ..."
SuperMarket_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;2;0      ..."
WareHouse_01 = "293;328;379;324;377;321;377;319;356;277;29    ..."
WareHouse_02 = "0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0     ..."

//Concatenating the two energy profile into one list
FullServiceRest = FullServiceRest_01 + FullServiceRest_02
hospital = hospital_01 + hospital_02
LargeHotel = LargeHotel_01 + LargeHotel_02
LargeOffice = LargeOffice_01 + LargeOffice_02
MediumOffice = MediumOffice_01 + MediumOffice_02
MidriseAppartment = MidriseAppartment_01 + MidriseAppartment_02
OutPatient = OutPatient_01 + OutPatient_02
PrimarySchool = PrimarySchool_01 + PrimarySchool_02
QuickServiceRest = QuickServiceRest_01 + QuickServiceRest_02
SecondSchool = SecondSchool_01 + SecondSchool_02
SmallHotel = SmallHotel_01 + SmallHotel_02
SmallOffice = SmallOffice_01 + SmallOffice_02
StandaloneRetail = StandaloneRetail_01 + StandaloneRetail_02
StripMall = StripMall_01 + StripMall_02
SuperMarket = SuperMarket_01 + SuperMarket_02
WareHouse = WareHouse_01 + WareHouse_02

# retrieve time-th item of the energy profile
item01 = listItem(FullServiceRest, time)
item02 = listItem(hospital, time)
item03 = listItem(LargeHotel, time)
item04 = listItem(LargeOffice, time)
item05 = listItem(MediumOffice, time)
item06 = listItem(MidriseAppartment, time)
item07 = listItem(OutPatient, time)
item08 = listItem(PrimarySchool, time)
item09 = listItem(QuickServiceRest, time)
item10 = listItem(SecondSchool, time)
item11 = listItem(SmallHotel, time)
item12 = listItem(SmallOffice, time)
item13 = listItem(StandaloneRetail, time)
item14 = listItem(StripMall, time)
item15 = listItem(SuperMarket, time)
```

```
item16 = listItem(WareHouse, time)

# the max item of all the heat demand profiles
maxItem = 3243
height=4

colorRatio_01 = (ln(maxItem) - ln(float(item01)))/ln(maxItem)
colorRatio_02 = (ln(maxItem) - ln(float(item02)))/ln(maxItem)
colorRatio_03 = (ln(maxItem) - ln(float(item03)))/ln(maxItem)
colorRatio_04 = (ln(maxItem) - ln(float(item04)))/ln(maxItem)
colorRatio_05 = (ln(maxItem) - ln(float(item05)))/ln(maxItem)
colorRatio_06 = (ln(maxItem) - ln(float(item06)))/ln(maxItem)
colorRatio_07 = (ln(maxItem) - ln(float(item07)))/ln(maxItem)
colorRatio_08 = (ln(maxItem) - ln(float(item08)))/ln(maxItem)
colorRatio_09 = (ln(maxItem) - ln(float(item09)))/ln(maxItem)
colorRatio_10 = (ln(maxItem) - ln(float(item10)))/ln(maxItem)
colorRatio_11 = (ln(maxItem) - ln(float(item11)))/ln(maxItem)
colorRatio_12 = (ln(maxItem) - ln(float(item12)))/ln(maxItem)
colorRatio_13 = (ln(maxItem) - ln(float(item13)))/ln(maxItem)
colorRatio_14 = (ln(maxItem) - ln(float(item14)))/ln(maxItem)
colorRatio_15 = (ln(maxItem) - ln(float(item15)))/ln(maxItem)
colorRatio_16 = (ln(maxItem) - ln(float(item16)))/ln(maxItem)

