Carnegie Mellon University

Master Thesis

Dynamic Energy Mapping

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Abbreviations

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

Symbols

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

Chapter 1

General Introduction

1.1 Project Overview

The burning of fossil fuels produces green house gas (GHG) and causes significant global climate changes including global sea level rise, temperature rise, ocean warming, ice sheet melting and extreme weather event [3]. Fossil fuels are finite: studies have shown that if the consuming 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 began to put 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].

Reducing the GHG emission and the 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 [7]. It contains "land use planning", "transportation management", "site planning" and "local energy supply and delivery planning" [7]. Community level energy planning and management achieves GHG reduction by means of :1) improving energy usage efficiency, 2) conserving the use of high quality energy and 3) switching to using more renewable energy source [8].

Energy Mapping makes the community energy planning alternatives visible to planners and policy makers [9] and thus flourishes with the increasing attention to community planing. Emerging explorations on 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." [9]. The "London Heat Map" project that helps developers and planners to "identify opportunities for decentralised energy projects" [10].

What information should an Energy Map hold and in what form should the information be conveyed or displayed is still not completely agreed between different approaches. Calgary Energy Mapping study depicts annual average energy use intensity and alternative renewable energy supply region [1]. London Heat Map contains mainly heating energy related features: high heating energy consumers, suppliers and district heating networks. Dutch Heat Map, an application of the Energy Potential Method (EPM) method developed by Dobbelsteen et al. [11], contains information of annual heating energy demand (or demand density), heating energy supply (or supply density), infrastructure network layout and CHP and Biomass plant location.

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" [9] was brought about:

i. It acts as a geo-database that efficiently holds
   - hourly energy profile data for each building and the aggregated energy profile data for the whole community [9];
   - hourly energy supply data of community [9].

ii. It visualizes the dynamic energy demand and supply changes with high spatial and temporal resoltion [9].

iii. It performs data analysis and supports district system sizing [9].

iv. It can be connected to simulation tools that can supports instant performance analysis [9].

With a Dynamic Energy Map, the temporal behavior of the demand and supply of heating, cooling and electricity are revealed and are available to be compared (function ii), analyzed (function iii) and updated (function i and iv). 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" [12]. The development of data-driven approaches and machine learning methods could also be coupled and can perform more complicated analysis of 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 Baird et al. in 2011-2012. The map consists of two parts: a geo-database that holds general building information (name, conditioned area) annual and monthly energy usage information (energy use intensity, annual peak demand value and monthly peak demand value); an excel screening tool that holds hourly energy usage information of each building and performs analysis and system comparison of a district energy system [9].

In the initial instance [9], function i) of holding spatial-temporal (although with low temporal resolution) energy data 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". One goal of the current project is to make the geo-database 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.

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

For function iii), the feasibility analysis of a district energy system is performed in a stand-alone excel tool [9] but it is possible that the analysis result could be linked in to the geo-database as the energy simulation result.

For function ii), the spatial and temporal information are visualized separately in the initial instance [9]: the spatial information of 3D building geometry and location could be visually inspected in the geo-database 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.

The authors 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 defined as to

1. Implement a Dynamic Energy Demand Map with the focus on creating a high-resolution spatial-temporal visualization of hourly thermal energy consumption 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) Support the sizing of a district energy system CHP plant

The community model is created in City Engine [13] based on the land use pattern of a mixed-use redevelopment project at Lower Hill District, Pittsburgh, PA [14]. 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 [15].

The hourly heating cooling and electricity energy consumption profile is retrieved from DOE Commercial Benchmark Building simulation [2].

An interface was designed to combine the 8760 heating-cooling energy choropleth map images from City Engine and the 8760 hourly heating-cooling energy data from EnergyPlus to form a Dynamic Energy Map. The interface provides users with the functions of 1) navigating through the dynamic map images, 2) dynamic data plots of single buildings, building sectors and aggregated community thermal energy demand.

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." [16]. It brings the energy generation near to the energy end users and reduces the energy transmission and distribution loss [17].

A district energy system produces thermal energy in a central plant and delivers the thermal energy to local buildings through a closed-loop pipeline network. Thermal energy are delivered in the form of steam, hot water or chilled water [9]. The central power plant can take on one of the following forms: 1) thermal power plant that only generates thermal energy, which can be either heating 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 serve space heating and service hot water to local buildings [15] 3) tri-generation system, where the central plant uses the heat generated by CHP plant to produce chilled water and supply both heating and cooling energy [18]. Corresponding to the different types of power plant, the network delivering thermal energy can be classified as 1) district heating network that only delivers steam or hot water 2) district thermal network that delivers both heating energy in the form of steam or hot water and cooling energy as chilled water.

A district thermal energy system corresponds to the three means of community level GHG reduction as follows:

- It has high energy generation efficiency

  Higher energy usage efficiency means with the same amount of input energy, more useful energy is produced and less are wasted. Buildings' electricity supply are mainly from centralized power plant that are far away from cities. Heat produced in power generation are normally dumped into oceans and lakes [9, 19], not only causing negative environmental impact [20], but also reduce the energy generation efficiency to be only about 1/3 [19]. District Energy System has high energy generation efficiency as a result of 1) it can utilize high efficiency large-scale energy generation equipment [15] and 2) it is closer to the energy end user which reduces the energy loss due to transmission and distribution [19].

- 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" [21]. 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 [11] is the low-temperature (or low-energy) district heating system [22] which has a supply temperature of around 50 ^{o}C and return temperature of around 25^{o} C [22].

- Multiple fuel choices including renewable energy sources

  The central 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 [15, 19].

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 [19] the flue gas [23].

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" [24], 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" [17]. 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 [17]. One of the well-known instances of a heat map is the "London Heat Map" [10]

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" [19]. It is a "GIS based system" that can be used to develop energy strategies, prioritize project, identify potential growth opportunities and impose planning restrictions [19]. Dobbelsteen et al. adopted the term "Energy Potential Mapping (EPM)" [11]. 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" [11]. 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" [17].

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 [1]. It can be used in supporting district heating system design [17, 25] by visualizing the heat sources and sinks.

1.3.4 Dynamic Energy Map

According to the study of Baird et al. , a Dynamic Energy Map is an Energy Map equipped with temporal information of energy supply and demand. 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. 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 [17].

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 [17].

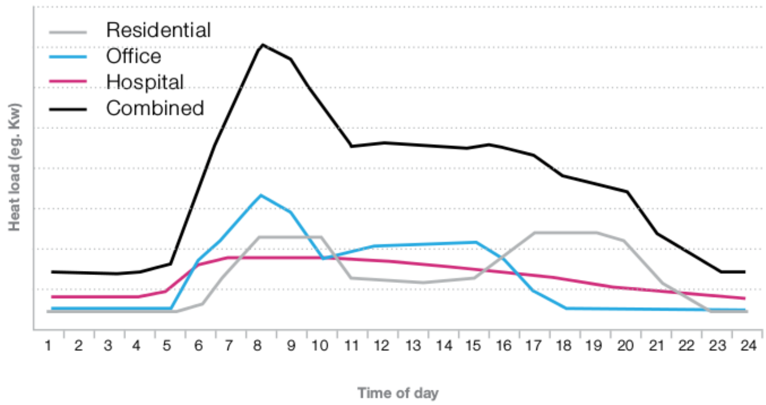


FIGURE 1.1: Mixing Load of Different Building Type [17]

1.4.2 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

Section 2.1 and section 2.2 provide an overview of the existing instances of static energy maps and dynamic energy maps. The static maps examples are arranged in the order of increasing layers of information from heat mapping to energy potential mapping of various energy sources and sinks. A summary of techniques used to produce these Static and Dynamic Energy Map instances are shown in Table 2.1:

Project Name	Type	Software
Calgary Map	Static, Stand-alone	?
London Heat Map	Static, web, interactive	ArcGIS WebApp
National Heat Map	Static, web, interactive	Google Map API
Water Source Heat Map	Static, web, interactive	Google Map API
Dutch Heat Map	Static, Stand-alone	?
Lowe Hill District Map	Dynamic, web, interactive	ArcScene, ArcMap, GIS Cloud, excel
Energy Mapping to Identify Opportunities for Future Network	Dynamic, Stand-alone	QGIS

Table 2.1: Map Technology Summary Table

2.1 Static Energy Map

2.1.1 UK 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" [10]. In this study, the term DE only refers to "combined heat and power systems connected to district heating networks" [17].

