Master's Thesis of Dept. of Environmental Planning

A Study of the Relationship between Urban Density, Land Use and Embodied Energy in Urban Environment

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Abstract

It is in urgent need to investigate the relationship between urban form and embodied energy to establish more holistic analysis of urban energy consumption and to make more informed decisions about urban planning and development. This study explores how important elements of urban form, urban density and land use, affect embodied energy. The main research questions of the thesis are: 1) How does urban density affect embodied energy intensity? 2) How does land use influence on embodied energy intensity? 3) How urban density, land use and other geometry measure jointly influence embodied energy intensity? and 4) How can the experiment results contribute to make comprehensive strategy to reduce urban energy consumption? To answer the main research questions, this thesis newly develops the model to estimate embodied energy and then applied it to two types of simulation experiments, hypothetical environment and real urban environment. As a result, regarding the first research question, the study supports the judgement that some preceding studies suggested that high density urban environments are advantageous in terms of embodied energy. However, the purpose of this thesis is not just to reveal that high-density development benefits in respect of embodied energy. The floor area ratio and the coverage ratio used as the most representative regulatory tools in urban planning (Zoning system) were selected as variables for urban density, and the relationship each variable has with embodied energy intensity and the effective range for reducing embodied energy intensity were discussed. For the second research question, the hypothetical environment experiment confirmed that land use had an effect on embodied energy and quantitatively assessed the impact of land use on embodied energy intensity. However, experiments with the real urban environment did not find the evidences that land use variables had significant effects on embodied energy intensity, except for the industrial land use ratio. Regarding the third research question, a multivariate linear regression analysis is conducted to determine the relationship and influence of the selected variables using both the Ordinary Least Squares method and the Geographically Weighted Regression method to consider spatial autocorrelation. The relative importance of the variable was found to be the largest floor−to−area ratio and the smallest industrial land use ratio. With regard to the fourth research question, the findings of this thesis suggest that three factors of energy consumption in the urban environment; transport energy, building operational energy, and embodied energy should be considered in a balanced manner.

Keyword : Embodied Energy, Urban Density, Land Use, Urban Form, Sustainable Development, Life Cycle Assessment
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Chapter 1. Introduction

1.1. Study Background

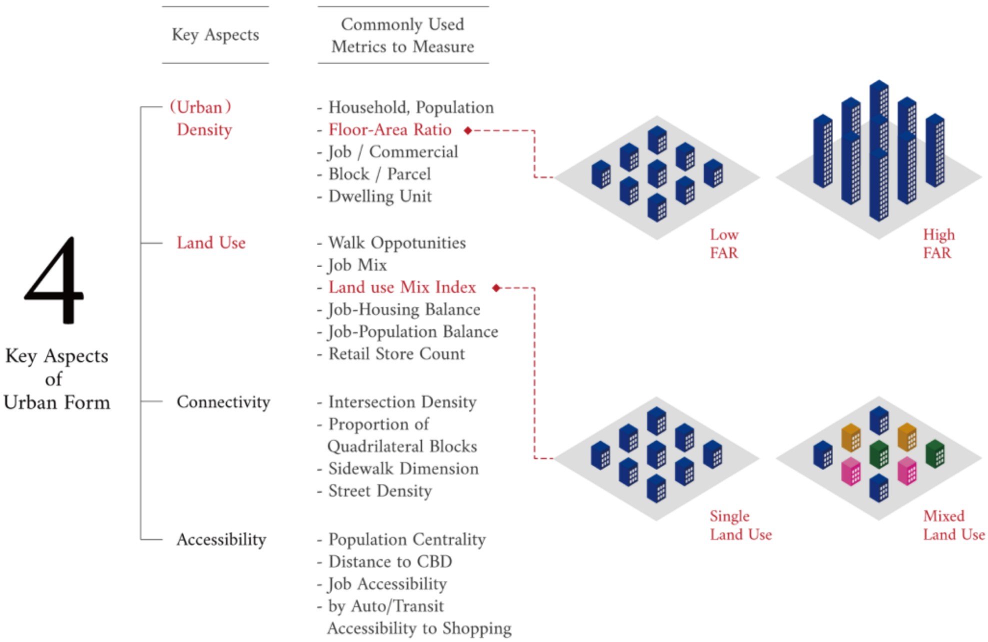
There has been a growing recognition of the significant contribution of urban areas to energy consumption and GHG emissions. According to The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014), urban areas account for 71~76% of CO_2 emissions from global final energy use and between 67~76% of global energy use. Furthermore, urban areas are expected to be rapidly expand. By 2050, the global urban population is expected to increase by between 2.5 to 3 billion, corresponding to 64% to 69% of the world population (IPCC, 2014). Therefore, it is in urgent need to find energy efficient solutions and minimize energy consumption in urban environments.

Troy et al. (2003) classified the principal components of energy consumption in the urban environment into three broad types: 1) Transport energy used by private and public vehicles, 2) Operational energy consumed by buildings, and 3) Embodied energy of the built form. Embodied energy of the built form, which has been largely ignored so far, represents all of the energy consumed over its life cycle including in material extraction, manufacturing, transportation, construction, and disposal. The typical effort drawing attentions in urban development policies to reduce urban energy consumption is to reduce operational energy consumed by buildings by improving building energy performance.

According to Quan (2016), those building-level efforts are scaled up to the neighborhood and even city scale, an understanding of the relationship between urban form and energy consumption becomes much more important and necessary. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) reported that urban form significantly affects direct and indirect GHG emissions, and are strongly linked to the throughput of materials and energy in a city, the wastes that it generates, and system efficiencies of a city (IPCC, 2014). According to Anderson et al. (1996), urban form is a key element of municipal planning process, and a better comprehension of the relationship between urban form, energy and the environment is significant to find strategies to achieve environmental targets.

The influence of urban form on other energy types such as transportation energy and building operation energy have been widely examined, however, there has been very rare on embodied energy (Bassett, 2013).

Figre 1.1.
Key Aspects of Urban Form (Redrawn by Auhter based on IPCC AR4 report 2014)



The urban environment consists of enormous quantities of materials and products used to construct the buildings and infrastructure and embodied energy is strongly related to the quantities of materials in the built form of the urban environment. Over the past decades, many researchers have reported that the significance of embodied energy, especially in building sector (Treloar, 1993; Junnila and Horvath, 2003; Itard and Klunder, 2007;

Sartori and Hestnes, 2007; Thormark, 2007; Huberman and Pearlmutter, 2008; Takano et al., 2015). While most studies have conducted at a microscopic level such as building or material level, there have been very little published research on investigating embodied energy at large scale.

Therefore, it is in urgent need to investigate the relationship between urban form and embodied energy to establish more holistic analysis of urban energy consumption and to make more informed decisions about urban planning and development. This thesis aims to contribute to this gap existing the current perspective by focusing two key factors of urban form, urban density and land use. As presented in Figure 1.1., these factors are classified as key aspects of urban form in IPCC AR5 report (2014). Urban planners have been mostly concerned urban density and land use, because they have been important concepts in zoning regulation to control urban built form which have greatly associated with embodied energy.

This thesis aims to investigates the relationship between important urban form factors, urban density and land use, and embodied energy by answering the research questions of whether, how and why these factors influence embodied energy of urban built form.

Chapter 2. Theoretical Background and Literature Review

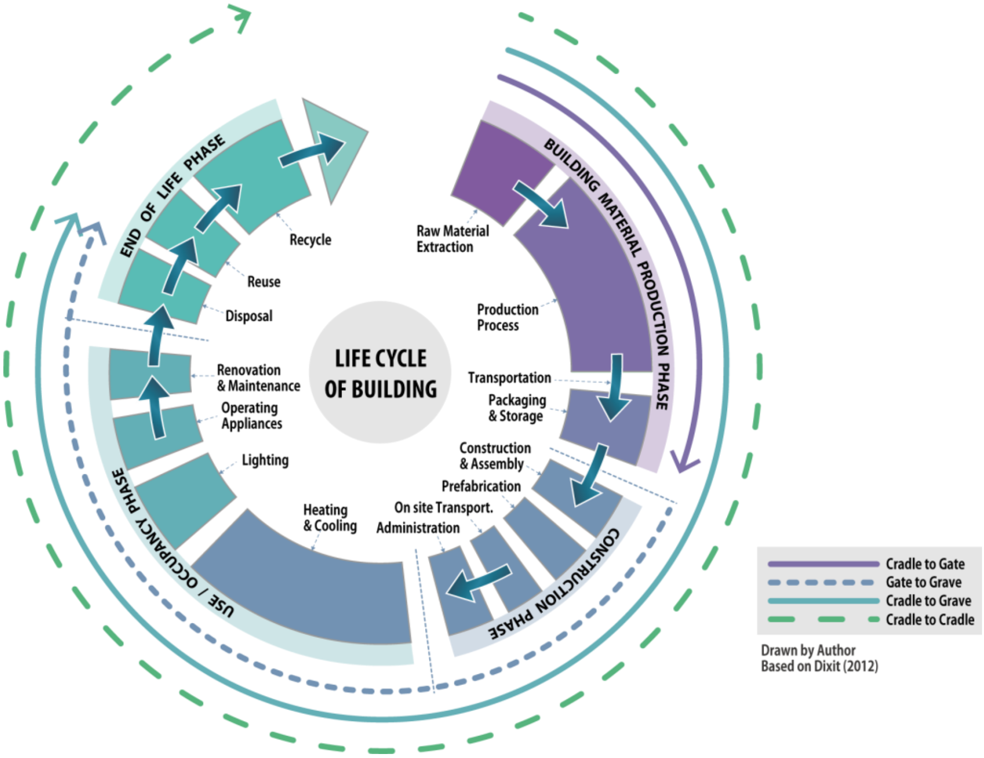
2.1. Embodied Energy in Building Sector

Traditionally, the energy consumption of buildings was only understood as operational energy which expended during the building use phase for managing inside environment such as heating and cooling, lighting and operating building appliances. Accordingly, the conservation of operational energy became the main interest to reduce the building energy consumption and there was achievement to reduce operational energy with strategies such as highly efficient appliances, advanced insulation technology, multiple-glazed windows, etc.

As illustrated in Figure 1.2., embodied energy is expended over life cycle of building including the energy required for extracting raw material, manufacturing products, transportation, construction of building, maintenance, and demolition. However, embodied energy which is the other component of life cycle energy use of building has been largely ignored so far.

While, recent researches have emphasized an issue that the increased use of energy intensive materials for reducing operational energy can lead to excessive embodied energy (TargetZero, 2012). Frey (2008) argued that, in the past, embodied energy was assumed to be relatively insignificant, accounting for no more than 10-15% of building’ s total energy. However, Gonzalez and Navarro (2006) indicated that the increased embodied energy of building materials could result in more carbon dioxide emissions problem. And there have been many studies for assessing building level embodied energy and most detailed studies have investigated single dwellings or multistory buildings in different countries.

Figure 2.1.
Life Cycle of Building -Redrawn by Auther based on Dixit (2012)



Treloar (1993) was one of the first to suggest that the embodied energy can be highly significant part of the total energy consumption of building. Junnila and Horvath (2003) conducted a comprehensive life-cycle assessment for a new high-end office building in Finland. The researchers concluded that most of energy is associated with electricity use and building material manufacturing, while construction and demolition has relatively insignificant impact.