Lot -->
        case landuse <= 1: //full service resturant
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_01))
            extrude(1*height)
            comp(f){top: top_fr | side: facade_fr}
        case landuse > 1 && landuse <= 2:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_02))
            //extrude(rand(8, 50))
            extrude(5*height)
        case landuse > 2 && landuse <= 3:   //Large Hotel
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_03))
            extrude(24)
            comp(f){top: top_lh | side: facade_lh}
        case landuse > 3 && landuse <= 4:    //Large Office
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_04))
            extrude(48)
            comp(f){top: top_lo | side: facade_lo}
        case landuse > 4 && landuse <= 5:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_05))
            extrude(12)
            comp(f){top: top_mo | side: facade_mo}
        case landuse > 5 && landuse <= 6:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_06))
            //assuming residential is 3 to 6 stories high
            //extrude(rand(12, 13))
            extrude(16)
            comp(f){top: top_ma | side: facade_ma}
        case landuse > 6 && landuse <= 7:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_07))
            //extrude(rand(8, 50))
            extrude(12)
        case landuse > 7 && landuse <= 8:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_08))
            //extrude(rand(8, 50))
            extrude(4)
        case landuse > 8 && landuse <= 9:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_09))
            extrude(4)
            comp(f){top: top_qr | side: facade_qr}
        case landuse > 9 && landuse <= 10:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_10))
            //extrude(rand(8, 50))
            extrude(8)
        case landuse > 10 && landuse <= 11:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_11))
            extrude(16)
        case landuse > 11 && landuse <= 12: //Small Office
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_12))
            extrude(4)
            comp(f){top: top_so | side: facade_so}
        case landuse > 12 && landuse <= 13: //Stand-alone Retail
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_13))
            extrude(4)
            comp(f){top: top_sr | side: facade_sr}
        case landuse > 13 && landuse <= 14:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_14))
            //extrude(rand(8, 50))
            extrude(4)
        case landuse > 14 && landuse <= 15: //Super Market
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_15))
            extrude(4)
            comp(f){top: top_su | side: facade_su}
        case landuse > 15 && landuse <= 16:
            s('0.6, '1, '0.6)
            center(xz)
            color(colorRamp("redToBlue", 1-colorRatio_16))
            extrude(4)
        else:
            color(0, 5, 0)
```

Appendix C

Implementing Dynamic Energy Map in ArcGIS

C.1 Introduction

This section records the process of implementing a dynamic energy map in ArcGIS. The computer used in this implementation is a Dell Precision T1600 Quad Core Intel Xeon, 3.10GHz machine with 16GB RAM in CMU Baker 140C cluster. The GIS software used is ArcScene 10.2 [76].

The common procedure is

Step 1 Exporting CityEngine models as either gdb file or as collada files and import the model to ArcScene

Step 2 Preprocessing the energy profile and write it to a csv file containing hourly energy consumption for all building types in the community.

Step 3 Joining the table to the 3D features

Step 4 Enabling time in the joint layer

Step 5 Configurating the setting of the animation and play the animation in ArcGIS.

Each step will be explained in more detail in the following session.

C.2 Explaining Each Steps

1) Exporting CityEngine model.

   The exported format could be a) gdb file that contains the object attributes of building lots or b) collada file that only contains the model geometry. The advantage of Method a) is its potential to pass attribute information from CityEngine to ArcGIS. Method b) requires a small script so that each building geometry could be exported as single collada files.

2) Producing a file containing the energy profile of all buildings in the community model into a csv file with one date-time column containing the time information and several energy profile information.

   The number of rows equals to $n \times 8760$ where n is the unique building types (if two building has different energy demand behavior, they are considered to have different types). Figure C.1 shows the file used in this implementation example. The first column contains the time information. The format of the time column is crutial because it will be converted to a "date" type in later steps. This conversion requires the input csv file have one of its suggested date-time format. The format addopted in this example is "yyyy/mm/dd one space HH:MM:SS". The range of the "HH" should be 0 to 23 (not 1 to 24). The second column is the hourly gas heating energy demand in kBtu and the third column is the hourly cooling energy demand in kBtu. The forth column contains a short integer corresponding to the building type this row of energy file represents.