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) [10, 17]. 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" [17]) 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 [17]. The physical constraint are also considered in finalizing the high DE potential regions.

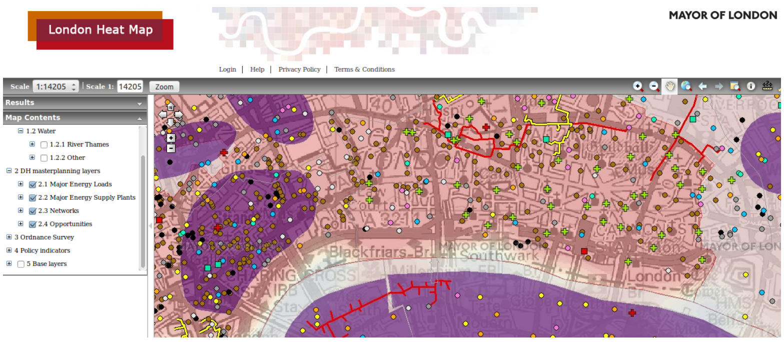


FIGURE 2.1: London Heat Map [26]

National Heat Map (Figure 2.2) is another UK energy mapping project that focuses more on the industry side [17]. 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 [17]. 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 [28].

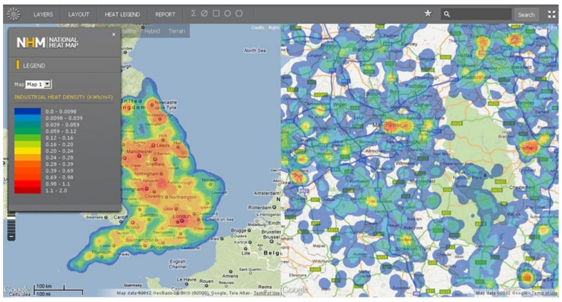


Figure 2.2: National Heat Map [29]

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 [30]. The map revealed the large thermal capacity of water bodies that could serve over one million buildings in the UK [30].

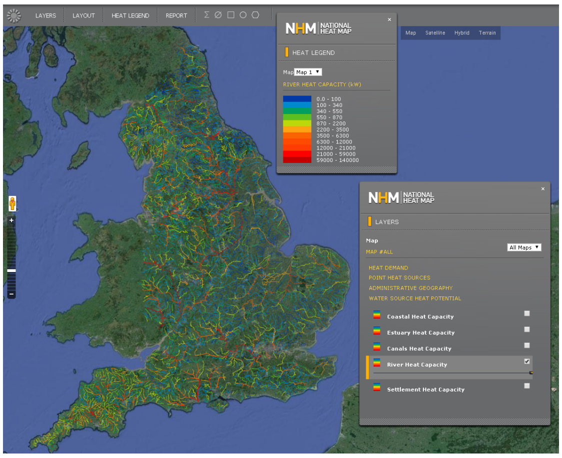


Figure 2.3: Water Source Heat Map [30]

2.1.2 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].

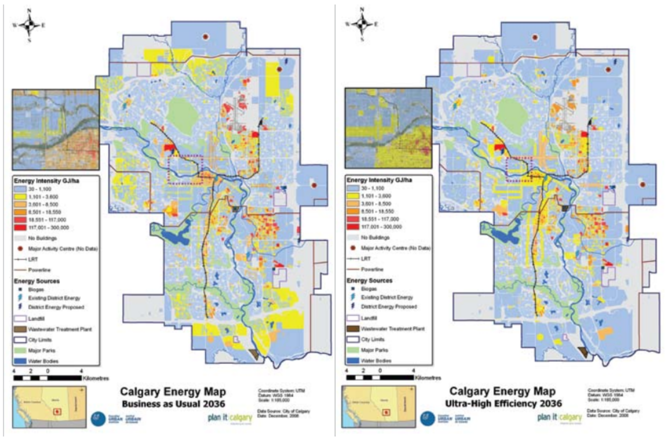


FIGURE 2.4: Calgary Energy Map (Business as Usual, Ultra-High Efficiency) [1]

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].

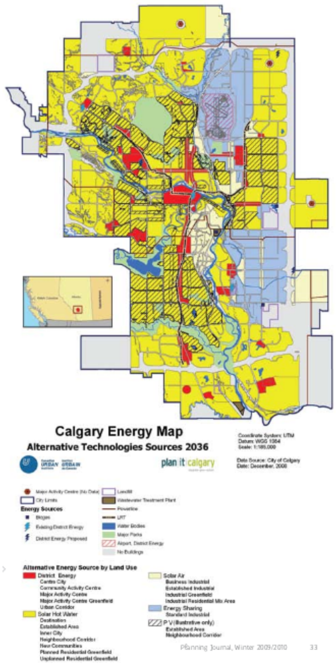


FIGURE 2.5: Calgary Energy Map Alternative Energy Source [1]

2.1.3 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 [11].

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 unit that facilitates easy comparison and facilitates the matching of supply and demand [11]. 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 [11].

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, we will discuss some valuable attempts towards realizing and exploring the power of dynamic energy mapping.

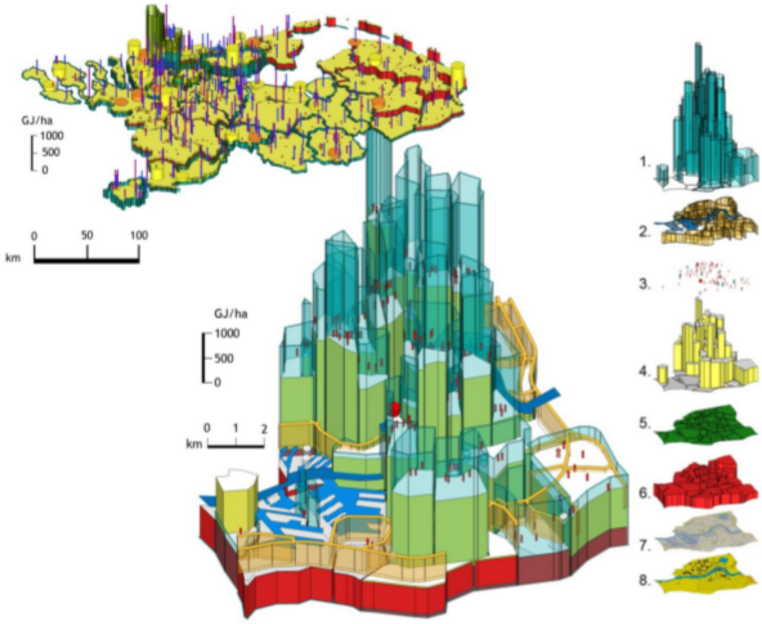


FIGURE 2.6: Heat Mapping of Netherlands and Rotterdam [11]

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 [9, 14]. 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).

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 2.7: Online Accessible GIS-database with GIS Cloud [9, 14]

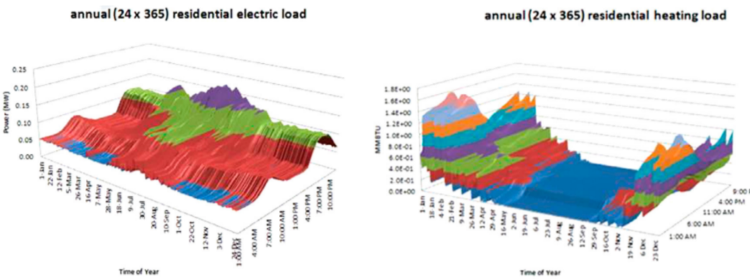


FIGURE 2.8: Heating Load and Electricity Load for Residencial Building [9]

2.2.2 Energy Mapping to Identify Opportunities for Future Networks Project

Another instance of energy demand dynamic map with high spatial resolution was found in the project "Energy Mapping to Identify Opportunities for Future Networks" [31]. 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 [31].

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" [32].

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 [33]. 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 [34].