Table 2.1.
The Share of Embodied Energy in Previous Studies

Author(s)	Year	Location	The Share of EE (%)
Itard and Klunder	2007	Netherland	30%
Sartori and Hestnes	2007	9 Countries	2-38%, 9-46%
Thormark	2007	Sweden	40-60%
Huberman and Pearlmutter	2008	Israel	60%
Plank	2008	U.K.	10%
Takano et al.	2015	Finland	46%
Koezjakov et al.	2018	Netherland	10-12%, 36-46%

Itard and Klunder (2007) examined two typical dwellings in Netherland and concluded that embodied energy can amount to 30% of total energy use. Sartori and Hestnes (2007) performed a literature survey on buildings' life cycle energy use for 60 cases, both residential and non-residential units, from nine countries. The researchers concluded that the embodied energy could account for 2-38% for conventional building, but this variation could be changed as 9-46% for low-energy buildings. Thormark (2007) examined three Swedish residential low energy dwelling. The researcher concluded that embodied energy accounted for 40-60% of the total life cycle energy and tackled the prevailing idea that operational energy accounts for the main part of energy. Huberman and Pearlmutter (2008) investigated buildings in the Negev desert region of southern Israel and concluded the embodied energy of the building accounts for approximately 60% of overall life-cycle energy use. On the other hand, Plank (2008) analyzed a heating dominated region in U.K. The researcher concluded that the embodied energy can explain only 10% of the total energy use.

Recently, Takano et al. (2015) investigated the life cycle energy of four residential building types (detached house, row house, townhouse and apartment block). The researchers concluded that especially in low-energy buildings, embodied energy contributes up to 46% of total energy use. Koezjakov et al. (2018) analyzed the relationship between heat demand and embodied energy use with Dutch residential building. The researchers concluded that the embodied energy use in standard homes accounts for approximately 10–12% of total energy use, while 36–46% in energy efficient homes.

2.2. Urban Form and Embodied Energy

How can we define urban form? And what are the key aspects of urban form? According to Lynch (1981) and Handy (1996), urban form is defined as the patterns and spatial arrangements of land use, and urban design elements, including the physical urban extent, layout of streets and buildings, as well as the internal configuration of settlements. IPCC' s Fifth Assessment Report (AR5) proposed that urban form can be characterized using four key aspects of urban form: 1) urban density, 2) land use, 3) connectivity, and 4) accessibility (Figure 1.1.). Of the four key aspects, 'Urban Density' and 'Land Use' are most relevant to embodied energy which is greatly associated with the built form.

With the increased interest in embodied energy, many researchers have investigated the embodied energy of building. However, as Bassett (2013) reported, lots of different calculation techniques are developed to estimate embodied energy for predominantly single or small numbers of buildings, while there were still less about at large scales. There have been very few of studies to evaluate the impact of urban form on embodied energy. There have been few studies on urban density and embodied energy in different location.

Norman et al (2006) took a comprehensive study to examine life–cycle energy by comparing typical high and low–density residential areas of Toronto. Researchers concluded that embodied energy of low–density residential area were approximately 2.5 times higher than high density on per capita basis, while 1.25 times higher on a unit area basis.

Waldron et al. (2013) conducted the theoretical study to compare high–rise, mid–rise, and low–rise urban layout in residential and commercial use. The researchers concluded that there was no significant difference in terms of embodied energy, while the results were dependent on use of building.

Nichols and Kocklelman (2014) analyzed the four different neigborhoods in Austin, Texas to assess how built environment variations influence various sources of energy. The researchers concluded that the more suburban neighborhoods, with mostly detached single-family homes consumed up to 320% more embodied energy than densely developed neighborhood with low-rise apartment and duplexes.

Guhathakurta and Williams (2015) investigated the impact of urban form on energy demands for building, infrastructure, and transport by comparing in central city and suburban neighborhoods in Phoenix. The researchers concluded that high density areas are the most energy efficient neighborhoods regardless of location in central city or suburbs and, in terms of embodied energy, low density area consumed more embodied energy on per capita unit.

Bowley and Evins (2020) compared building energy and transportation energy for three hypothetical types of development: single detached, low rise apartments and the mothership (a high-density mixed-use development). The researchers found that both operational use and embodied energy use tended to decrease as density increased. Compared to single detached home base cases, building energy reductions of the mothership were estimated around 69%.

2.3. Methodology to Calculate Embodied Energy

As Langston and Langston (2008) argued, while measuring operational energy is easy and less complex, analyzing embodied energy is more complicated and time consuming. There is currently no consensus of the generally accepted method to evaluate embodied energy accurately and consistently because it needs the great intensity of data from many different sources. The major processes of embodied energy analysis are statistical analysis, process analysis, input/output analysis and hybrid analysis (Ding, 2004).

2.3.1. Statistical Analysis

Statistical analysis is the earlier method using available statistical data for the whole economy or particular industry. However, it cannot explain indirect energy requirements or distinguish between different output from the same industry. (Roberts, 1978)

2.3.2. Process-based Analysis

Process-based analysis is one of the most widely used method because it can provide relatively accurate and reliable results (Crawford, 2003). This method is a bottom-up approach starting with gathering data of actual energy use from manufacturers and takes into account all possible direct and indirect energy inputs chasing the process of production of building material (Dixit, 2017). Accordingly, this method can provide reliable energy consumption figures for particular processes. However, this method has limit of truncation of system boundary because it is almost impossible and impractical to account every energy and the product input of whole complex process in life cycle. Beyond certain point, gathering energy use data becomes difficult and impractical (Dixit, 2017). Accordingly, some processes are excluded from the calculation results causing various uncertainty (Lenzen, 2000).

2.3.3. Input/output-based Analysis

Input/output-based analysis which is originally developed by economists utilizes inter-industry tabular datasets which is made by the national government describing relationships among various sectors of industry (Hammond, 2008). The coupled national economic input-output accounts with environmental data for industrial sectors to determine the total supply-chain effects of material purchases (Ding, 2004). Then, by converting input/output table into energy base table using average energy tariffs, the embodied energy can be calculated (Crawford, 2003). This method has advantage of including nearly the entire system boundary, however, this method inherently relies on many assumptions such as homogeneity and proportionality of each industry sector (Dixit, 2010).

2.3.4. Hybrid Analysis

Hybrid analysis is invented to combine the strengths of Process-based analysis and Input/output-based analysis and to eliminate inherent errors and limitations of both methods (Dixit, 2010). This method utilizes Process-based analysis for available energy input data of the process to the final production and Input/output-based analysis for complex upstream processes (Lenzen, 2006). However, it can cause overestimating problem when applied for complex materials which include more than one material and the most important deficiency with this method is the lack of comprehensive and reliable database of energy consumption data from industry (Fey et al., 2000). According to Treloar (1997) and Treloar et al. (2000), using embodied energy coefficients for materials were derived from hybrid analysis method.

2.4. Identifying Research Gap

When compared with operational energy and transportation energy, research on embodied energy has been lacking compared to its importance. The overall results of the previous studies suggest that the embodied energy is a significant part of total building energy use. The method to calculate the embodied energy is still incomplete. Since calculating the embodied energy requires a variety of conditions to be assumed and at the same time dependent on numerous data, no agreement has yet been reached on which method is the best, instead, calculations have been applied differently depending on the subject or scale of the study. While most studies have conducted at a microscopic level such as building or material level, there have been very little published research on investigating embodied energy at large scale. Therefore, as a research gap, the number of results is too limited to make a proper assessment of how urban planning influences embodied energy and comprehensive energy consumption at a city level.

Therefore, this study has worth to be conducted to suggest an insight to understand the impact of urban density on embodied energy. Additionally, in terms of building type, the previous studies at urban scale have dealt with mainly residential building type due to data consistency and failed to encompass the share of other building types such as office, commercial, educational building, etc., though the energy consumption of other type of buildings is also significant in the building sector. Consequently, their conclusion and scope are mainly about residential density which seems to be helpful for the development of residential area. Therefore, another contribution of this study is to extend the boundary of study to include the various building types at city scale.

In terms of land use, no prior study was found to have done in-depth research on the relationship between land use and Embodied Energy of urban environment, and instead, Embodied Energy of buildings of various uses was done at the building level. This study differs from the preceding study in that it determines the influence of urban density and land use on Embodied Energy, which are two important factors of urban form, on urban scale, and also takes into account the combined effects of the two.

Chapter 3. Research Question and Methodology

3.1. Research Questions

This thesis investigates the relationship between urban density, land use and embodied energy. The main research questions of the thesis are:

1. How does urban density affect Embodied Energy Intensity?
2. How does land use influence on Embodied Energy Intensity?

To answer the main research questions, this thesis conducts two types of simulation experiments, hypothetical environment and real urban environment. To clarify the purpose of experiments, the main questions can be extended and sub questions are developed.

1. How does urban density affect Embodied Energy Intensity?
   a. How does Floor-to-Area Ratio affect Embodied Energy Intensity in hypothetical environment experiments?
   b. How does Floor-to-Area Ratio affect Embodied Energy Intensity in real environment experiments?
2. How does land use influence on Embodied Energy Intensity?
   a. How does land use affect Embodied Energy Intensity in homogeneous hypothetical environment?
   b. How does land use and land use mix affect Embodied Energy Intensity in heterogeneous real environment?
3. How urban density, land use and other geometry measure jointly influence Embodied Energy Intensity?
4. How can the experiment results contribute to make comprehensive strategy to reduce urban energy consumption?

3.2. Hypotheses

To clearly answer the research questions, this thesis makes prediction about each research questions and assesses each hypothesis with simulation results. The hypotheses are made based on the research of theoretical background and literature review (Chapter 2).

1. How does urban density affect Embodied Energy Intensity?
   a. How does Floor-to-Area Ratio affect Embodied Energy Intensity in hypothetical environment experiments?
      : **Floor-to-Area Ratio will have a negative relationship with Embodied Energy Intensity.**
   b. How does Floor-to-Area Ratio affect Embodied Energy Intensity in real environment experiments?
      : **Floor-to-Area Ratio will have a negative relationship with Embodied Energy Intensity.**

2. How does land use influence on Embodied Energy Intensity?
   a. How does land use affect Embodied Energy Intensity in homogeneous hypothetical environment?
      : **Different land use will make notable difference in Embodied Energy Intensity.**
   b. How does land use and land use mix affect Embodied Energy Intensity in heterogeneous real environment?
      : **Land use and land use mix will be significant variables in regression model.**

3. How urban density, land use and other geometry measures jointly influence Embodied Energy Intensity?
   : **Variables in hypothetical experiment will also significant in real urban environment.**

3.3. Variables

Table 3.1.
Variables in the Thesis

Category	Variables	Description
EE	EEI	Embodied Energy Intensity of Block = Total Embodied Energy / Block Area
Urban Density	FAR	Floor to Area Ratio = Total Bldg Floor Area / Block Area
	CVR	Coverage Ratio = Total Bldg Footprint Area / Block Area
Land Use	Land Use Type	Residential (R) Office (O) Industrial (I) Commercial (C) Educational & Institutional (E)
	Land Use Mix	Land Use Diversity Index $= ((-1)/\ln n) * \sum_{i=1}^{n} (p_i \ln p_i)$ p_i = the ratio of land use type i floor area of the total floor area n = the number of different land use types
Geometrical	SVR	Surface to Volume Ratio; Relationship between envelope-floor area = Block Average of (Surface Area / Volume of Bldg)

Embodied Energy Intensity

Embodied Energy Intensity is the dependent variable of this thesis. Because the spatial unit of this thesis is urban block, Embodied Energy Intensity is defined in here as the total amount of embodied energy (MJ) normalized by total floor areas (sqm) of the block. In terms of boundary condition of embodied energy, this thesis adopts cradle-to-gate boundary condition which includes the extraction of materials (the cradle) and manufacturing activities until the product/material is ready to leave the factory gate. As illustrated in Figure2.1., energy use for construction phase, use phase, and demolition phase are not included in the system boundary of this study.