```
2015/01/01 01:00:00,0.005637635323098419,418.1951217975104,1
2015/01/01 02:00:00,0.0,0.0,1
2015/01/01 03:00:00,0.0,0.0,1
2015/01/01 04:00:00,0.0,0.0,1
2015/01/01 05:00:00,0.0,0.0,1
2015/01/01 06:00:00,0.020720590790235208,474.3641951092042,1
2015/01/01 07:00:00,0.04091094860228904,442.2806012872507,1
2015/01/01 08:00:00,0.03864358951445788,393.01392921371047,1
2015/01/01 09:00:00,0.005390469085569592,372.53354631071613,1
2015/01/01 10:00:00,0.0,368.98644737088273,1
2015/01/01 11:00:00,0.019739094999106255,335.0757279327133,1
2015/01/01 12:00:00,0.0,300.6025122500754,1
2015/01/01 13:00:00,0.0,266.3767543444386,1
2015/01/01 14:00:00,0.0,254.73074163258178,1
2015/01/01 15:00:00,0.0,263.066443102175,1
2015/01/01 16:00:00,0.0,271.24440484571915,1
2015/01/01 17:00:00,0.03276377815582866,263.3583653846412,1
2015/01/01 18:00:00,0.0,261.16079735680626,1
2015/01/01 19:00:00,0.0,254.14211457864826,1
2015/01/01 20:00:00,0.0,244.38229514062922,1
2015/01/01 21:00:00,0.0,239.7963777655892,1
2015/01/01 22:00:00,0.0,263.0934676760495,1
```

FIGURE C.1: A screenshot of the energy profile in csv format to be imported to ArcScene

3) After importing the table to the working file geodatabase, one should use the "convert time field" to covert the time column in the imported csv table to type "date".

4) Create the centroid for each building geometry footprint

   As is mentioned in Section 3.2.4, aggregating the energy data of the whole year to the 3D building geometry is not achievable with the machine used in this example. So here the researcher chose to aggregate the energy data into a simplefiled geometry representation of the buildings in the community model: the centroid of each building. The steps of aggregating energy data to 3D building features is the same as the steps of aggregating energy data to building centroid by just changing the layer to which the data is joined. An animated version of such aggregation can be accessed at this link. Figure C.2 shows a screenshot of the ArcScene Dynamic Map showing the hourly gas heating energy demand.

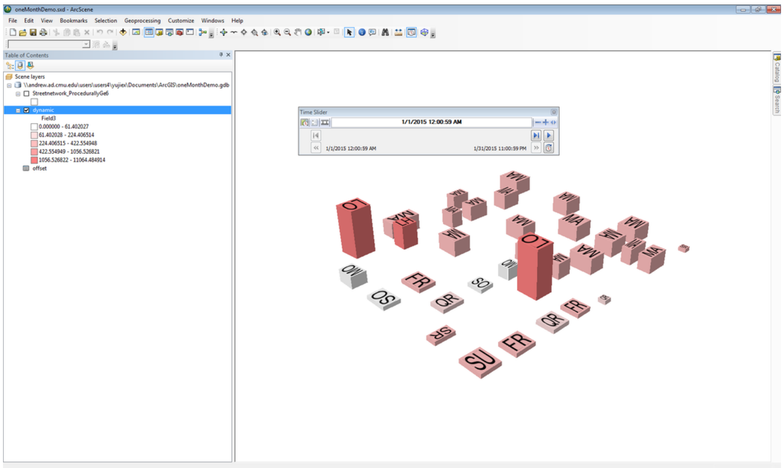


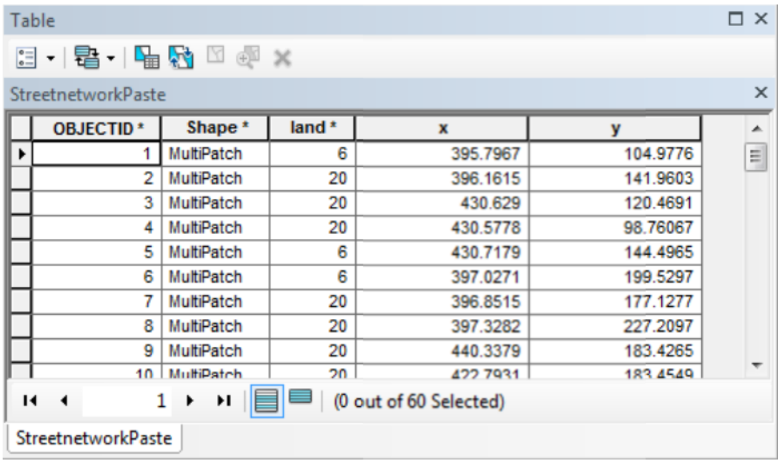
FIGURE C.2: A screen shot of a dynamic energy map in ArcGIS, the legend on the left shows the hourly gas heating energy demand

   The way to create building centroid is to first add two extra field in attribute table of the imported building lot feature class ("streetnetworkPaste") and use "Calculate Geometry" to retrieve the x, y coordinate of the centroid for each building lot (Figure C.3).

   Then export the table to the working gdb and use "make x y event layer" tool to create a point feature ("cen") (Figure C.4)

5) Import the centroid layer ("cen") to the working gdb.