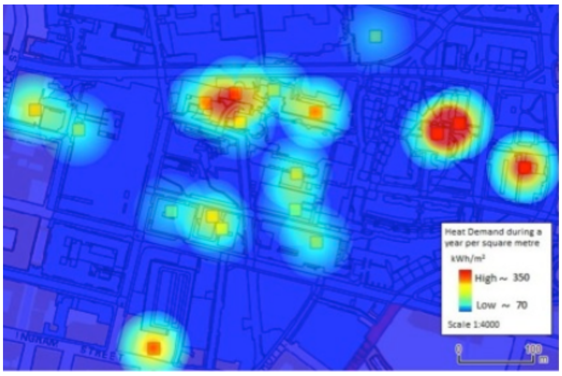


FIGURE 2.9: Campus Level Heat Demand Density Map [33]

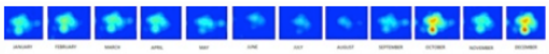


FIGURE 2.10: Campus Level Monthly Heat Demand Map in Small Multiples[33]

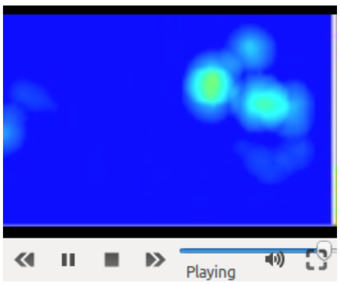


FIGURE 2.11: Campus Level Monthly Heat Demand Map in Animation[33]

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 [35].

City level map does not contain temporal mapping analysis and is left out from the case study [36].

Chapter 3

Building from Previous Work

Looking back at the static energy mapping instances, the energy demand and supply depicted on the map are mainly average, peak or total values. With these information alone, the time-dependent feature of energy demand and supply is missing from the coversation.

(add more)

As is mentioned in the introduction, a dynamic energy map has four major functions: 1) holding, 2) visualizing and 3) analyzing community level high spatial-temporal resolution energy demand and supply data 4) connection to simulation engine for iterative performance analysis.

In the initial instance of Dynamic Energy Map by Baird et al. [9], function 1) of holding spatial-temporal (although with low temporal resolution) energy data 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". The further improvement of the current project is to make the geo-database hold more high resolution energy data, meaning the 8760 hourly energy data should be contained in the dynamic energy map.

Function 4) of connecting to building simulation data is also realized by importing simulation result csv files to the geo-database (although with low temporal resolution).

For function 3), the feasibility analysis of a district energy system is performed in a stand-alone excel tool [9] but it is possible that the analysis result could be linked in to the geo-database as the energy simulation result.

For function 2), 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 geo-database but not the hourly energy consumption information. 2) 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. The authors 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.

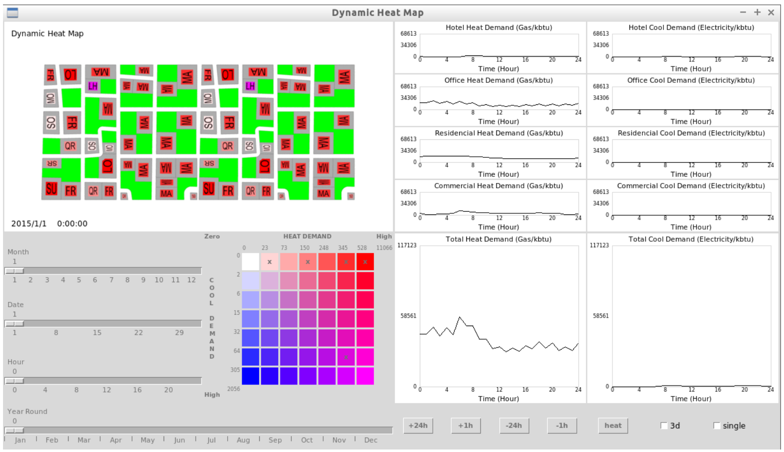


FIGURE 3.1: Unified Dynamic Energy Map Display System

Chapter 4

Methodology

4.1 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 [14] as a prototype. The land use of the conceptual urban environment is created based on extracted topological patterns from this redevelopment projec.

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

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

The inputs to the dynamic energy map include the hourly energy consumption data and the urban environment layout. For the conceptual setting, the energy data is retrieved from the simulation of DOE Benchmark buildings of new construction which comply with ASHRAE 90.1-2004 Standard [2].

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

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

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

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

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

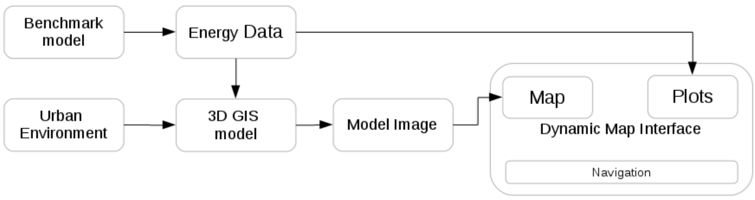


FIGURE 4.1: General Work Flow

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

4.2 Input

4.2.1 Benchmark Models and Energy Data

In the Lower Hill District project, the DOE benchmark buildings were substituted for buildings in the community model in the district system feasibility analysis. This approach allows for a fast initial assessment of the district system [9].

Following the same approach, the energy profile used in the current study is retrieved from simulation results of commercial building benchmark buildings developed by U.S. Department of Energy (DOE) [2]. There are 16 building types in the benchmark models (Figure 4.1). The building types involved in the current project include: Large Office (LO), Medium Office (MO), Small Office (SO), Stand-alone Retail (SR), Supermarket (SU), Quick Service Restaurant (QR), Full Service Restaurant (FR), Large Hotel (LH) and Midrise Apartment (MA). The two-letter shorthand in the parenthesis after each building type is used in the building label for the dynamic map display. The general information for the benchmark buildings are shown in Table 4.1:

Building Type Name	Shorthand	Floor Area (ft2)	Number of Floors
Large Office	LO	498,588	12
Medium Office	MO	53,628	3
Small Office	SO	5,500	1
Warehouse	WH	52,045	1
Stand-alone Retail	SR	24,962	1
Strip Mall	SM	22,500	1
Primary School	PS	73,960	1
Secondary School	SS	210,887	2
Supermarket	SU	45,000	1
Quick Service Restaurant	QR	2,500	1
Full Service Restaurant	FR	5,500	1
Hospital	HO	241,351	5
Outpatient Health Care	OP	40,946	3
Small Hotel	SH	43,200	4
Large Hotel	LH	122,120	6
Midrise Apartment	MA	33,740	4

Table 4.1: DOE Benchmark Building General Information [2]

The benchmark buildings comply with the ASHRAE Standard 90.1-2004. The HVAC system types are shown in Table 4.2. The major heating systems of the benchmark buildings are furnace and boilers, except that the small hotel and the warehouse has individual space heaters other than furnaces. The cooling systems are chillers for Large

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

Table 4.2: Benchmark Building HVAC System

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

4.2.1.1 Input for Identifing Energy Recovery Opportunities

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

The heat rejection in cooling mode happens during the condensing process when the high temperature refrigerant gas condenses with one of the following heat rejection forms [37]:

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

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

$$THR = RE * f \text{ [37]} \tag{4.1}$$

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

To help users identify energy recovery opportunities, the energy information needed to retrieve include: space heating energy demand and space cooling energy demand. The space cooling demand (RE in Equation 4.1) is an indicator for heat rejection that could be recovered and shared within a single building or a building group.

From Table 4.4, Large Hotel, Medium Office, Midrise Apartment, OutPatient Healthcare, Small Hotel and Stand-alone Retail use both electricity and natural gas for space heating, the rest of the building types uses only natural gas for space heating. We thus use the EnergyPlus simulation output parameters “heating:electricity” and “heating:gas” to represent the space heating demand of reference buildings.