According to Hammond and Jones (2008), the cradle-to-gate scope was the most commonly specified boundary condition for the life-cycle assessments of construction materials, while data intricacies and inconsistencies made it difficult to maintain the same boundary conditions. Junnila and Horvath (2003) reported that energy required for construction and demolition were found to have insignificant impacts and Stephan et al. (2012) also concluded that the energy required for demolition phase is only approximately 1% of the total life cycle energy use. Besides, Hammond and Jones (2008) argued that, in many studies for materials with high embodied energy and high density, the difference between cradle−to−gate and cradle−to−site (the impacts of transportation for the specific site is included) could be negligible.

Floor−to−Area Ratio

Urban density is an important concept in urban planning to control the development intensity. Before investigation it is necessary to make clear definition of urban density because the results could largely differ by how to determine density. According to Densityatlas (MIT, 2011), urban density can be determined as three most widely used definition: dwelling units per acre (DU/area), population density (person/area), and floor area ratio (Floor−to−Area Ratio). In this study, the definition of urban density is used as floor area ratio (Floor−to−Area Ratio). This measure is one of the most commonly used metrics in zoning systems in U.S. and Korea as a tool to control development intensity and therefore urban planners are mostly concerned. Floor−to−Area Ratio determines how much floor area can be built relative to the size of site area. Because the spatial unit of this thesis is urban block, Floor−to−Area Ratio in this project is defined as the total floor area of buildings within block divided by the area of block.

Coverage Ratio

Coverage ratio or building−to−land ratio measures the relationship between the built land and the non−built land (Berghauser Pont & Haupt 2009). It has been used as an important regulatory tool with Floor−to−Area Ratio in Korean zoning system. Floor−to−Area Ratio, Coverage Ratio and numbers of stories area tightly associated each other, therefore, these three parameters are commonly utilized to understand urban density and, further, to set the development limits in planning field. Because the spatial unit of this thesis is urban block, Coverage Ratio is calculated as the total footprint area of buildings within block divided by the area of block.

Table 3.2.
Land Use and Corresponding Building Function Type

Land Use	Building Function	Resource
Residential (R)	Single Detached Housing	DOE Building Energy Codes Program
	Midrise Apartment	DOE Reference Building
	Highrise Apartmnet	DOE Building Energy Codes Program
Office (O)	Large Office	DOE Reference Building
	Medium Office	DOE Reference Building
	Small Office	DOE Reference Building
Industrial (I)	Warehouse	DOE Reference Building
Commercial (C)	Stand-Alone Retail	DOE Reference Building
	Strip Mall	DOE Reference Building
	Supermarket	DOE Reference Building
	Quick Service Restaurant	DOE Reference Building
	Full Service Restaurant	DOE Reference Building
	Small Hotel	DOE Reference Building
	Large Hotel	DOE Reference Building
	Hospital	DOE Reference Building
Educational & Institutional (E)	Outpatient Healthcare	DOE Reference Building
	Primary School	DOE Reference Building
	Secondary Scool	DOE Reference Building

Land Use

Zoning system determines the location, size, and use of building s and decides the density of city blocks (City of New York 2015). In other words, every lot in urban environment is subject to a series of regulations describing possible building functions.

This thesis develops the Embodied Energy Intensity estimation model including 18 different functions of building types. Therefore, rather than using land use classification which is actually applied to the research area, this thesis will use five different land use type to classify the developed types most effectively: Residential (R), Commercial (C), Office (O), Industrial (I) and Educational & Institutional (E). The classification and the building functions that belong to it are summarized in Table3.2.

Land Use Mix

Land use mix generally refers to the diversity of land uses and there are various indexes to measure it. In this thesis, land use mix is defined as entropy scores or Shannon’ s entropy, which were derived from variations in the Shannon index, which was originally used to analyze the accuracy of information transfer (Krebs, 1999). Shannon’ s entropy equal one when land use is totally heterogeneous and zero when land use is completely homogeneous (Table 3.1.). In planning field, Shannon’ s entropy is used to analyze urban sprawl and land consumption patterns (Kumar et al., 2007; Sudhira, Ramachandra & Jagdish, 2004; Yeh & Li, 2001).

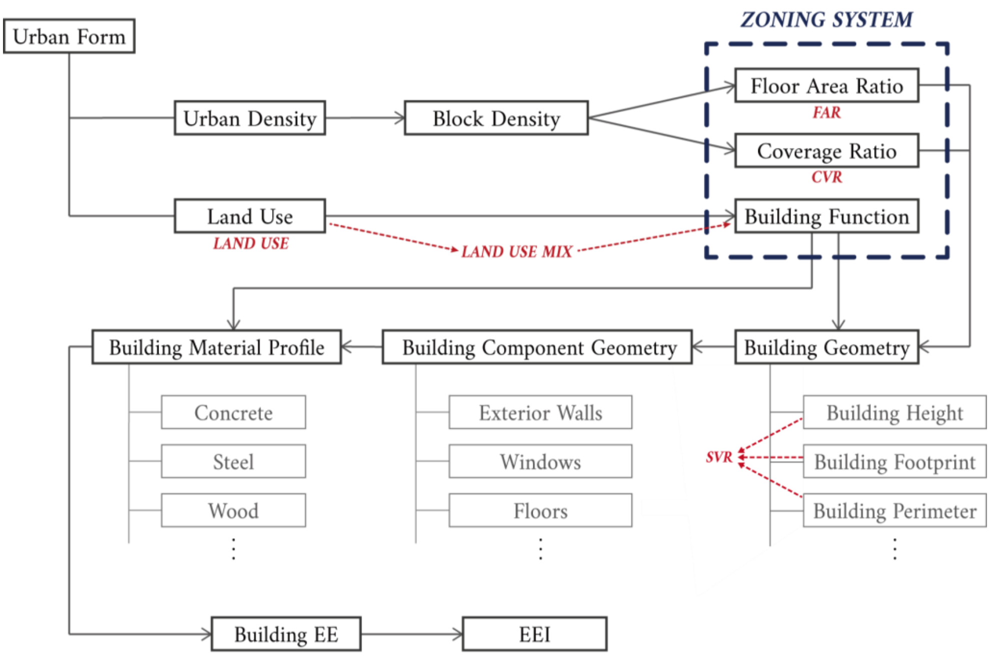
Surface-to-Volume Ratio

Surface to volume ratio is the ratio between the building’s envelope area and the volume. In passive house design, it is often expressed as the ‘heat loss form factor’, which is the ratio for the external surface area of the building to the treated floor area (Passivehouseplus, 2020). This variable is adopted to assess the effect of the geometrical measure reflecting the characteristics of urban form on Embodied Energy Intensity. Further, this variable can provide the broader perspective to understand holistic energy perspective as an important variable in operational energy study. Because the spatial unit of this thesis is urban block, Surface-to-Volume Ratio in this project is defined as the average Surface-to-Volume Ratio of the buildings within block.

3.4. Conceptual Framework

The study of the relationship between urban density, land use and embodied energy is based on the assumption that different urban density and land use can lead to different embodied energy. Therefore, it is important to clearly understand how these variables are causally related. Figure 3.1. is the conceptual framework presenting how different urban density and land use are linked to Embodied Energy Intensity.

Figure 3.1.
Conceptual Framework of the Study



3.4. Research Methodology

3.4.1. Process

Figure 3.2.
Methodology Process

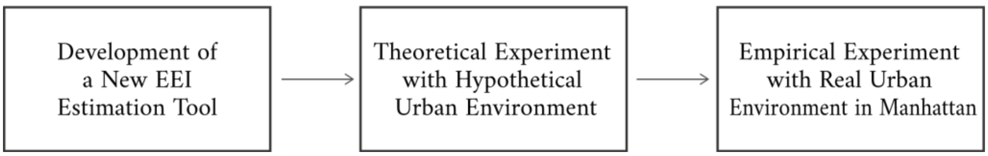


Figure 3.2. presents the methodology process of this thesis. To answer research questions questions, firstly, this thesis newly develops the model to estimate embodied energy of building using reliable databases. The model is developed in five phases which are

presented in Figure.3.3: 1) Building Prototype Model, 2) Building Component-based Material Estimation Model, 3) Component-based Embodied Energy Estimation Model, and 4): GIS based Urban Embodied Energy Intensity Estimation Model. As software program, Microsoft Excel is utilized to work as a calculator and ArcGIS is used as GIS software program and to synthesize the spatial information of case study area. In the next step, the developed model is applied to two types of experiments.

3.4.2. Simulation Experiments

To examine the relationships between urban density, land use and embodied energy, the developed model is applied to two experiments:

1) Theoretical experiment
2) Empirical experiment.

In theoretical experiment, the variables of urban density, land use and other geometric measures are tested in theoretical urban form. A hypothetical environment provides the advantage of effectively investigating the influence of one variable by controlling the other, though there's a weakness in the lack of realism. In addition, in a hypothetical environment, the results of optimal values or ranges can be obtained for each variable, which can be helpful in designing a new urban environment. The block prototype is based on the statistical values of Manhattan, which is the test site of the empirical experiment.

In empirical experiment, the variables are tested in real urban form. Urban form in the real world is very complex and various measurements of urban form are highly associated each other, it is almost impossible to test every variable to affect embodied energy. Using complex real data that cannot control a variable is difficult to reveal how one variable has an effect, but it is possible to find clues about how different variables work in the real world. The aim of the second experiment is to examine how the variables are jointly influence embodied energy of urban environment to better understand the impact on existing complex urban environment.

Spatial Unit

A research unit of two experiments is 'block'. Spatial unit should be decided by the research topic and objectives. This thesis adopts a simplified spatial scale system based on Pont and Haupt's scheme: lot – urban block – neighborhood – district (Table 3.3.).

Table 3.3.
Spatial Unit of study

Spatial Unit	Interest	Diagram
District	Policy Makers Planners	
Neighborhood	Policy Makers Planners	
Block	Planners	
Lot	Architects Realtors Planners	
Building	Architects	

Urban block contains one or several lots and is decided by boundaries as streets of city. Block scale is the most common scale for studies for concern of urban planning field. In terms of urban density, using block scale, the calculation of urban density can be clearly made by using the total floor area of buildings on the block and the area of the block. Different zoning systems may apply to all parcels. Therefore, it was determined that the block unit, a group of parcels, was appropriate to calculate the influence of land use and land use mix.

Case Study City

The case study city is Manhattan. The built environment of Manhattan has characteristics which are suitable for research purposes.

1) Complex urban form; Manhattan has a complex urban environment based on various densities and land uses. Therefore, it is possible to analyze the various densities and land uses in the study.

2) Clear street system; Manhattan has clear and regular grid street system, therefore, area and boundary of block, which is the research unit of the thesis, could be clear in calculation.

3) Data availability; NYC provides detailed public data generated by various New York city agencies and other city organizations. In order to conduct a geospatial data-based study, the availability of data can be an important criterion for selecting a case study site.