   This step is important, because in the documentation about "join", "When you create a join in such a case (one-to-many or many-to- many), there are differences between



Table

StreetnetworkPaste

OBJECTID *	Shape *	land *	x	y
1	MultiPatch	6	395.7967	104.9776
2	MultiPatch	20	396.1615	141.9603
3	MultiPatch	20	430.629	120.4691
4	MultiPatch	20	430.5778	98.76067
5	MultiPatch	6	430.7179	144.4965
6	MultiPatch	6	397.0271	199.5297
7	MultiPatch	20	396.8515	177.1277
8	MultiPatch	20	397.3282	227.2097
9	MultiPatch	20	440.3379	183.4265
10	MultiPatch	20	422.7931	183.4549

1 (0 out of 60 Selected)

StreetnetworkPaste

FIGURE C.3: Calculated Centroid

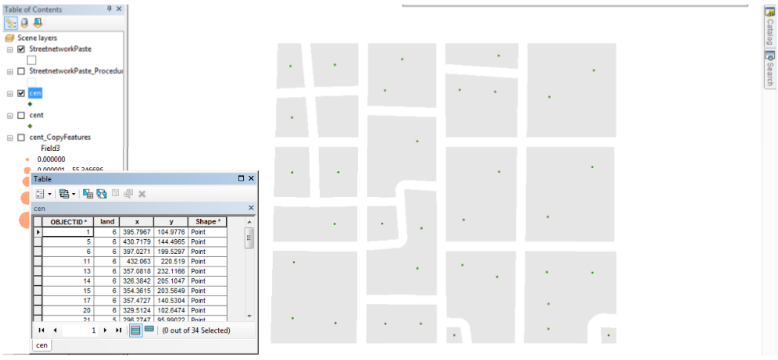


FIGURE C.4: The centroid feature is created with the x y table

how tools and other layer-specific settings work depending on the data source. If you are using geodatabase data to create the join, all matching records are returned. If you are using nondatabase data, like shapefiles or dBASE tables, to create the join, only the first matching record is returned." [77] If one do not import it to gdb file, the record that retains are only one row for each building type, which is not desirable for the current situation. In order to retain all 8760 matching records for each building type, importing the feature class and table to gdb is crutial.

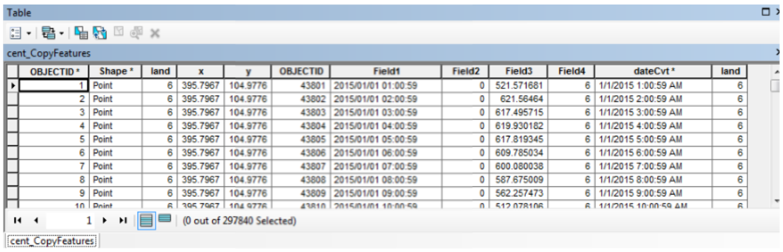
6) Add "Attribute Index" to the feature class to the centroid layer to be joint.

   The index acted as search keys in the database. Adding index makes searching of matching data faster. In our current case, the search key should be "landuse"

7) Use "Add join" tool to join the centroid and the energy profile table with "landuse" as a matching field

After the add join, when opening the "attribute table" of the centroid layer, one could not see all the matching records, but one can still have a feeling they are retained because the model will become very slow.

8) Use "copy features" tool to copy the joint centroid layer to a new layer, then all the matching features are visible ("cent_CopyFeatures") (Figure C.5)



Table

cent_CopyFeatures

OBJECTID *	Shape *	land	x	y	OBJECTID	Field1	Field2	Field3	Field4	dateCvt *	land
1	Point	6	395.7967	104.9776	43801	2015/01/01 01:00:59	0	521.571681	6	1/1/2015 1:00:59 AM	6
2	Point	6	395.7967	104.9776	43802	2015/01/01 02:00:59	0	621.56464	6	1/1/2015 2:00:59 AM	6
3	Point	6	395.7967	104.9776	43803	2015/01/01 03:00:59	0	617.495715	6	1/1/2015 3:00:59 AM	6
4	Point	6	395.7967	104.9776	43804	2015/01/01 04:00:59	0	619.930182	6	1/1/2015 4:00:59 AM	6
5	Point	6	395.7967	104.9776	43805	2015/01/01 05:00:59	0	617.819345	6	1/1/2015 5:00:59 AM	6
6	Point	6	395.7967	104.9776	43806	2015/01/01 06:00:59	0	609.785034	6	1/1/2015 6:00:59 AM	6
7	Point	6	395.7967	104.9776	43807	2015/01/01 07:00:59	0	600.080038	6	1/1/2015 7:00:59 AM	6