TABLE 4.4: Annual Total Heating Demand by Fuel Type [2]

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

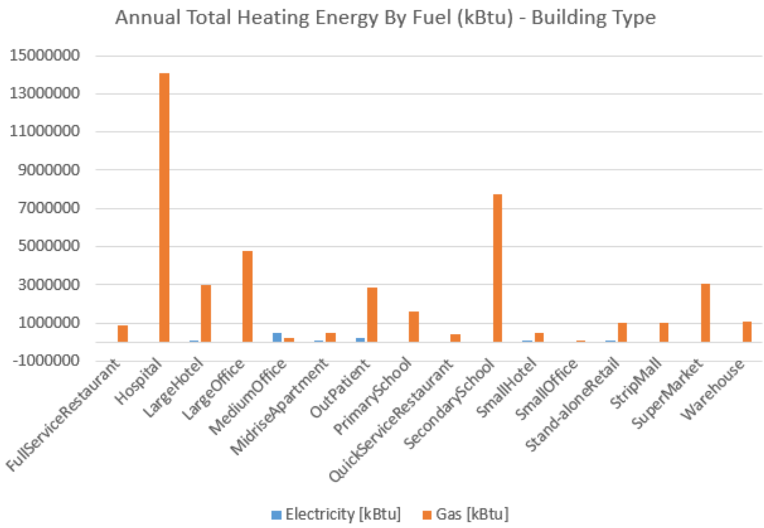


FIGURE 4.2: Heating Fuel

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 [37], the heat recovery potential will be calculated with

$f = 1.15$ for Large Office and Hospital, and $f = 1.25$ for the remaining building types:

$$\text{Heat Recovery Potential} = \text{cooling:electricity} \times f \tag{4.2}$$

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

4.2.1.2 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 [9] 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 4.2.1.1 . It contains the space heating demand and the service hot water demand. From the summary files of benchmark models, the fuel used for providing service hot water is natural gas for all building types (Table 4.5)

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

TABLE 4.5: Service Hot Water by Fuel Type

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

4.2.2 Simulation Data Analysis of the benchmark models

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

The energy output retrieved from EnergyPlus include "Heating:Gas", "Heating:Electricity", "Cooling:Electricity", "Water Heater:WaterSystems:Gas" and "Electricity:Facility". This section will include some basic aggregated analysis of the data distribution. The meaning of each output variable is listed in Table 4.6:

TABLE 4.6: Table of EnergyPlus output and their meaning

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

4.2.2.1 Single Output

By analysing the EnergyPlus [38] simulation result of the output above, we anticipate to gain a basic understanding of the energy profile data distribution involved in the current project. We would also want to use this as a basis to compare with the additional analysis one can performed in a dynamic energy map in the following sections.

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

Hourly gas heating demand of the benchmark buildings range from 0 to 14000 kBtu. The majority (75%) of all hourly consumption are below 2000 kBtu. All building types have a large amount of outliers above the 75% quartile. This indicates gas heating demand of all building types are severely right skewed. Hospital has the highest median gas heating demand of about 1100 kBtu. Outpatient Health Care has the second larges hourly gas heating demand. In terms of peak demand, Secondary School and Large Office have the highest peak hourly gas heating demand (Figure 4.3).

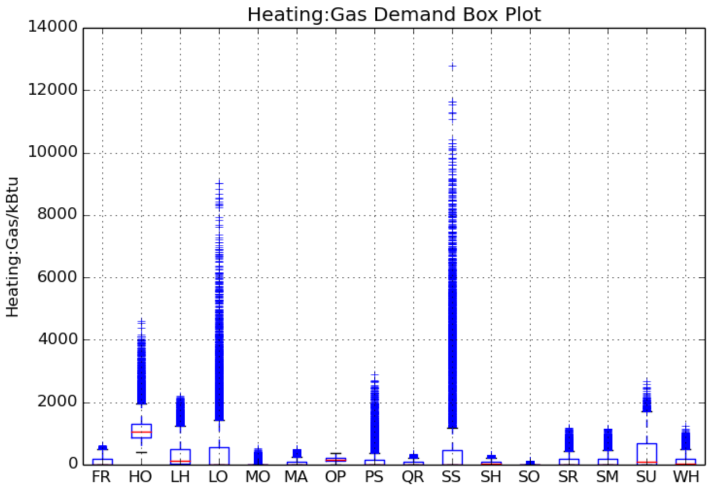


Figure 4.3: Heating:Gas Box Plot

Hourly hot water demand of the benchmark buildings range from 0 to 2500 kBtu, about 1/6 of the range of space heating gas demand. Most buildings have median hot water hourly demand below 100 kBtu, except that the median hot water demand of Large Hotel is around 700 kBtu. From Table 4.5, we can see that Stand-alone Retail, Strip Mall and Warehouse has zero demand for service hot water. Large Hotel also have a large amount of outliers above the 75% quartile. This indicates gas hot water demand of the Large Hotel is severely right skewed. Hospital has the second largest median gas hot water demand of about 100 kBtu. Large Hotel also stands out in peak demand. (Figure 4.4).

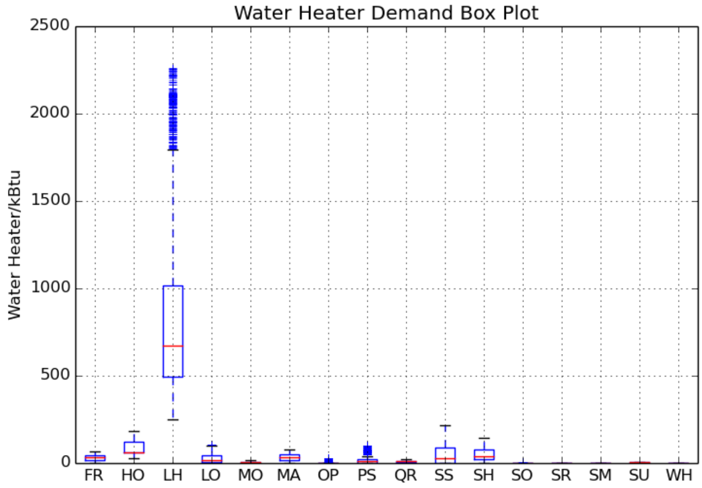


FIGURE 4.4: Water Heater:WaterSystem:Gas Box Plot

From Table 4.4, only Large Hotel, Medium Office, Midrise Apartment, OutPatient Healthcare, Small Hotel and Stand-alone Retail use electricity besides natural gas for space heating. Hourly electricity heating demand of these buildings range from 0 to 1000 kBtu. All of them has nearly zero median electricity heating demand and a large amount of outliers above (except for Midrise Apartment) the 75% quartile. This indicates electricity heating demand of all the five building types are severely right skewed. Medium Office has the highest hourly electricity heating peak demand and Outpatient Healthcare has the second largest hourly electricity heating peak demand (Figure 4.5).

Hourly cooling demand benchmark building types range from 0 to 3000 kBtu, which is about 20% of that of the peak gas heating demand. The hospital has the largest median cooling demand of about 1500 kBtu. Large Hotel has the second largest median cooling demand. Both Hospitals and Large Hotels do not have outliers, indicating their hourly cooling demand distributions are less skewed. On the contrary, all other building types have a large amount of outliers above the 75% quartile, indicating a severe right skew for their hourly cooling demand distribution. There are four building types with non-zero median hourly cooling demand: Hospital, Large Hotel, Outpatient Health Care and Small Hotel. This means they need space cooling for at least 50% of the year. The constant cooling demand creates the opportunities for energy recovery of cooling

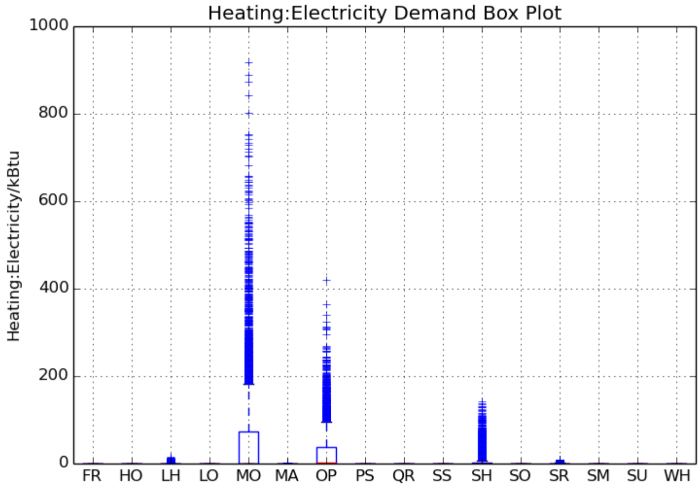


FIGURE 4.5: Heating:Electricity Box Plot

induced reject heat. The building types with zero median hourly cooling demand then require cooling only in the cooling season. In terms of hourly cooling peak demand, the Secondary School has the highest peak demand of about 2700kBtu and Hospital has the second largest peak demand(Figure 4.6).