Chapter 4. A New Urban Scale Embodied Energy Modeling

As Langston and Langston (2008) argued, while to measure operational energy is relatively easy and less complex, to estimate embodied energy is much more complicated and time consuming. There is currently no consensus of the generally accepted method to evaluate embodied energy accurately and consistently because it needs the great intensity of data from many different sources. Therefore, to develop the model to estimate embodied energy, three different areas of applied knowledge are synthesized:

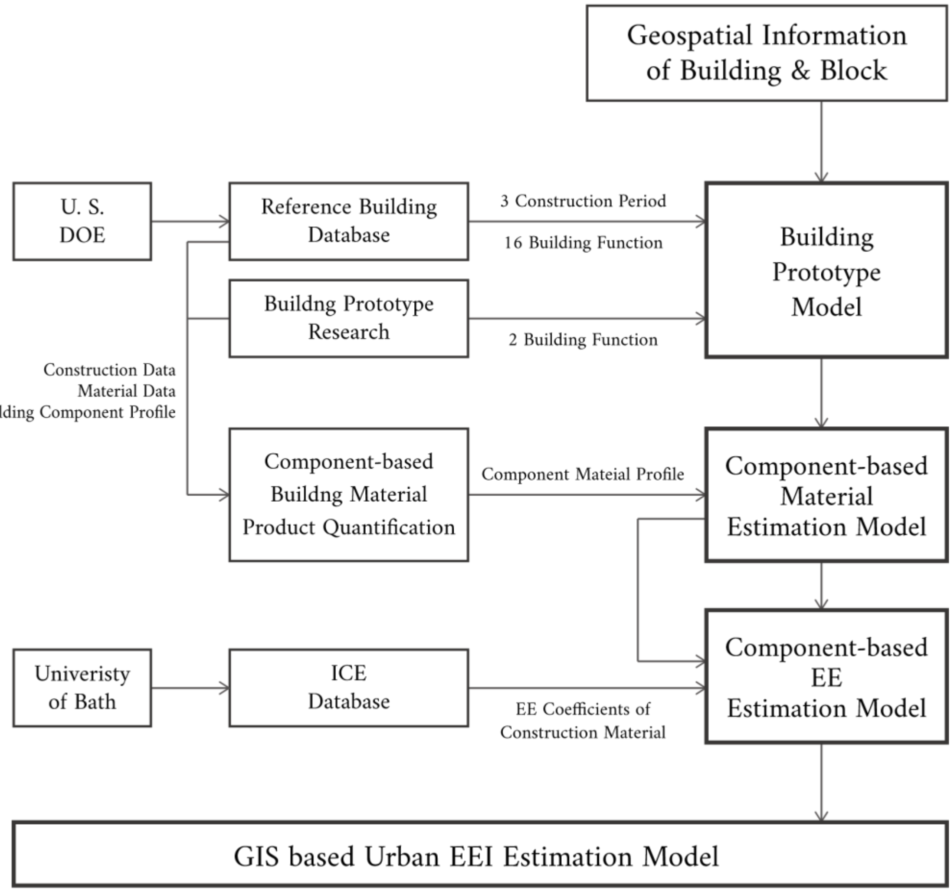
1) Database for 'cradle-to-gate' embodied energy coefficients associated with construction materials developed by Hammond and Jones of University of Bath.

2) The most common type of building models and construction practices of each model developed by U.S. Department of Energy

3) The collection of information on the characteristics of buildings compiled in geographical information systems.

This represents that this thesis is a cross disciplinary study which includes architectural science, urban planning and life cycle assessment study. Utilizing databases instead of acquiring specific data inevitably has limits in accuracy of building level estimation. However, it is almost impossible and impractical to model every different building for large scale study. The purpose of this thesis is to contribute to understanding the embodied energy at city level scale which is identified as the important research gap in the field rather than to calculate the exact figures of embodied energy.

Figure 4.1.
Schematic Diagram of the Model Development



Therefore, utilizing reliable databases is appropriate method to fit the purpose of the thesis. In terms of the methodology for calculating embodied energy, this method uses hybrid analysis method because it utilizes embodied energy coefficient for the corresponding material. According to Peters (2010), in the study of urban and regional scale, the process-based hybrid method is most appropriate. Considering the characteristics of the calculation methods described earlier and the related studies, the process-based calculation method is most suitable for calculating the embodied energy of individual materials and the input-output calculation method is appropriate for country level study.

4.1. Data

4.1.1. Reference Building Database

The term 'reference building' is the most common type of building based on statistic data. The reference building approach which is widely used for building operational energy simulation. In United States, the reference building data is developed by the Department of Energy (DOE) and it is most well-organized and detailed reference building models based on national scale surveys across U.S. cities (2003, Commercial Building Energy Consumption Survey; CBECS).

The database includes reference building models for sixteen building type and there are three vintages (new construction, post-1980 construction, and pre-1980 construction) of each building type in 16 locations result in 768 models which represent approximately 70% of the commercial building in country (the rest is composed of several building types which are not easily determined by model).

4.1.2. Inventory of Carbon and Energy (ICE)

To calculate the embodied energy of building, this thesis adopts Inventory of Carbon & Energy as a database. ICE database is one of most widely used embodied energy inventory for Life Cycle Assessment (LCA) studies. It contains most recent estimates of embodied energy intensities of about 200 construction materials and has been continuously updated with contemporary studies. The database was extracted from peer-reviewed literature, Life Cycle Assessments (LCA's), books, conference papers, etc. The system boundary for this inventory is cradle-to-gate, which is identical for this study, to apply at city scale study.

Table 4.1
Embodied Energy Coeffieicnt of Main Construction Material

Material	Density	EEC (MJ/kg)
Concrete	2240.00	1.11
Insulation	265.00	45.00
Wood	540.00	7.40
Gypsum	784.90	6.75
Stucco	1858.00	1.80
Metal	7688.86	25.30
Asphalt Shingle	1121.29	51.00
CeilingTile	288.00	28.00
Glass	2500.00	15.00

4.2. Model Development

The model is developed in five phases which are presented Fig.3: 1) Building Prototype Model, 2) the Component-based Material Estimation Model, 3) the Component-based Embodied Energy estimation Model, and 4) GIS-based Urban Embodied Energy Intensity Estimation Model.

The first model, the building prototype model, is to classify the 'real-world' buildings into corresponding building types. In other words, the model plays a role in determining which type of building to classify the various kinds of buildings in the actual urban environment. This thesis uses 16 different building types in Reference building database and added additional 2 building prototype by conducting building prototype research. As a result, 18 different functions and 3 construction period can be utilized to determine the building class. The building classification is conducted referring to information on the size and function of the building and the year it was constructed.

The second model, the component-based material estimation model, is to calculate the volume and stock of construction product/material as the former step to calculate embodied energy. The construction information and properties of construction product/material is extracted in the DOE reference building dataset. Besides, to compensate the missing information in construction product and material properties, the database from the Chartered Institution of Building Services Engineers (CIBSE) is referred. By organizing the construction layer of each component of the building, it is possible to calculate what kind of material is included in the component of 1 square meter. By using the method of quantifying building materials based on component, this model has an advantage in accuracy over the model that predicts Embodied Energy based on floor area, which was mainly used in prior research. The specific method and formula for quantifying each component of the building and for calculating the amount of materials are attached to the Appendix 2.

The third model, the component-based Embodied Energy estimation Model, calculates Embodied Energy by multiplying the Embodied Energy Coefficient to the amount of material contained in each component which is calculated in the second model. Embodied Energy Coefficient is the embodied energy (MJ) for the 1 kilogram of the material. The specific method and formula for calculating the amount of embodied energy are attached to the Appendix 3.

Finally, GIS-based urban Embodied Energy Intensity estimation model, is associated with the geospatial information of target area. As software program, ArcGIS developed by Esri is used to synthesize the geospatial information and embodied energy calculation from the previous model which is based on Microsoft Excel. Then, embodied energy of buildings across a large area and wide range of building types can be calculated with this model.

4.3. Model Validation

It is almost impossible to measure the actual Embodied Energy of the urban environment to determine the validity of the model. In the thesis, Embodied Energy estimation of the model is done by predicting the amount of material and then multiplying it by Embodied Energy Coefficient. Therefore, it is possible to assess how accurately the model predicted the amount of material stock.

In this study, in order to judge the validity of the model, the amount of demolished material was calculated based on demolished building data and compared it with local waste report. And as another comparison group, this study compared the results of applying the model to predict building demolition waste from a nationwide study based on data from buildings actually demolished.

As presented in Figure 4.2., the amount of demolished building waste of the five boroughs in NYC is calculated by applying a model. To calculate the C&D waste in residential sector, the waste characterization studies are available provided by The New York City Department of Sanitation (DSNY, 2013, 2017). To calculate the C&D waste in commercial sector, as DSNY only manages the waste in residential sector, the amount provided by New York City Commercial Solid Waste Study and Analysis (DSNY, 2012) is applied.

As mentioned, as another comparison group, the model in Characterization of Building-related Construction and Demolition Debris in the United States by The U.S. Environmental Protection Agency (EPA, 1998) is applied. This report analyzed the generation rate of demolition waste by the types of buildings; single-family type, multi-family type, and non-residential type.

Figure 4.3. presents the result of comparing the amount of the demolition waste in each borough calculated in three ways. Considering the material boundary of each method is slightly different and the purpose of this thesis is to contribute to understanding of the embodied energy on an urban scale rather than to calculate the exact figures, this thesis evaluated the model as reasonable. The details of the specific calculation figures are attached to the Appendix 4.

Figure 4.2.
The Schematic Diagram of Model Validation

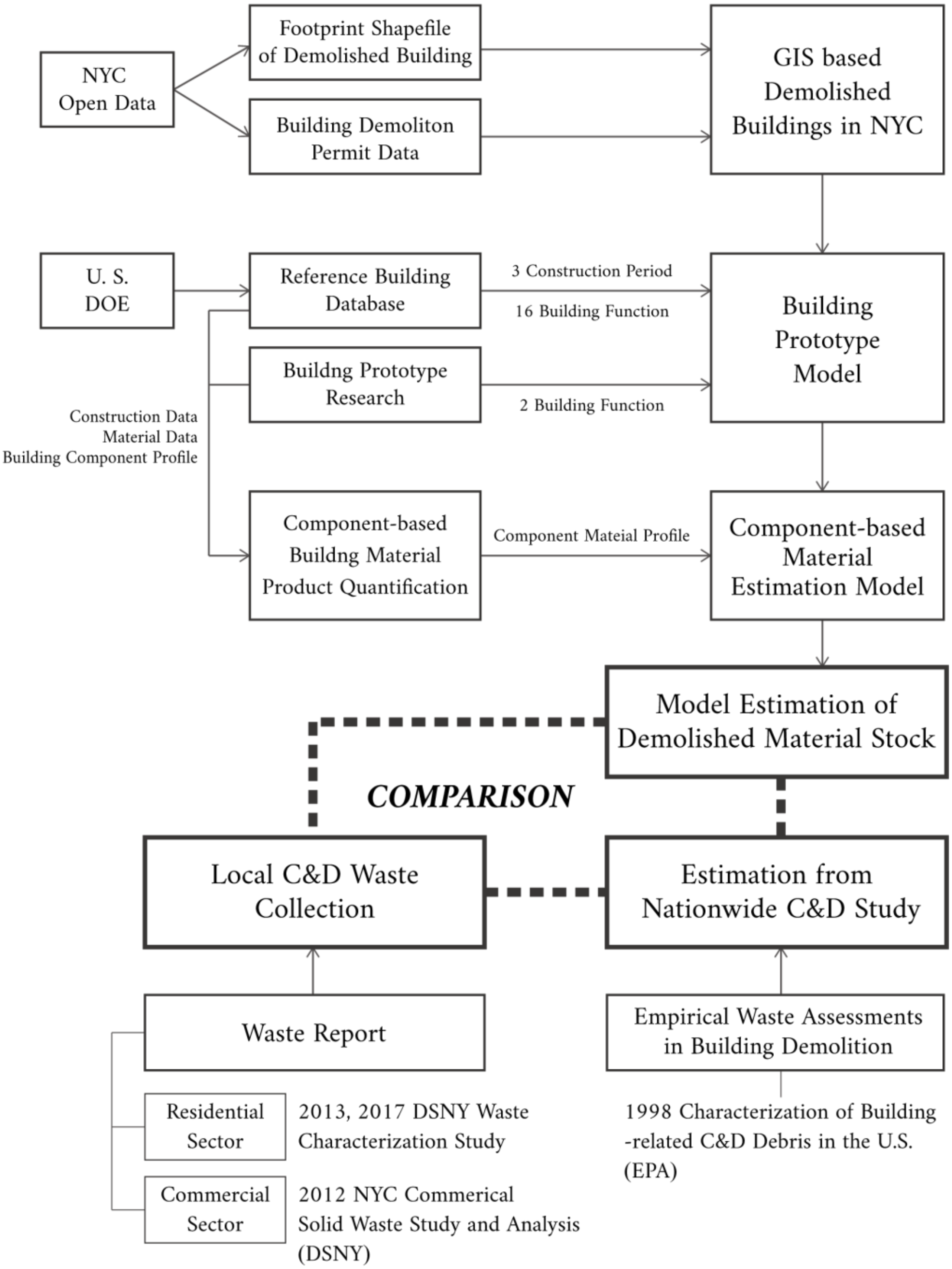
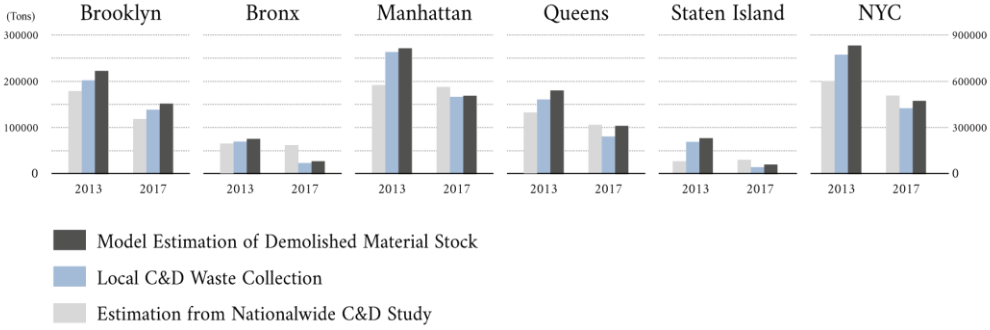