8	Point	6	395.7967	104.9776	43808	2015/01/01 08:00:59	0	587.675009	6	1/1/2015 8:00:59 AM	6
9	Point	6	395.7967	104.9776	43809	2015/01/01 09:00:59	0	562.257473	6	1/1/2015 9:00:59 AM	6
10	Point	6	395.7967	104.9776	43810	2015/01/01 10:00:59	0	512.078106	6	1/1/2015 10:00:59 AM	6

1 (0 out of 297840 Selected)

cent_CopyFeatures

Figure C.5: The copied table retains all 8760 building energy information of the buildings in the community model, there are in total $8760 \times 34 = 297840$ rows of data entries in the table because there are 34 buildings in the community model

An alternative of "add join + copy features" of creating a feature class that aggregates the spatial geometry and the temporal energy demand is through the tool "make query table", detailed explanation of this tool is explained in [78].

9) Change the symbol to be graduated symbols, with "Quantile method" as the current classification method to ensure a larger variation in symbol changes for demonstration purpose. The "sample size" of classification breakpoint should be reset so that it is at not smaller than the total number of data points (number of rows in the final attribute table)

10) Enable "time" on the final layer ("cent_CopyFeatures") with aggregated time, energy data and geometry.

11) Add the time-column as an Attribute Index to the final layer and one can configure the animation play back to play the animated maps.

    Although it is surprising that this step is not done automatically, this step is crucial. If one does not add it, one may find the render of the image in the slider very slow even though one set the "playback" to fast.

C.3 Final Output

In order to make the symbol more visible, an orthogonal top view was chosen as the map view port. The building geometry layer is for providing a spatial context, thus a transparent filling was applied to this layer. Figure C.6 shows a screen shot of the animated map interface inside stand-alone ArcScene. The exported animation version could be found through this link.

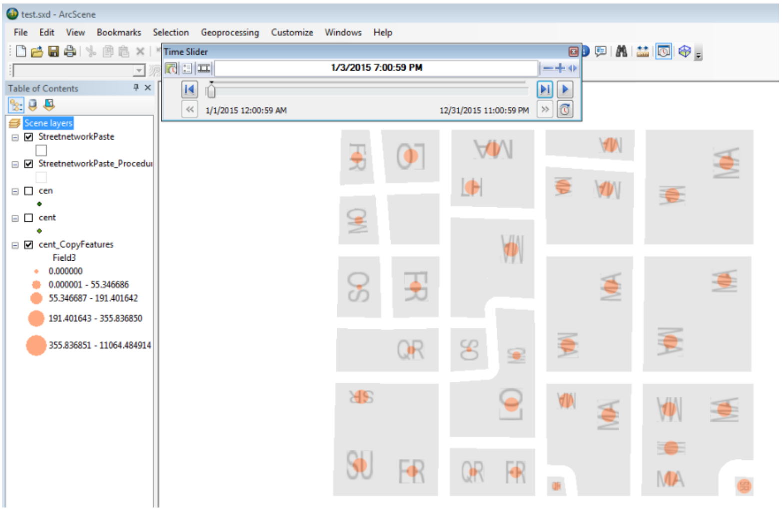


FIGURE C.6: A screenshot of the dynamic map interface in ArcScene 10.2, the hourly heating energy are represented as a graduated-sized point symbol with larger size for larger demand

One issue regarding using ArcScene as the generator of images for 3D visualization is that the “DataFrame” module in image exporting does not work for ArcScene, this means one cannot export 3D map image sequences for later post processing and display. This acts as another drawback that disables us from using ArcGIS in producing map images for implementing a dynamic energy map.

Appendix D

Rule File Used in Final Dynamic Map Interface

The session records the final version of rule file that implements the bi-variate choropleth map used in the final version of the interface design.