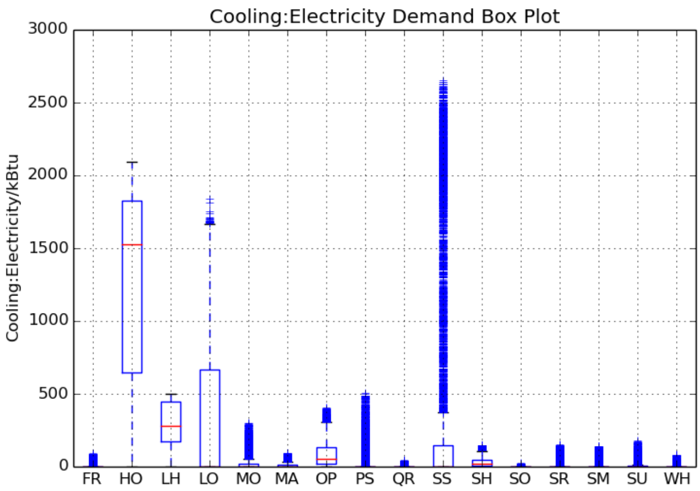


FIGURE 4.6: Cooling:Electricity Box Plot

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

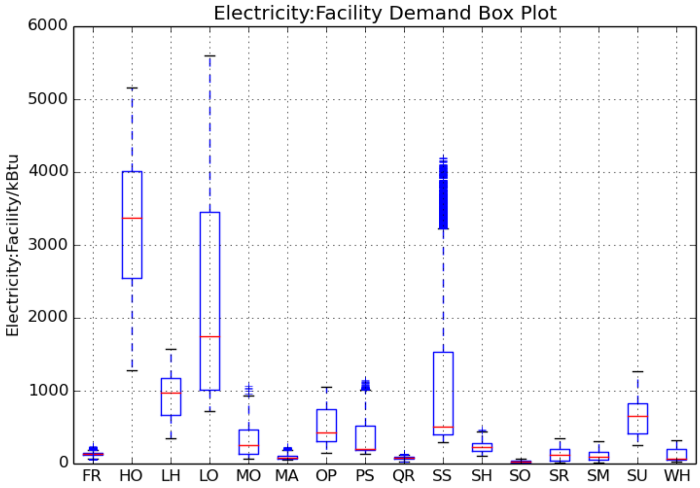
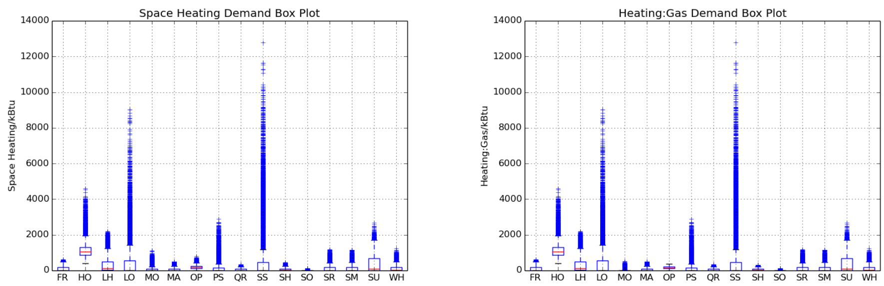


FIGURE 4.7: Electricity:Facility Box Plot

4.2.2.2 Space Heating Demand vs. Space Cooling Demand

Hourly space heating demand of the benchmark buildings mainly closely follows the distribution of gas heating demand, with minor demand increase in Medium Office and Outpatient Health Care (Figure 4.9a).

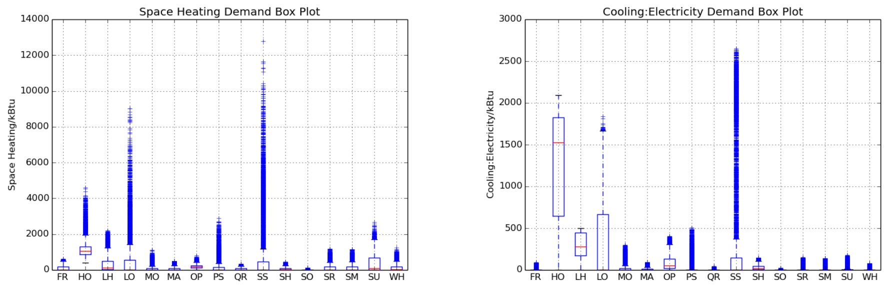


(A) Space Heating Demand Box Plot (B) Heating:Gas Box Plot

FIGURE 4.8: Comparing Heating:Gas and Space Heating

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

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

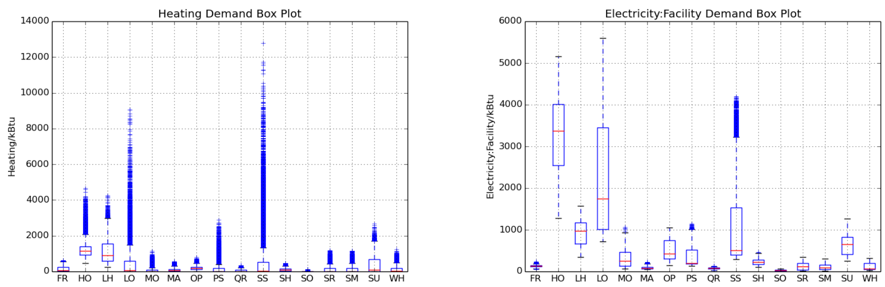


(A) Space Heating Demand Box Plot (B) Cooling:Electricity Box Plot

FIGURE 4.9: Comparing Space Heating and Space Cooling Demand

4.2.2.3 Heating Demand vs. Electricity Demand

Comparing the heat and power demand of each benchmark building type with the "heat to power ratio"(HTPR), one of the important parameters of a CHP plant. Depending on the prime mover types, a CHP plant can produce 0.6 to 10 unit of waste heat for one unit of electricity generation [39]. From Figure 4.11, we can see the range of HTPR is from 0 to 25 and the median of HTPR are all below 1. The building types with a high median HTPR include Large Hotel, Midrise Appartment, Outpatient Health Care and First Service Restaurant. Increase the number of buildings with high HTPR ratio is helpful in more fully reuse of the waste heat from power generation. In addiction, the large range of Heat to Power ratio also indicates the necessity of heat storage equipment.



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

FIGURE 4.10: Comparing Heating and Electricity Demand

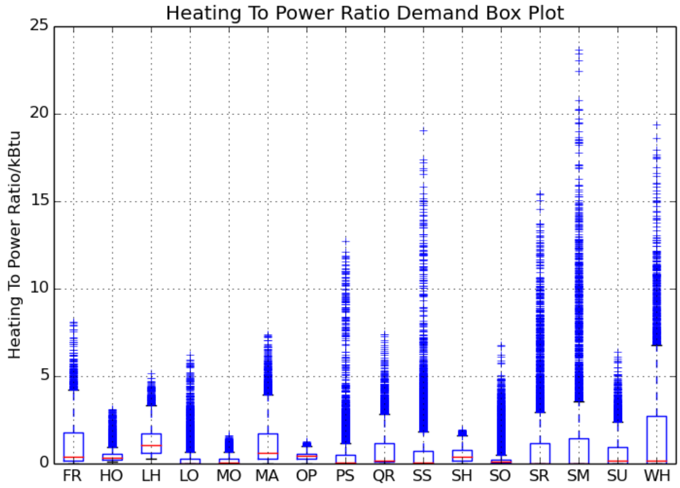


FIGURE 4.11: Heat to Power Ratio Box Plot

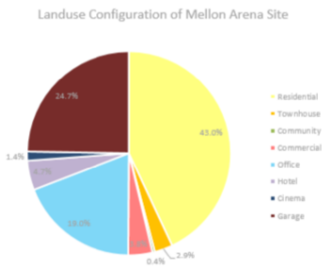
4.2.3 3D GIS Model Geometry

The conceptual community model is constructed in CityEngine [13]. CityEngine is a software developed by Esri [40]. It can aggregate geographic information into buildings and is capable of smoothly transition models to ArcGIS[41], one of the widely applied tools for Geo-referenced data presentation and analysis. Buildings in CityEngine is defined with "rules" using CGA (Computer Generated Architecture) shape grammar that is unique to CityEngine. The rule-based modeling of urban environment enables fast construction and easy adjustability of urban density, skyline and terrain control. It also enables easy aggregation of Energy profile data into 3D urban environment models, which is difficult to do in the current ArcGIS, the technical details will be explained in Appendix A.