Figure 4.3.
The Comparison Result to Assess the Model Validity



Chapter 5. Theoretical Experiment with Hypothetical Urban Environment

In theoretical experiment, the variables of urban density, land use and other geometric measures are tested in theoretical urban form. In theoretical urban form, the effect of one variable can be effectively measured by controlling other variables. The effect of each variable is investigated in the theoretical block prototype which is made by using statistical values of the blocks in Manhattan.

Figure 5.1.
Schematic Diagram of Methodology of Theoretical Experiment

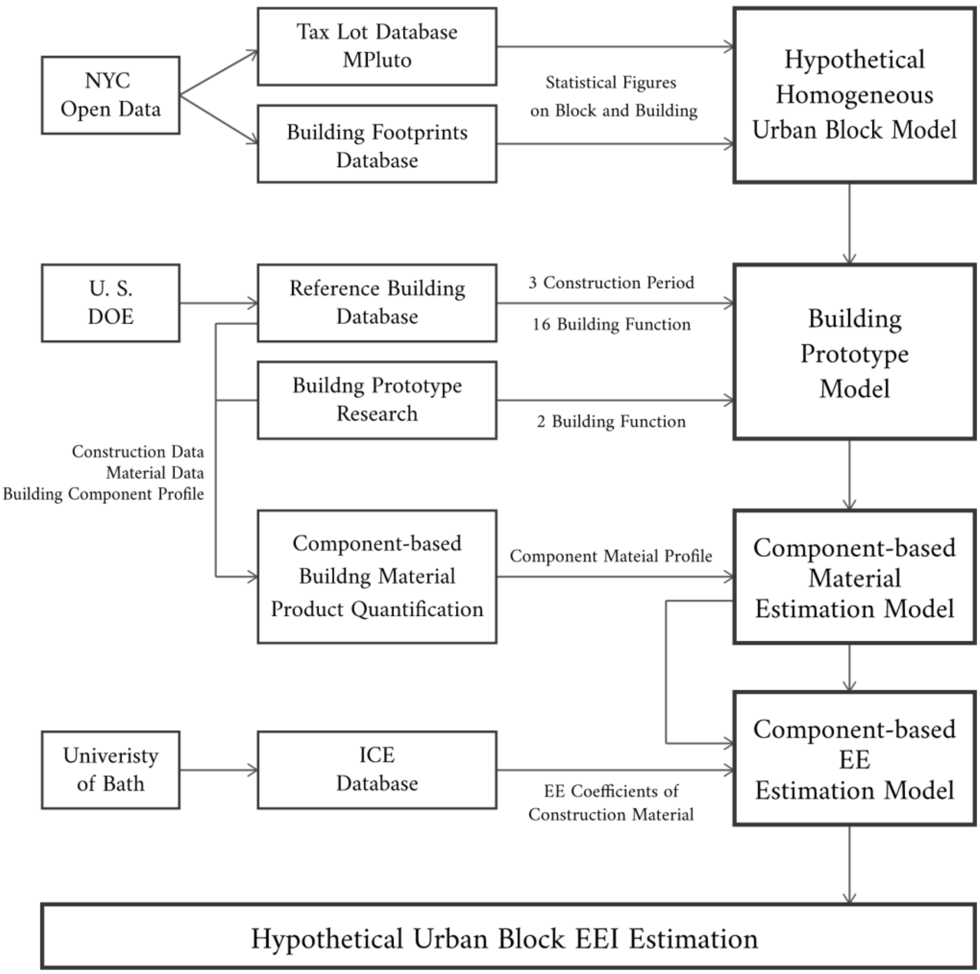


Figure 5.1. presents schematic diagram of methodology of the theoretical experiment.

5.1. Experiment Setting

Environment

The theoretical urban block is modeled by reference to the statistical values of 45,920 buildings and 2,876 blocks in Manhattan, where is the site of the empirical experiment. The detailed properties of the theoretical urban block are summarized in Table 5.1.

Table 5.1.
Experiment Environment

	Parameter	Value		Decision
Block	Block Area	11148	(sqm)	MN* Mean (W: 200ft x H: 600ft)
	CVR	0.68		MN Mean
	The Number of Buildings	16		MN Mean
	FAR	2.67		Calculated Result
Building	Building Type	316		MN Mode
	The Number of Stories	4		Building Prototype
	Building Footprint	465	(sqm)	Calculated Result
	Building Perimeter	108	(m)	Calculated Result
	Floor to Floor Height	3.05	(m)	Building Prototype

*MN = Manhattan

The modelled blocks were made with a width of 200 ft and a length of 600 ft based on statistics of block size in Manhattan. Similarly, in reference to statistics, 16 buildings were placed in one block and the coverage ratio was set at 68%. The building type was determined as the most frequent type, mid-rise apartment constructed before 1980, in Manhattan.

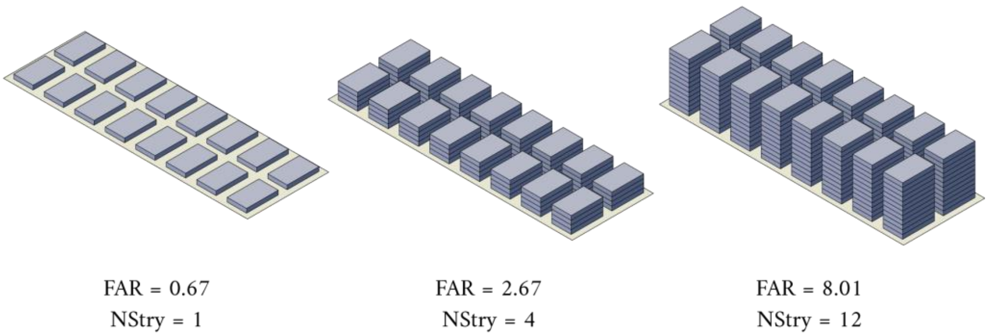
5.2. Simulation

The simulation range and steps of each variable is summarized in the Table 5.2. To evaluate the relationship between Floor-to-Area Ratio and Embodied Energy Intensity, Floor-to-Area Ratio is controlled by increasing the number of stories in the building (as described in Figure 5.2.). During the simulation, the variables that are fixed are fixed by the figures expressed in Table 5.1.

Table 5.2.
Experiment Variables and Simulation Setting

Category	Variables	Simulation Range	Steps
Urban Density	FAR	0.7 ~ 33.4 (1~50stry)	0.7 (1stry)
	CVR	0 ~ 1	0.05
Land Use	Land Use Type	Residential (R) Office (O) Industrial (I) Commercial (C) Educational & Institutional (E)	
Geometrical	SVR	0.24 ~ 0.86	0.02
Others	ConstYr	Before 1980, 1980~2004, After 2004	

Figure 5.2.
Hypothetical Urban Block Model (CVR = 0.68)



5.3. Results

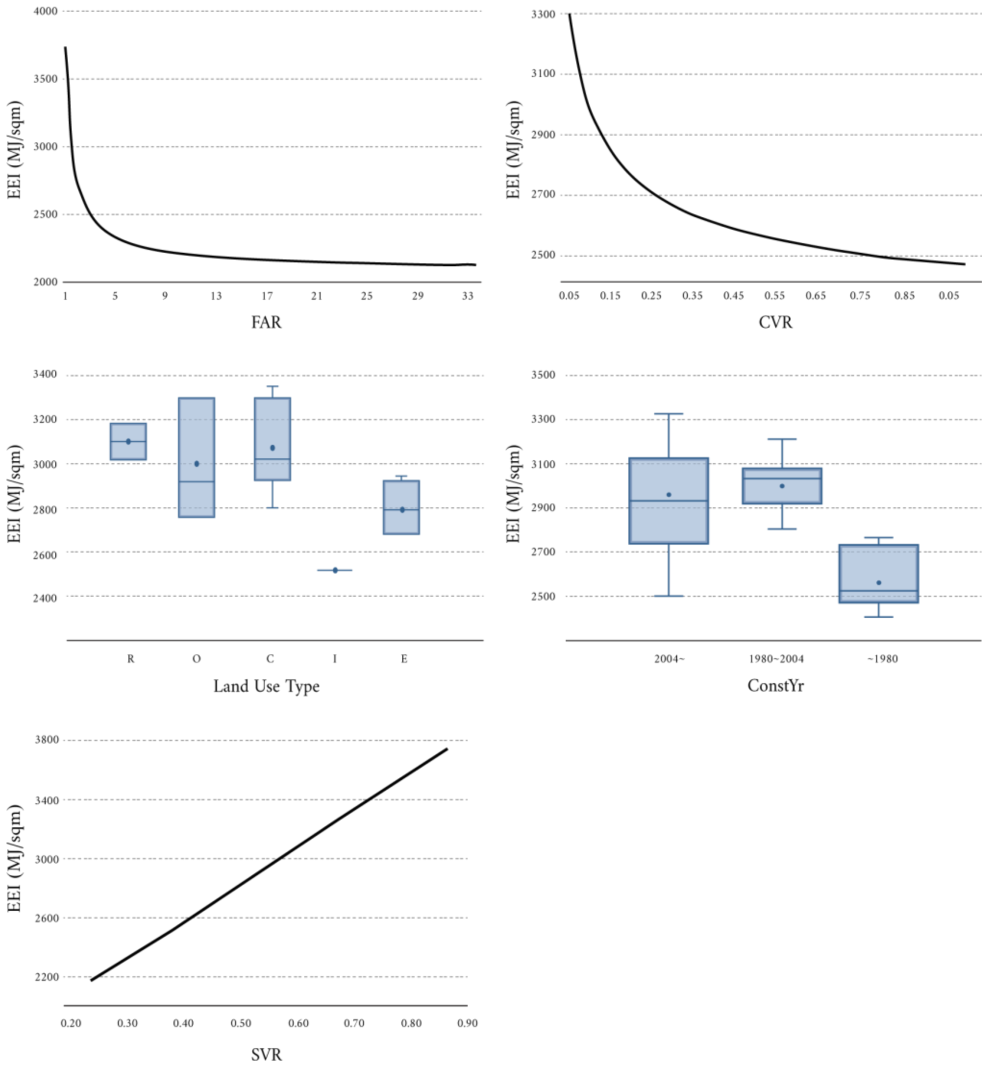
The Figure 5.3. presents the simulation results showing the relationship between each variable and Embodied Energy Intensity.