```
/**
 * File:    symbolicBuilding.cga
 * Created: 31 May 2015 21:47:21 GMT
 * Author:  yujiex
 */

version "2015.0"

attr landuse = 1
@Range(0, 8759)
attr time = 0

//The following color encoding can be replaced for different
//use case (different encoding method or energy profile)
SmallOffice_01 = "#FFD5D5;#FFD5D5;#FFD5D5;#FFD5D5;#FFD5D5  ..."
SmallOffice_02 = "#FFFFFF;#D5D5FF;#AAAAFF;#AAAAFF;#AAAAFF  ..."
FullServiceRestaurant_01 = "#FF2B2B;#FFFFFF;#FFFFFF;#FFFFFF..."
FullServiceRestaurant_02 = "#2B2BFF;#2B2BFF;#2B2BFF;#2B2BFF..."
MidriseApartment_01 = "#FF2B2B;#FF0000;#FF0000;#FF0000     ..."
MidriseApartment_02 = "#2B2BFF;#2B2BFF;#2B2BFF;#2B2BFF     ..."
LargeOffice_01 = "#FF0000;#FF0000;#FF0000;#FF0000;#FF0000  ..."
LargeOffice_02 = "#0000FF;#0000FF;#0000FF;#0000FF;#0000FF  ..."
SuperMarket_01 = "#FF0000;#FF0000;#FF0000;#FF0000;#FF0000  ..."
SuperMarket_02 = "#2B2BFF;#2B2BFF;#2B2BFF;#2B2BFF;#2B2BFF  ..."
MediumOffice_01 = "#FFD5D5;#FFD5D5;#FFAAAA;#FFD5D5;#FFAAAA ..."
MediumOffice_02 = "#2B2BFF;#2B2BFF;#2B2BFF;#2B2BFF;#2B2BFF ..."
StandaloneRetail_01 = "#FF8080;#FF8080;#FF8080;#FF8080     ..."
StandaloneRetail_02 = "#2B2BFF;#2B2BFF;#2B2BFF;#2B2BFF     ..."
LargeHotel_01 = "#DC07DC;#DC07DC;#C61CC6;#D52BAA;#C61CC6   ..."
LargeHotel_02 = "#0000FF;#0000FF;#0000FF;#2B00FF;#0000FF   ..."
QuickServiceRestaurant_01 = "#FF8080;#FFFFFF;#FFD5D5       ..."
QuickServiceRestaurant_02 = "#5555FF;#5555FF;#5555FF       ..."