Although the urban environment in this study is a conceptual setting, we still want it to reflect the topological and density pattern in a real urban environment. To construct the model, we first extracted the topological pattern from an existing urban design project, the Mellon Arena Project [9] (Figure 4.12a. There are eight building types in the project: Residential (43%), Town House (2.9%), Community Center (0.4%), Commercial (3.8%), Office (19%), Hotel (4.7%), Cinema (1.4%) and Garage (24.7%).

The 16 building types in DOE commercial benchmark models do not perfectly correspond to those in the Mellon Arena Site. In order to adapt the topological pattern of

(A) Mellon Arena Project Site Plan View



(B) Mellon Arena Site Land use Configuration

the Mellon Arena Project, a mapping (function) from building types of Mellon Arena Site to building types of DOE models is created as is shown in Table 4.7.

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

TABLE 4.7: Mapping of Mellon Arena to Building Types of DOE benchmark model

The four major building sectors involved in the current project are residential, commercial, office and hotel. Their topological pattern is represented in Figure 4.13. The conceptual model construction follows the building type topological pattern and the urban density as the Lower Hill District Project (Figure 4.14)

After the land use is assigned (Figure 4.14), one rule file is applied to all the building lots and generates building geometries by extruding the building lot (with an offset to the interior) according to the number of floors of the benchmark buildings. We intend to make the building geometry simple in order to highlight the color of each building that encodes its energy demand.

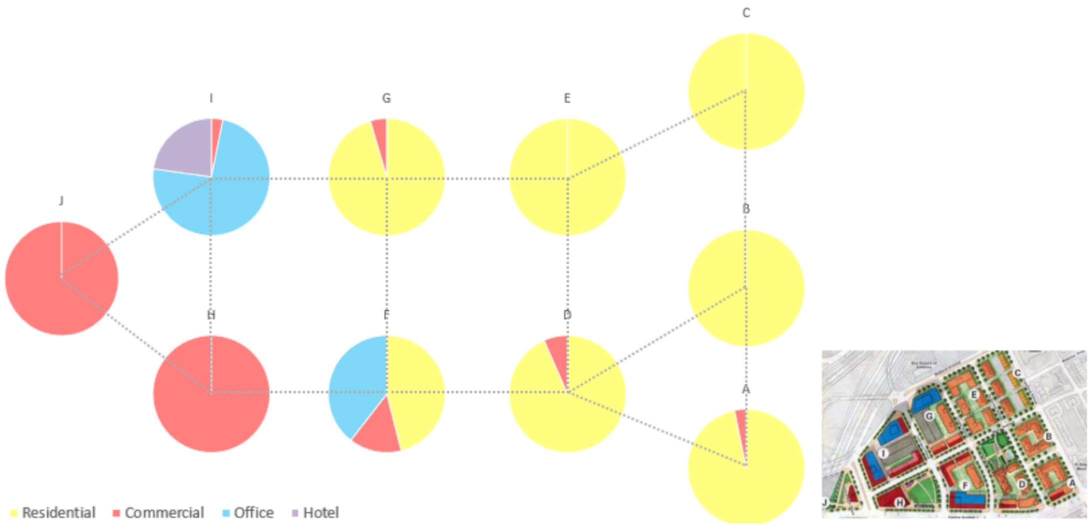


FIGURE 4.13: Building Type Topological Pattern, Mellon Arena

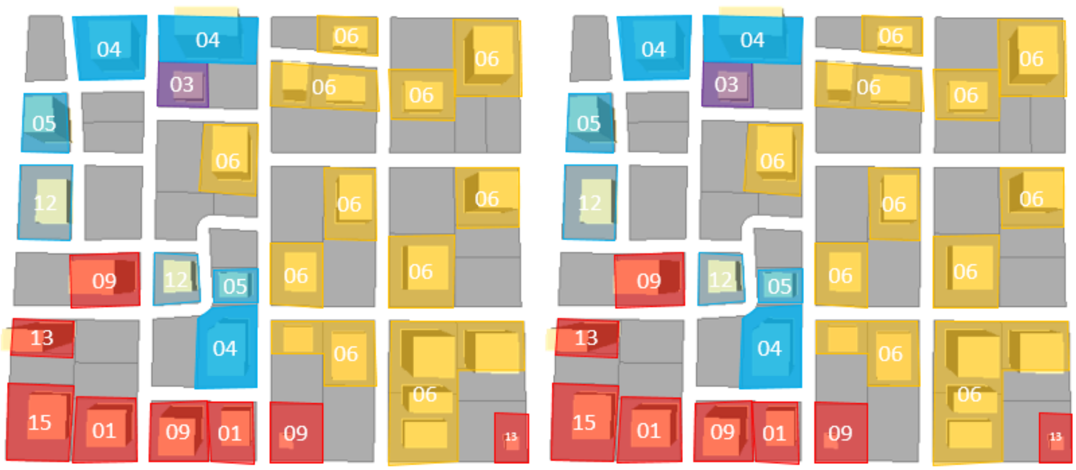


FIGURE 4.14: Site Plan of Conceptual Model
(01: Full Service Restaurant, 03: Large Hotel, 04: Large Office, 05: Medium Office, 06: Midrise Apartment, 09: Quick Service Restaurant, 12: Small Office, 13: Stand-alone Retail, 15: Super Market)

4.2.4 Aggregating Hourly Energy Data to 3D GIS Model

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

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

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

The second approach has the advantage of 1) ready-to-use data classification method and map symbol templates that facilitates choropleth map design 2) the "time-slider" function for creating a time-wise navigation and animated map. Figure 4.15 shows the interface slider and the dynamic map of heating energy demand for the conceptual model using ArcGIS. There are several problems of this approach: 1) its high requirement of computational power makes it infeasible to model or view on a typical PC. The authors only succeeded in importing the hourly energy profile data when using point features to represent building geometry. Even for the relatively simple 3D models in the current study, a relatively higher performance machine (Dell Precision T1600 Quad Core Intel Xeon, 3.10GHz RAM - 16GB was used) was used in importing the data, the authors only suceeded in importing one month of data, never for one year. This technical issue makes it impossible to using the current ArcGIS platform to implement high temporal resolution dynamic maps without either truncating time range or reducing the complexity for building geometry representation. 2) The time dimension only exist inside the map file. This means even one produced a dynamic energy map, one cannot share it without packing all related files and send to others. This requires the viewer end to have the same high performance computer. Although the animated map can be exported, the output animation contains neither any form of temporal label nor the control of playback. Without time legend, when and for how long the dynamic changes happen are not shown. 3) For 3D GIS model, it does not contain a proper function to extract single frames of map images, making it impossible to implement exterior interface that deals with 3D maps images.

The first approach, on the contrary, provides more flexibility but also requires much user-end work including: pre-processing of energy profile data, implementing data classification method and the bivariate color ramp. An interface is also needed for visualising the image sequence.

Due to limited time, the experimented GIS software are only restricted to ArcGIS and CityEngine. There could be better alternatives to achieve a dynamic map with more

Figure 4.15: ArcGIS Time Slider for Temperal Data Display

elegance. Find a better alternative software to implement a dynamic map could be part of the work of the next stage of the project.

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 rest at. The detailed rule file is included in Appendix B.

The general process is to find a base map if it is a real site or generate a random urban environment layout if it is a conceptual setting. Add attributes of "landuse" and "time" to the building lot. Then write a rule file with energy consumption data (or the color representation of each energy consumption data) for each building type held in string lists in the rule file and then apply the rule files to the building lot. Finally set the attribute of "landuse" and "time" in the rule file to be driven by the value of the object attribute "landuse" and "time". The "time" attribute is 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 blocks are set to 10, all the 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

A.2.1 Create a Urban Environment Layout

If one is working with a real project, an OSM Map [42] 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.