In the Floor−to−Area Ratio−Embodied Energy Intensity relationship, the graph suggests that it is nonlinear relationship. Embodied Energy Intensity decreases greatly with increasing Floor−to−Area Ratio in the range of Floor−to−Area Ratio = 1~4. Because Floor−to−Area Ratio is determined by the number of stories, the results can be interpreted as Embodied Energy Intensity is sharply decreased when the number of stories are increased from 1(Floor−to−Area Ratio = 0.67) to 6 (Floor−to−Area Ratio = 4.01). After Floor−to−Area Ratio = 9 (the number of stories = 15), Embodied Energy Intensity is gradually decreased but the extent is relatively insignificant.

In the Coverage Ratio−Embodied Energy Intensity relationship, the graph presents that it is also nonlinear relationship as in the Floor−to−Area Ratio. But the decreasing slope of the beginning is relatively small than Floor−to−Area Ratio. Approximately, in the range of Coverage Ratio = 0~0.35, Embodied Energy Intensity is decreased dramatically. After Coverage Ratio = 0.35, Embodied Energy Intensity is gradually decreased within a small range.

For the Land use type, considering the average value only, Embodied Energy Intensity is higher in order Residential, Commercial, Office, Educational and Institutional, and Industrial. But the range of each land use type is different. In the same built form, the building function of ‘Small Hotel’ shows the highest (Embodied Energy Intensity = 3351) and the lowest is ‘Warehouse’ (Embodied Energy Intensity = 2521).

Figure 5.3.
Variables-EEI Result Graphs



For the constructed year, the general trend seems that Embodied Energy Intensity is higher with the buildings built in the more recent period. It is clear that the 'constructed before 1980' shows low Embodied Energy Intensity, but the 'constructed after 2004' has a wide range. Finally, in the relationship between Surface-to-Volume Ratio and Embodied Energy Intensity, Embodied Energy Intensity linearly increases with increasing surface to volume ratio.

5.4. Discussions

As a result of the first experiment, one of the main research questions can be answered in part to the question of how urban density affects Embodied Energy Intensity. It is confirmed that the hypothesis that urban density would have a negative relationship with Embodied Energy Intensity was correct. Interestingly, the relationship turned out to be nonlinear. Using this relationship, Embodied Energy Intensity can be effectively reduced by planning the number of floors of the building around six stories (Floor-to-Area Ratio = 4.01). The reduction effect of Embodied Energy Intensity does not appear dramatic in the number of floors above six stories.

Coverage Ratio, like Floor-to-Area Ratio, presented a negative nonlinear relationship with Embodied Energy Intensity. Although it draws a gentler form in terms of curvature compared to Floor-to-Area Ratio, it can be seen that, like Floor-to-Area Ratio, increasing the Coverage Ratio is more effective in a lower range. Considering that Manhattan's Coverage Ratio average, which was used in setting up the experimental environment, is 68%, it can be seen from the Coverage Ratio perspective that Manhattan has an urban environment with a sufficiently efficient Embodied Energy Intensity.

With respect to the land use type, it may partially accept the assumption that the land use type will make a change in the Embodied Energy Intensity, but it seems that attention is needed to interpret it. It is supposed that the reason why different kinds of land use types show different Embodied Energy Intensities is mainly because of the difference in construction material. In the experiment, the simulation is changing only the building function controlling the other geometrical features (height of building, height of story, etc.). However, in real building, features like the height of building and the height of story are highly associated with building function (generally, the floor height of office and warehouse is higher than residential buildings). Therefore, merely understanding the experiment result as the efficiency of land use would be problematic. Instead, it provides the general understanding of the relative Embodied Energy Intensity difference in same built form.

For the constructed year, the reason why Embodied Energy Intensity depends on when the building was built is mainly because of the difference in insulation thickness. Along with the demand for eco−friendliness, the insulation standards for buildings have been increasing and models in different vintage reflect this in insulation thickness of exterior wall and roof. As presented in Table 4.1., insulation material has relatively high embodied energy coefficient than other material. Therefore, changes in insulation systems are likely to make a big difference in Embodied Energy Intensity.

Finally, seeing the Embodied Energy Intensity increase together as the Surface−to−Volume Ratio increases, it can be inferred that the envelope of building accounts for a large portion of the Embodied Energy Intensity.

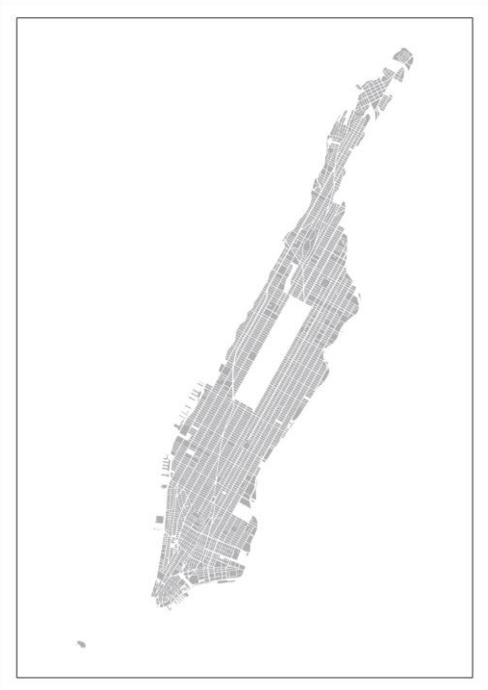
Chapter 6. Empirical Experiment with Real Urban Environment in Manhattan

The former experiment tested variables in the simplified hypothetical urban environment. In this chapter, the variables are examined in the real urban environment of Manhattan. Urban form in the real world is very complex and various measurements of urban form are highly associated each other. The purpose of the second experiment is to examine how the variables are jointly influence embodied energy of urban environment to find answers to the research questions.

6.1. Experiment Setting and Simulation

As presented in Figure 6.1, The 2,686 urban blocks in Manhattan were selected for analysis. The 42,354 lots were tied up to calculate the blocks and 45,920 buildings included in the model.

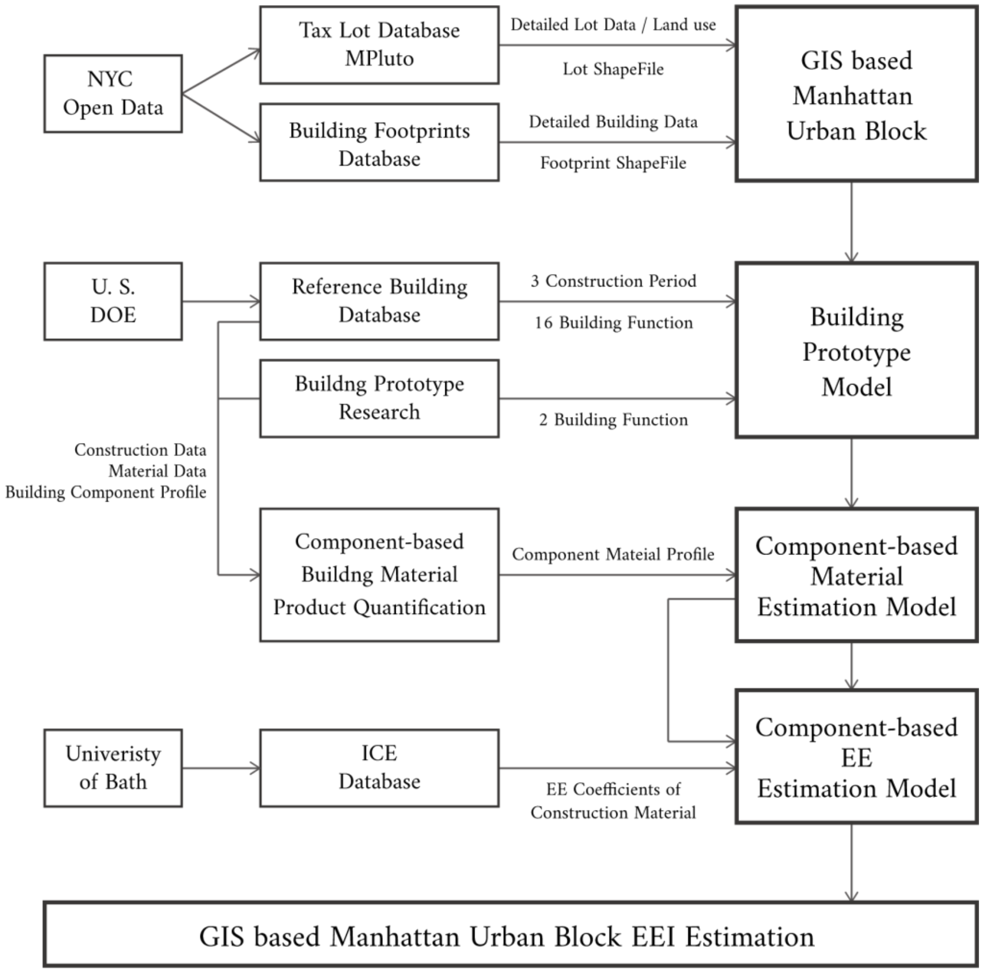
Figure 6.1.
Experiment Environment



The Number of Blocks		2686
The Number of Buildings		45920
The Size of Block (sqm)	Min	519
	Mean	10947
	Max	95691
	St.Dev	9347

The blocks exceeding 100,000 square meters or less than 500 square meters were excluded from the analysis to eliminate anomalies. In the process, the data of lot and building footprint data were aggregated and the information was geocoded. During the geocoding process, some of the lost information not provided in the database was determined at the discretion of the researcher, using either the average or most frequent values of the entire data. Figure 6.2. presents schematic diagram of how the model is applied to the experiment.

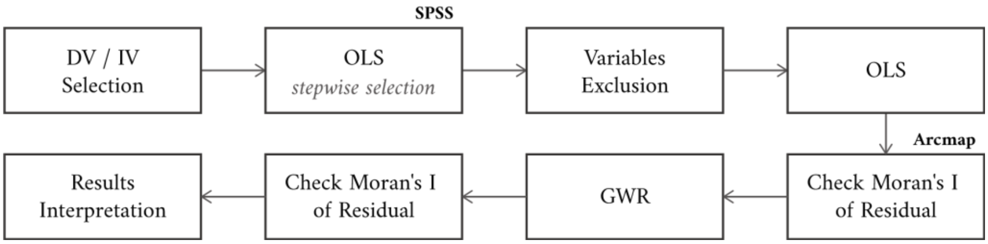
Figure 6.2.
Schematic Diagram of How the Model is Applied to the Experiment



6.2. Multivariate Linear Regression Analysis

Multivariate linear regression analysis is performed to determine how different variables affect Embodied Energy Intensity in real urban environments. Because this experiment performs a regression analysis on spatial data, the experiment was planned in the order expressed in figure 6.3. To outline the order, the first step is to select an independent variable to identify its impact on the dependent variable Embodied Energy Intensity. Independent variables were selected for the purpose of finding answers to research questions.

Figure 6.3.
Process of Empirical Experiment



The next step is to conduct an Ordinary Least Squares method analysis, which uses stepwise method to eliminate variables that cause multicollinearity. The following step is to remove the variables by referring to the results of the stepwise method and the various indicators that can confirm the multicollinearity. After removing the variables, leaving only the variables that will eventually be included in the regression model, the variables are analyzed once again to determine whether the model is problematic in terms of spatial autocorrelation, nonstationarity, and heteroscedasticity. If the model is assessed to need improvement in the previous step, Geographically Weighted Regression analysis is conducted. The final step is to verify that the model's explanatory power and spatial autocorrelation have improved before interpreting the results.