FullServiceRestaurant =(FullServiceRestaurant_01 +
                        FullServiceRestaurant_02)
//Hospital = Hospital_01 + Hospital_02
LargeHotel = LargeHotel_01 + LargeHotel_02
LargeOffice = LargeOffice_01 + LargeOffice_02
MediumOffice = MediumOffice_01 + MediumOffice_02
MidriseApartment = MidriseApartment_01 + MidriseApartment_02
//OutPatient = OutPatient_01 + OutPatient_02
//PrimarySchool = PrimarySchool_01 + PrimarySchool_02
QuickServiceRestaurant = (QuickServiceRestaurant_01 +
                          QuickServiceRestaurant_02)
//SecondarySchool = SecondarySchool_01 + SecondarySchool_02
//SmallHotel = SmallHotel_01 + SmallHotel_02
SmallOffice = SmallOffice_01 + SmallOffice_02
StandaloneRetail = StandaloneRetail_01 + StandaloneRetail_02
//StripMall = StripMall_01 + StripMall_02
SuperMarket = SuperMarket_01 + SuperMarket_02
//Warehouse = Warehouse_01 + Warehouse_02

# retrieve time-th item of the energy profile
item01 = listItem(FullServiceRestaurant, time)
//item02 = listItem(Hospital, time)
item03 = listItem(LargeHotel, time)
item04 = listItem(LargeOffice, time)
item05 = listItem(MediumOffice, time)
item06 = listItem(MidriseApartment, time)
//item07 = listItem(OutPatient, time)
//item08 = listItem(PrimarySchool, time)
item09 = listItem(QuickServiceRestaurant, time)
//item10 = listItem(SecondarySchool, time)
//item11 = listItem(SmallHotel, time)
item12 = listItem(SmallOffice, time)
item13 = listItem(StandaloneRetail, time)
//item14 = listItem(StripMall, time)
item15 = listItem(SuperMarket, time)
//item16 = listItem(Warehouse, time)

# the max item of all the heat demand profiles
height=4

Lot -->
        case landuse <= 1: //full service resturant
            s('0.6, '1, '0.6)
            center(xz)
            color(item01)
            extrude(1*height)
            comp(f){top: top_fr | side: facade_fr}
        case landuse > 1 && landuse <= 2:
            s('0.6, '1, '0.6)
            center(xz)
            //color(item02)
            extrude(5*height)
        case landuse > 2 && landuse <= 3: //Large Hotel
            s('0.6, '1, '0.6)
            center(xz)
            color(item03)
            extrude(24)
            comp(f){top: top_lh | side: facade_lh}
        case landuse > 3 && landuse <= 4: //Large Office
            s('0.6, '1, '0.6)
            center(xz)
            color(item04)
            extrude(48)
```