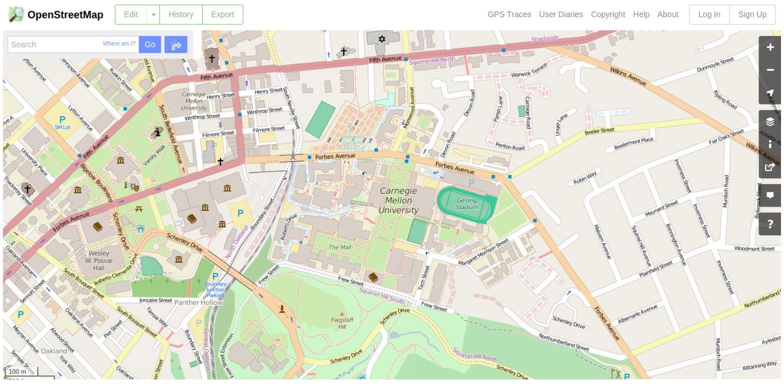


Figure A.1: CMU OSM Map [42]

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

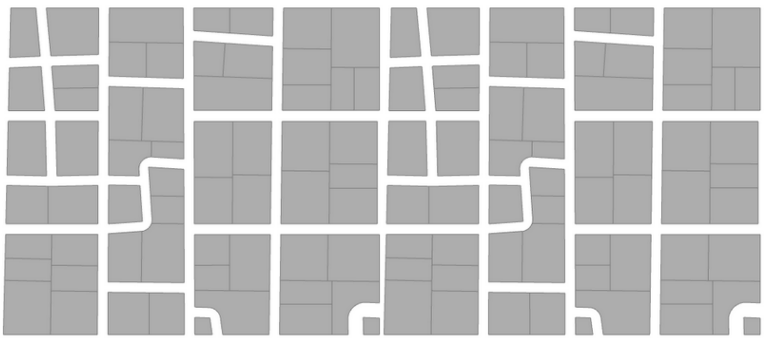


Figure A.2: Conceptual City Generated with CityEngine

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 we would like it to be integer but there is no integer types in object attribute) ranges from 0 to 8760 (not 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">"
```

A.2.3 Importing Base Map (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 [43] 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).

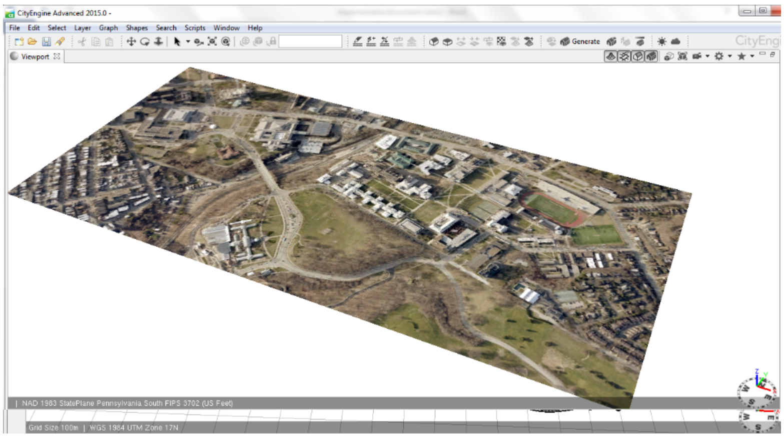


Figure A.3: Example of Geo-referenced Image in CityEngine

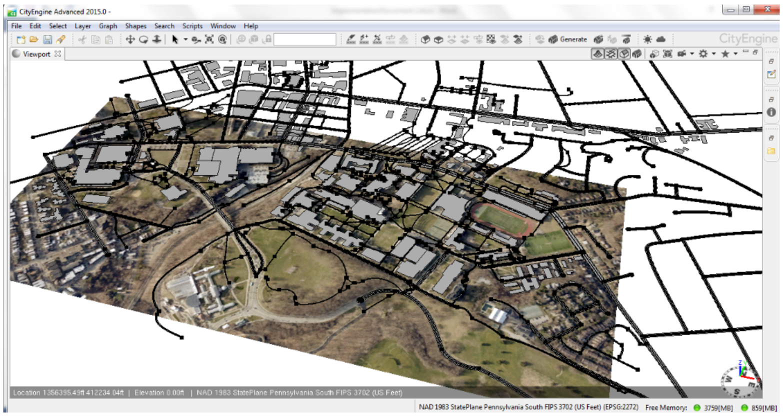


Figure A.4: Geo-tif with OSM Map

A.2.4 Writing Rule File for Building Generation

We 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, we 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. We used the continues red-to-blue color ramp in the stand-alone CityEngine based Dynamic Energy Map implementation.

A.2.5 Deciding Data Encoding

The first approach for representing energy information with color is to encode it with a graduated color symbol from red to blue, with red indicating low heating demand and blue indicating high heating demand. 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 A.1).

$$\frac{E_{current} - E_{max}}{E_{max}} \tag{A.1}$$

$E_{current}$ is the energy consumption for the current time spot, 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 A.5).

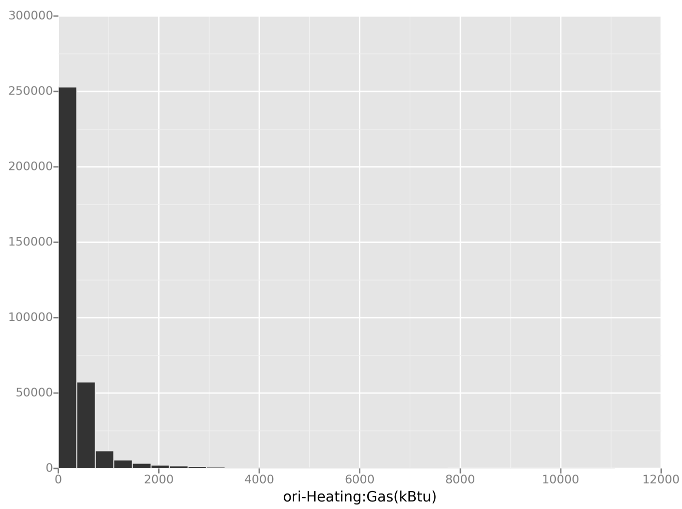


FIGURE A.5: A histogram of hourly energy consumption per building, for the 68 buildings in the community

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 has used discovered that the annual total energy consumption of the 6500 buildings in Cambridge MA area follows a "log-normal" distribution [44]. By applying similar log scaling for the hourly heating energy data of the community, we found that the hourly heating energy distribution also roughly follows a normal distribution (Figure A.6). We apply log scaling to make the distribution less skewed and calculate the color from energy ($E_{current}$) as follows:

$$\frac{\ln(E_{current}) - \ln(E_{max})}{\ln(E_{max})} \tag{A.2}$$

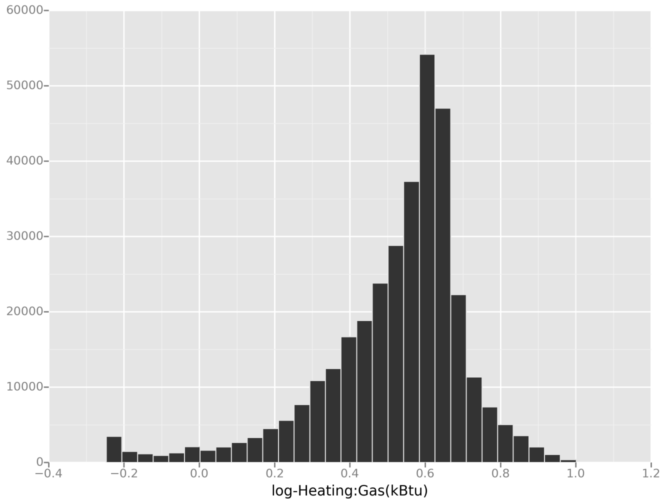


FIGURE A.6: Heating Demand of Conceptual City

Figure A.7 is one snapshot of the conceptual urban environment model under the log scaled calculation method in Equation A.2.

A.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. 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 each 8760 rule files need to be generated 2) the "slider-bar" feature associated with the object attribute will not be available if implemented this way.

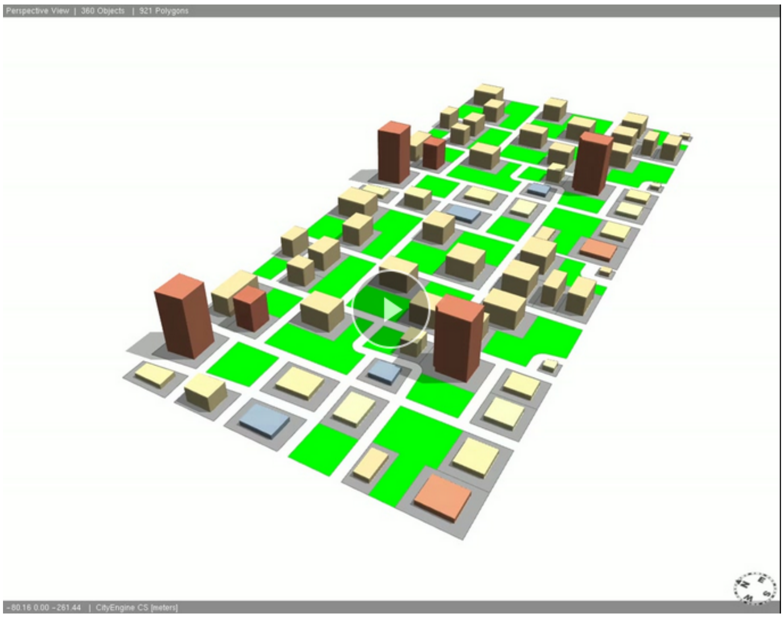


FIGURE A.7: Animated demonstration of the log-scaled dynamic energy heating demand map
Click here to go to the animation link.

We want to use 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" [45].

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.8 and the community example is depicted in (Add figure here !!!)

A.2.7 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 lot attribute function. Since the dynamic map operates on setting the building lot object attribute, when shared with publishing "web scene", the temporal 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,

Figure A.8: Slider in Campus Example

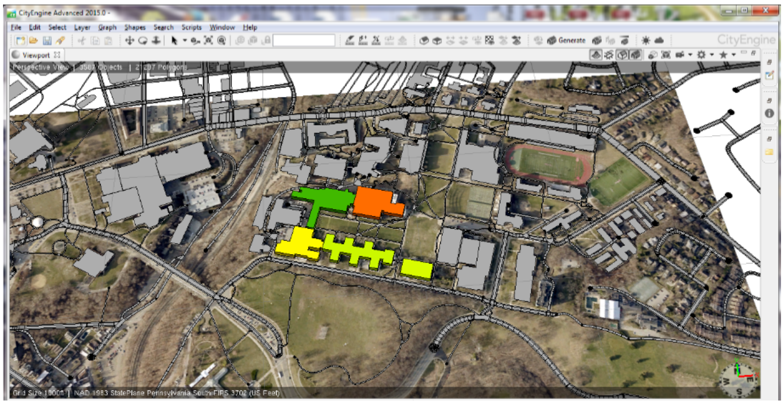
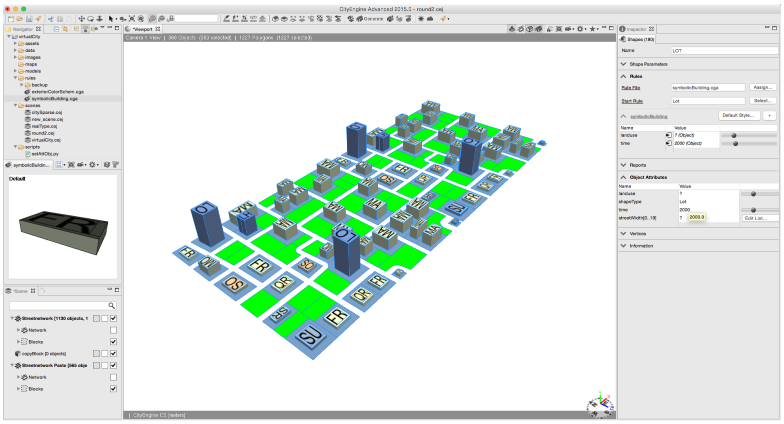