Variable Selection

In this experiment, the variables selected to answer the research questions were summarized in Table 6.1 with the technical statistics.

To illustrate the difference from the first experiment, each Land Use Type was transformed into a proportion to test whether a particular Land Use Type could explain the Embodied Energy Intensity change. To explain the difference from the first experiment in the variables, each Land Use Type was transformed into a proportion to test whether a particular Land Use Type could account for the change in Embodied Energy Intensity. In addition, values were given for three ranges for the constructed year to convert to a measure available for regression analysis. And Land Use Mix variables were added to the Land Use category to determine whether the complexity of land use is related to Embodied Energy Intensity.

Table 6.1.
Descriptive Statistics of Selected Variables

Category	Variables	Descriptive Statistics			
		Mean	Min.	Max.	St. Dev
EE	EEI (DV)	2679	1941	9694	589
Urban Density	FAR	7.04	0.00	49.49	6.75
	CVR	0.68	0.00	0.95	0.19
Land Use	Residential Ratio	0.55	0.00	1.00	0.38
	Office Ratio	0.21	0.00	1.00	0.32
	Industrial Ratio	0.02	0.00	1.00	0.11
	Commercial Ratio	0.16	0.00	1.00	0.24
	E&I Ratio	0.07	0.00	1.00	0.20
	Land Use Mix	0.45	0.00	1.00	0.35
Geometrical	SVR	469.11	7.92	86237.12	2155.31
Others	ConstYr Before 1980 = 1 1980~2004 = 2 After 2004 = 3	2.55	1	3	0.51

*N = 2,686

Variable Exclusion

Ordinary Least Squares method analysis was performed by stepwise method, and variables with problems with multicollinearity were excluded by comprehensively considering TOL, VIF, scatterplot, and status index. The variables excluded by the judgement of multicollinearity or significance are as follows: Residential Ratio, Office Ratio, Commercial Ratio, Land Use Mix, and Surface−to−Volume Ratio. Residential ratio and Land use mix were excluded from the multicollinearity issue, while the rest were left out.

Ordinary Least Squares Method Regression Result

After leaving only the variables to be included in the model through the exclusion of variables, the Ordinary Least Squares method analysis was performed again. The analysis results are summarized in Table6.2. The model represented 30.1% explanatory power with adj.=0.301. The coefficient shows how much each variable has of which kind of relationship, and the relative influence of the variable through standardized coefficients. Floor−to−Area Ratio is B=−32.702 ($p<.001$), having a significant impact on Embodied Energy Intensity. Because the sign of B is negative, an increase in Floor−to−Area Ratio by 1 lead to lower the Embodied Energy Intensity by 32.702. All variables except Industrial land use ratio showed a negative relationship with Embodied Energy Intensity. On the other hand, the relative importance of the variable was found to be the largest Floor−to−Area Ratio and the smallest Industrial land use ratio.

Though the result of the analysis, F=232.643 ($p<.001$) suggests that this regression model is suitable. However, the result table also presents the possibility of a problems, spatial autocorrelation, nonstationarity, and heteroscedasticity, through Koenker Statistic, Jacques−Bera Statistic, and Moran I index.

Table 6.2.
OLS Regression Result

Variables	Coefficient B	Coefficient SE	Standardize Coefficient β	t-value (p)	*TOL*	*VIF*
Constant	3891.071	51.850		75.044		
FAR	-32.702	1.593	-0.374	-20.529***	0.783	1.277
ConstYr	-221.258	20.751	-0.191	-10.662***	0.809	1.235
CVR	-587.566	60.092	-0.191	-9.778***	0.680	1.470
Educational & Institutional	-411.220	48.889	-0.137	-8.411***	0.975	1.026
Industrial	268.669	86.610	0.051	3.102**	0.978	1.023
F(p)			232.643***			
adj.R^2			0.301			
Durbin-Watson			2.001			
Koenker Statistic			397.736***			
Jarque-Bera Statistic			275728.283***			
Moran I index			0.013***			

*p<.05, **p<.01, ***p<.001

Geographically Weighted Regression Analysis Result

Geographically Weighted Regression was performed to improve the model. The results of the Geographically Weighted Regression analysis are summarized in Table 6.3 with Ordinary Least Squares method results. The results indicate that the influence of each variable varies from region to region. Comparing the R2 values of Ordinary Least Squares method, we can see that the explanatory power of the model has improved, and we can also see that the problem of spatial autocorrelation has been solved by checking the Moran I index.

Table 6.3.
OLS / GWR Regression Result

	OLS			GWR		
	Coefficient	t(p)	VIF	Coefficient Min	Coefficient Mean	Coefficient Max
Intercept	3891.071	75.044	-	2699.584	4078.176	6567.684
FAR	-32.702	-20.529***	1.277	-251.717	-75.873	-17.132
ConstYr	-221.258	-10.662***	1.235	-753.481	-316.841	2.133
CVR	-587.566	-9.778***	1.470	-3145.169	-232.389	1069.229
E & I	-411.220	-8.411***	1.026	103.245	166.101	801.875
Industrial	268.669	3.102**	1.023	146.232	621.463	2456.332
R2		0.303			0.497	
Adjusted R2		0.301			0.472	
Moran I index		0.013***			-0.006***	
	Koenker Statistic	397.736***		Neighbors		381
	Jarque-Bera Statistic	275728.283***		Bandwidth methods		AICc
				Kernel type		Adaptive

*p<.05, **p<.01, ***p<.001

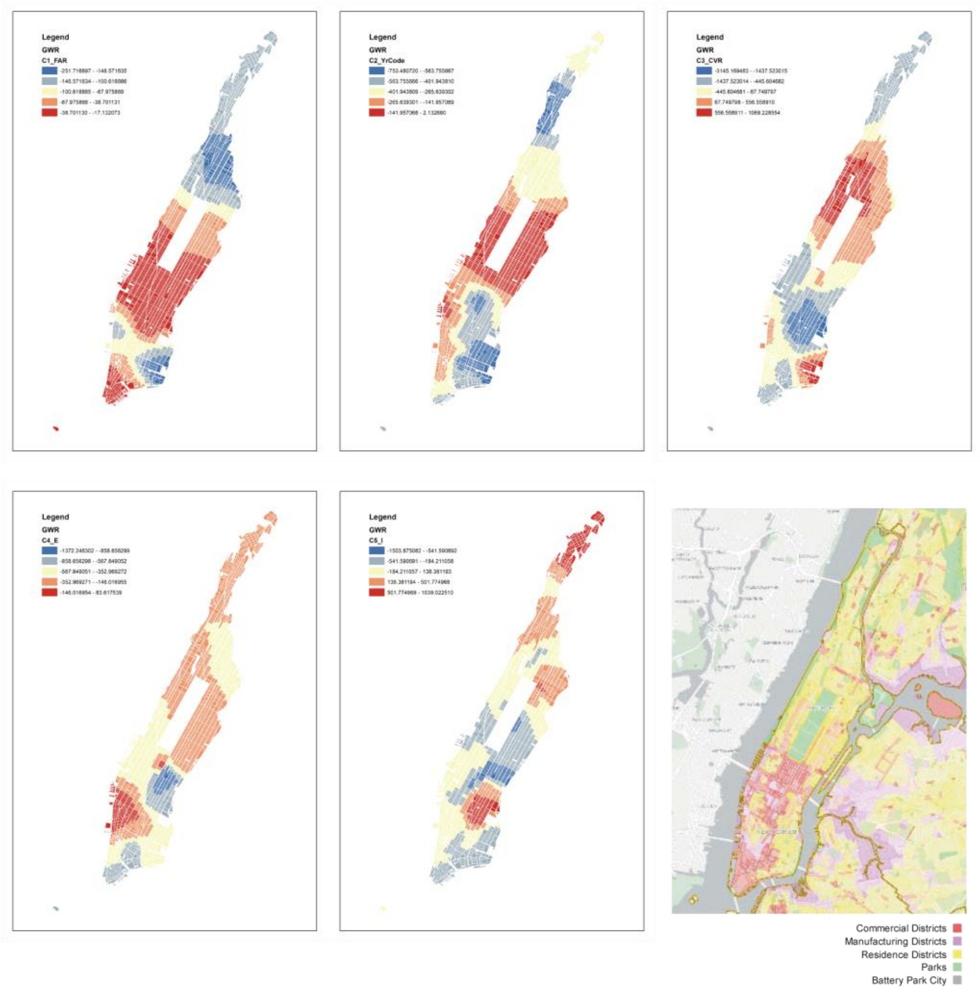
Figure 6.4 is a regional mapping of the coefficients of each variable.

6.3. Discussions

In the second experiment, the selected variables were tested for their relationship with Embodied Energy Intensity in the actual urban environment, and both methods of Ordinary Least Squares method and Geographically Weighted Regression were utilized to more rationally analyze the results.

As a result of the second experiment, it is possible to answer some assumptions about the research questions set above. First of all, the assumption that Floor-to-Area Ratio will have a negative relationship with Embodied Energy Intensity can be evaluated as correct in the experiments applied to the actual urban environment.

Figure 6.4.
GWR Variables Coefficient & Manhattan Zoning Map



However, the assumption that the variables of land use and the mix of land use will also be significant in the actual urban environment is considered wrong. Only Educational & Institutional ratio and industrial ratio have been found to have significant relationships with Embodied Energy Intensity and their relative importance is also lowest, given the standardized coefficients of Ordinary Least Squares method analysis results. And the assumption that the variables in the first experiment would also be significant in the second experiment was also proved wrong, since Surface-to-Volume Ratio, which demonstrated a strong relationship with Embodied Energy Intensity in the first experiment, was not judged significant in the empirical experiment. On the one hand, variables such as Floor−to−Area Ratio, Coverage Ratio, and the Constructed Year also showed significant positive relationships in the second test.

Interestingly, in Figure 6.4, if the mapped results are compared to the zoning map in Manhattan, it can be seen that the mapping results of variables such as Floor−to−Area Ratio and Coverage Ratio show some effect of the zoning system. Although this thesis did not quantify the influence of the zoning system, further research on it is also considered meaningful.

Chapter 7. Conclusion

In this thesis, to determine the impact of urban density and land use on Embodied Energy Intensity, a model to estimate Embodied Energy was developed and the results were obtained through two experiments. In the first experiment, the variables selected to answer the research questions were tested for their relationship with Embodied Energy Intensity in a controlled, hypothetical environment. The first experiment determined that the assumption that Floor–to–Area Ratio would have a negative relationship with Embodied Energy Intensity was correct and that land use affected Embodied Energy Intensity was also able to assess it as being right. In the second experiment, variables were tested in real urban environments with high complexity and interrelationships, and the assumption that Floor–to–Area Ratio would have a negative relationship with Embodied Energy Intensity still proved correct, but the rest of the assumptions were not appropriate.

As a result, the study supports the judgement that some preceding studies suggested that high–density urban environments are advantageous in terms of Embodied Energy. However, the purpose of this study is not just to reveal that high–density development benefits in respect of embodied energy. In this study, the concept of urban density was investigated in terms of floor area ratio and coverage ratio, which are the most representative regulatory tools to control urban development (Zoning system), and discussed the specific range to effectively reduce embodied energy intensity. These findings could help with policies such as the establishment of a zoning system. Regarding land use, experiments in hypothetical urban environments quantitatively assessed the impact of land use on Embodied Energy Intensity and discussed the reasons. However, experiments with the actual environment did not find the evidences that most land use variables had significant effects on EEI. Meanwhile, it is supposed that the mapping results of the coefficients derived from the Geographically Weighted Regression analysis are related to the zoning system and further research is needed.