```
            comp(f){top: top_lo | side: facade_lo}
        case landuse > 4 && landuse <= 5:
            s('0.6, '1, '0.6)
            center(xz)
            color(item05)
            extrude(12)
            comp(f){top: top_mo | side: facade_mo}
        case landuse > 5 && landuse <= 6:
            s('0.6, '1, '0.6)
            center(xz)
            color(item06)
            extrude(16)
            comp(f){top: top_ma | side: facade_ma}
        case landuse > 6 && landuse <= 7:
            s('0.6, '1, '0.6)
            center(xz)
            //color(item07)
            extrude(12)
        case landuse > 7 && landuse <= 8:
            s('0.6, '1, '0.6)
            center(xz)
            //color(item08)
            extrude(4)
        case landuse > 8 && landuse <= 9:
            s('0.6, '1, '0.6)
            center(xz)
            color(item09)
            extrude(4)
            comp(f){top: top_qr | side: facade_qr}
        case landuse > 9 && landuse <= 10:
            s('0.6, '1, '0.6)
            center(xz)
            //color(item10)
            extrude(8)
        case landuse > 10 && landuse <= 11:
            s('0.6, '1, '0.6)
            center(xz)
            //color(item11)
            extrude(16)
        case landuse > 11 && landuse <= 12: //Small Office
            s('0.6, '1, '0.6)
            center(xz)
            color(item12)
            extrude(4)
            comp(f){top: top_so | side: facade_so}
        case landuse > 12 && landuse <= 13: //Standalone Retail
            s('0.6, '1, '0.6)
            center(xz)
            color(item13)
            extrude(4)
            comp(f){top: top_sr | side: facade_sr}
        case landuse > 13 && landuse <= 14:
            s('0.6, '1, '0.6)
            center(xz)
            //color(item14)
            extrude(4)
        case landuse > 14 && landuse <= 15: //Super Market
            s('0.6, '1, '0.6)
            center(xz)
            color(item15)
            extrude(4)
            comp(f){top: top_su | side: facade_su}
        case landuse > 15 && landuse <= 16:
            s('0.6, '1, '0.6)
            center(xz)
            //color(item16)
            extrude(4)
        else:
            color(0, 5, 0)
            //color(255, 255, 255)
//01
top_fr -->
    split(y){'0.1:a_fr|'0.8:b_fr|'0.1:c_fr}
b_fr -->
    split(x){'0.1:e_fr|'0.8:f_fr|'0.1:g_fr}
f_fr -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/FR.jpg")
projectUV(0)
//03 Large Hotel
top_lh -->
    split(y){'0.1:a_lh|'0.8:b_lh|'0.1:c_lh}
b_lh -->
    split(x){'0.1:e_lh|'0.8:f_lh|'0.1:g_lh}
f_lh -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/LH.jpg")
projectUV(0)
//04 Large Office
top_lo -->
    split(y){'0.1:a_lo|'0.8:b_lo|'0.1:c_lo}
b_lo -->
    split(x){'0.1:e_lo|'0.8:f_lo|'0.1:g_lo}
f_lo -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/LO.jpg")
projectUV(0)
//05 Medium Office
top_mo -->
    split(y){'0.1:a_mo|'0.8:b_mo|'0.1:c_mo}
b_mo -->
    split(x){'0.1:e_mo|'0.8:f_mo|'0.1:g_mo}
f_mo -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/MO.jpg")
projectUV(0)

//06 Midrise Apartment
top_ma -->
    split(y){'0.1:a_ma|'0.8:b_ma|'0.1:c_ma}
b_ma -->
    split(x){'0.1:e_ma|'0.8:f_ma|'0.1:g_ma}
f_ma -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/MA.jpg")
projectUV(0)

//09 Quick Service Resturant
top_qr -->
    split(y){'0.1:a_qr|'0.8:b_qr|'0.1:c_qr}
b_qr -->
    split(x){'0.1:e_qr|'0.8:f_qr|'0.1:g_qr}
f_qr -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/QR.jpg")
projectUV(0)

//12 Small Office
top_so -->
    split(y){'0.1:a_so|'0.8:b_so|'0.1:c_so}
b_so -->
    split(x){'0.1:e_so|'0.8:f_so|'0.1:g_so}
f_so -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/SO.jpg")
projectUV(0)
//12 Standalone Retail
top_sr -->
    split(y){'0.1:a_sr|'0.8:b_sr|'0.1:c_sr}
b_sr -->
    split(x){'0.1:e_sr|'0.8:f_sr|'0.1:g_sr}
f_sr -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/SR.jpg")
projectUV(0)

//15 Super Market
top_su -->
    split(y){'0.1:a_su|'0.8:b_su|'0.1:c_su}
b_su -->
    split(x){'0.1:e_su|'0.8:f_su|'0.1:g_su}
f_su -->
setupProjection(0, scope.xy, scope.sx, scope.sy)
texture("assets/SU.jpg")
projectUV(0)
```

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