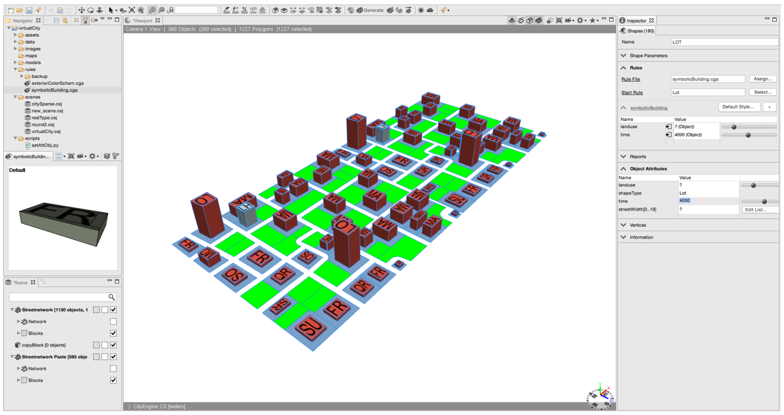
Figure A.9: Finished Campus Example

all functions of the dynamic energy map one implemented inside CityEngine can be retained. The drawback is that it requires the views of the dynamic energy map 1) having CityEngine software, which is not free 2) having 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 will be explained in a separate section X. Here only the procedure is presented.



(A) Conceptual Community Setting Slider Winter



(B) Conceptual Community Setting Slider Summer

Appendix B

Rule File for Implementing Dynamic Energy Map in Stand-alone 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;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;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;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;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;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;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;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;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;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;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;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;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;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 [46].

The common procedure is 1) to export CityEngine models as either gdb file or as collada files and import the model to ArcScene 2) preprocess the energy profile and write it to a csv file containing hourly energy consumption for all building types in the community. 3) join the table to the 3D features 4) enable time in the joint layer and 5) configurate 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. Method a), the advantage 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 one collada file.

2) Produce 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 01:00:00,0.005637635323098419,418.195121797510 4,1
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 06:00:00,0.020720590790235208,474.364195109204 2,1
2015/01/01 07:00:00,0.04091094860228904,442.2806012872507,1
2015/01/01 08:00:00,0.03864358951445788,393.0139292137104 7,1
2015/01/01 09:00:00,0.005390469085569592,372.5335463107161 3,1
2015/01/01 10:00:00,0.0,368.9864473708827 3,1
2015/01/01 11:00:00,0.019739094999106255,335.075727932713 3,1
2015/01/01 12:00:00,0.0,300.602512250075 4,1
2015/01/01 13:00:00,0.0,266.376754344438 6,1
2015/01/01 14:00:00,0.0,254.7307416325817 8,1
2015/01/01 15:00:00,0.0,263.066443102175,1
2015/01/01 16:00:00,0.0,271.2444048457191 5,1
2015/01/01 17:00:00,0.03276377815582866,263.358365384641 2,1
2015/01/01 18:00:00,0.0,261.1607973568062 6,1
2015/01/01 19:00:00,0.0,254.1421145786482 6,1
2015/01/01 20:00:00,0.0,244.3822951406292 2,1
2015/01/01 21:00:00,0.0,239.796377765589 2,1
2015/01/01 22:00:00,0.0,263.093467676049 5,1
```

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 type "date".

4) Create the centroid for each building geometry footprint As is mentioned in Section 4.2.4, 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 authors 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 aggregation 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.

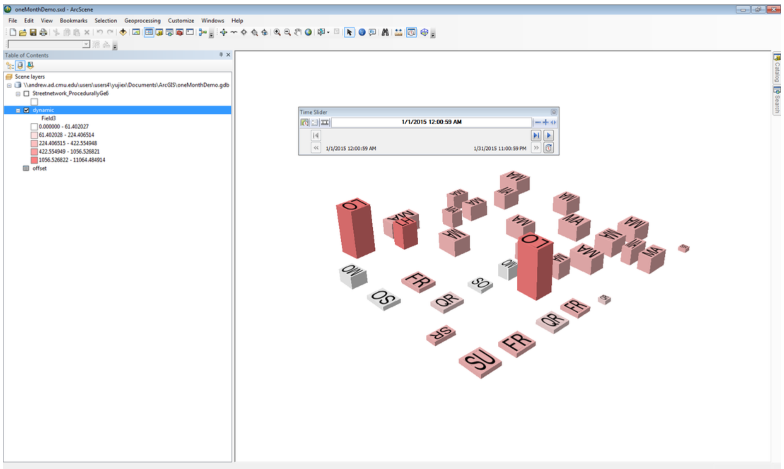


FIGURE C.2: Screen shot of a dynamic energy map in ArcGIS, the legend on the left shows the hourly gas heating energy demand

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