1. How does urban density affect Embodied Energy Intensity?
2. How does land use influence on Embodied Energy Intensity?
3. How urban density, land use and other geometry measures jointly influence Embodied Energy Intensity?
4. How can the experiment results contribute to make comprehensive strategy to reduce urban energy consumption?

So far, this thesis discussed the answers to the three main research questions set in the introduction through two experiments, now the study leaves only the last main research question of a major research question: How can the experiment results contribute to make comprehensive strategy to reduce urban energy consumption?

Regarding the results of the study, the answer that can be given in this study is that three factors of energy consumption in the urban environment; Transport Energy, Building Operational Energy, and Embodied Energy should be considered in a balanced manner.

In general, prior studies on urban density suggested that high density urban environments are also advantageous in Transportation Energy and Operational Energy. In this regard, the study supports that a is also advantageous for Embodied Energy, suggesting that Floor-to-Area Ratio can create synergies for all three energy types. On the other hand, for Land Use Mix variable, which is related to Transportation Energy savings, this thesis failed to find significance in terms of Embodied Energy that would help with an integrated view. However, through the theoretical experiment, this study suggests that Surface-to-Volume Ratio is also significant to Embodied Energy having a synergy effect with Operational Energy. And the findings also suggest that while the improvement of insulation performance over time is positive in

Operational Energy, there is a tradeoff effect in Embodied Energy.

The thesis could help policy makers and experts in urban planning and design to better understand how density and land use which are widely used measures in zoning system and how urban form influences embodied energy of environment. Additionally, it can provide the insight to understand the existing built environment and new development in terms of material and embodied energy. According to Pullen (2007), the mapping embodied energy of existing built environment can suggest the potential for quantifying resources which can be reused to the new development.

Future work will involve more various building types for a refined estimation of embodied energy and material stock. In real urban environment, infrastructures such as roads such as roads and pipelines are also important elements in terms of energy consumption of urban environment. However, these elements are not considered in this thesis.

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Appendix

Appendix 1
List of Abbreviations

M_k	*k-th material layer in Construction*	
T_k	*Thickness of M_k*	(*m*)
D_k	*Density of M_k*	(*kg/sqm*)
P	*Length of perimeter*	(*m*)
A	*Footprint area*	(*m*)
S	*Number of stories*	
FH	*Floor Height*	(*m*)
WWR	*Window to Wall Ratio*	10-12%, 36-46%
IWC	*Interior Wall Coefficient*	*Caculated from Typical Builiding
IFC	*Interior Furnishing Coefficient*	*Caculated from Typical Builiding
EE	*Embodied Energy*	
EEC	*Embodied Energy Coefficient*	(MJ/kg)
EEI	*Embodied Energy Intensity*	(MJ/sqm)
TEE	*Total Embodied Energy*	(MJ)
ew	*Exterior Wall*	
w	*Window*	
r	*Roof*	
es	*Exterior Slab*	
ft	*Floor Topside*	
fu	*Floor Underside*	
c	*Ceiling*	

Appendix 2
Building Stock Calculation

Building Component		Total Area (sqm)	Weight per Area (kg/sqm)	Weight (kg)
Facade	Exterior Wall	$P * FH * S * (1 - WWR)$	$\sum_{1}^{k}(ewT_k * ewD_k)$	$P * FH * S * (1 - WWR) * \sum_{1}^{k}(ewT_k * ewD_k)$
	Window	$P * FH * S * WWR$	$\sum_{1}^{k}(wT_k * wD_k)$	$P * FH * S * WWR * \sum_{1}^{k}(wT_k * wD_k)$
Roof		A	$\sum_{1}^{k}(rT_k * rD_k)$	$A * \sum_{1}^{k}(rT_k * rD_k)$
Exterior Slab		A	$\sum_{1}^{k}(esT_k * esD_k)$	$A * \sum_{1}^{k}(esT_k * esD_k)$
Floor Unit	Topside	$A * (S - 1)$	$\sum_{1}^{k}(ftT_k * ftD_k)$	$A * (S - 1) * \sum_{1}^{k}(ftT_k * ftD_k)$
	Underside	$A * (S - 1)$	$\sum_{1}^{k}(fuT_k * fuD_k)$	$A * (S - 1) * \sum_{1}^{k}(fuT_k * fuD_k)$
	Ceiling	$A * S$	$\sum_{1}^{k}(cT_k * cD_k)$	$A * S * \sum_{1}^{k}(cT_k * cD_k)$
Interior Wall		$A * S * IWC$	$\sum_{1}^{k}(iwT_k * iwD_k)$	$A * S * IWC * \sum_{1}^{k}(iwT_k * iwD_k)$
Interior Furnishing		$A * S * IFC$	$\sum_{1}^{k}(ifT_k * ifD_k)$	$A * S * IFC * \sum_{1}^{k}(ifT_k * ifD_k)$
Total Building Stock(kg)		$S * \{P * FH * (1 - WWR) * \sum_{1}^{k}(ewT_k * ewD_k) + P * FH * WWR * \sum_{1}^{k}(wT_k * wD_k) + A * \sum_{1}^{k}(ftT_k * ftD_k) + A * \sum_{1}^{k}(fuT_k * fuD_k) + A * \sum_{1}^{k}(cT_k * cD_k) + A * IWC * \sum_{1}^{k}(iwT_k * iwD_k) + A * IFC * \sum_{1}^{k}(ifT_k * ifD_k * ifEEC_k)\} + A * \sum_{1}^{k}(rT_k * rD_k) + A * \sum_{1}^{k}(esT_k * esD_k) - A * \sum_{1}^{k}(ftT_k * ftD_k) - A * \sum_{1}^{k}(fuT_k * fuD_k)$		
Building Stock Intensity (kg/sqm)		$S * \{P * FH * (1 - WWR) * \sum_{1}^{k}(ewT_k * ewD_k) + P * FH * WWR * \sum_{1}^{k}(wT_k * wD_k) + A * \sum_{1}^{k}(ftT_k * ftD_k) + A * \sum_{1}^{k}(fuT_k * fuD_k) + A * \sum_{1}^{k}(cT_k * cD_k) + A * IWC * \sum_{1}^{k}(iwT_k * iwD_k) + A * IFC * \sum_{1}^{k}(ifT_k * ifD_k * ifEEC_k)\} + A * \sum_{1}^{k}(rT_k * rD_k) + A * \sum_{1}^{k}(esT_k * esD_k) - A * \sum_{1}^{k}(ftT_k * ftD_k) - A * \sum_{1}^{k}(fuT_k * fuD_k) / A * S$		

Appendix 3
Embodied Energy Calculation

Building Component		Total Area (sqm)	Weight per Area (kg/sqm)	Weight (kg)
Facade	Exterior Wall	$P * FH * S * (1 - WWR)$	$\sum_{1}^{k} (ewT_k * ewD_k * ewEEC_k)$	$P * FH * S * (1 - WWR) * \sum_{1}^{k} (ewT_k * ewD_k * ewEEC_k)$
	Window	$P * FH * S * WWR$	$\sum_{1}^{k} (wT_k * wD_k * wEEC_k)$	$P * FH * S * WWR * \sum_{1}^{k} (wT_k * wD_k * wEEC_k)$
Roof		A	$\sum_{1}^{k} (rT_k * rD_k * rEEC_k)$	$A * \sum_{1}^{k} (rT_k * rD_k * rEEC_k)$
Exterior Slab		A	$\sum_{1}^{k} (esT_k * esD_k * esEEC_k)$	$A * \sum_{1}^{k} (esT_k * esD_k * esEEC_k)$
Floor Unit	Topside	$A * (S - 1)$	$\sum_{1}^{k} (ftT_k * ftD_k * ftEEC_k)$	$A * (S - 1) * \sum_{1}^{k} (ftT_k * ftD_k * ftEEC_k)$
	Underside	$A * (S - 1)$	$\sum_{1}^{k} (fuT_k * fuD_k * fuEEC_k)$	$A * (S - 1) * \sum_{1}^{k} (fuT_k * fuD_k * fuEEC_k)$
	Ceiling	$A * S$	$\sum_{1}^{k} (cT_k * cD_k * cEEC_k)$	$A * S * \sum_{1}^{k} (cT_k * cD_k * cEEC_k)$
Interior Wall		$A * S * IWC$	$\sum_{1}^{k} (iwT_k * iwD_k * iwEEC_k)$	$A * S * IWC * \sum_{1}^{k} (iwT_k * iwD_k * iwEEC_k)$
Interior Furnishing		$A * S * IFC$	$\sum_{1}^{k} (ifT_k * ifD_k * ifEEC_k)$	$A * S * IFC * \sum_{1}^{k} (ifT_k * ifD_k * ifEEC_k)$
Total Embodied Energy of Building (MJ)		$S * \{P * FH * (1 - WWR) * \sum_{1}^{k} (ewT_k * ewD_k * ewEEC_k) + P * FH * WWR * \sum_{1}^{k} (wT_k * wD_k * wEEC_k) + A * \sum_{1}^{k} (ftT_k * ftD_k) + A * \sum_{1}^{k} (fuT_k * fuD_k) + A * \sum_{1}^{k} (cT_k * cD_k * cEEC_k) + A * IWC * \sum_{1}^{k} (iwT_k * iwD_k * iwEEC_k) + A * IFC * \sum_{1}^{k} (ifT_k * ifD_k * ifEEC_k)\} + A * \sum_{1}^{k} (rT_k * rD_k * rEEC_k) + A * \sum_{1}^{k} (esT_k * esD_k * esEEC_k) - A * \sum_{1}^{k} (ftT_k * ftD_k * ftEEC_k) - A * \sum_{1}^{k} (fuT_k * fuD_k * fuEEC_k)$		
Embodied Energy Intensity (MJ/sqm)		$S * \{P * FH * (1 - WWR) * \sum_{1}^{k} (ewT_k * ewD_k * ewEEC_k) + P * FH * WWR * \sum_{1}^{k} (wT_k * wD_k * wEEC_k) + A * \sum_{1}^{k} (ftT_k * ftD_k) + A * \sum_{1}^{k} (fuT_k * fuD_k) + A * \sum_{1}^{k} (cT_k * cD_k * cEEC_k) + A * IWC * \sum_{1}^{k} (iwT_k * iwD_k * iwEEC_k) + A * IFC * \sum_{1}^{k} (ifT_k * ifD_k * ifEEC_k)\} + A * \sum_{1}^{k} (rT_k * rD_k * rEEC_k) + A * \sum_{1}^{k} (esT_k * esD_k * esEEC_k) - A * \sum_{1}^{k} (ftT_k * ftD_k * ftEEC_k) - A * \sum_{1}^{k} (fuT_k * fuD_k * fuEEC_k) / A * S$		

Appendix 4
Calculation Figures for Validation

Borough	Method		Waste Estimation (tons)	
			2013	2017
Brooklyn	C&D Waste Report	Residential	123745	65202
		Commerical*	51919	51919
	National Report**		198851	135899
	Thesis Model		214331	149031
Bronx	C&D Waste Report	Residential	41384	38102
		Commerical*	24432	24432
	National Report**		72856	24651
	Thesis Model		76720	28005
Manhattan	C&D Waste Report	Residential	21085	17029
		Commerical*	171027	171027
	National Report**		264316	165926
	Thesis Model		271396	168222
Queens	C&D Waste Report	Residential	86052	59136
		Commerical*	45811	45811
	National Report**		160150	80273
	Thesis Model		180100	102947
Staten Island	C&D Waste Report	Residential	14124	17439
		Commerical*	12216	12216
	National Report**		65180	11895
	Thesis Model		76186	18905
NYC	C&D Waste Report	Residential	286390	194201
		Commerical*	305405	305405
	National Report**		761354	418644
	Thesis Model		818732	467111

*The same applies in two years because data on the commercial sector exists only for one year.

**As a result of compiling the report, 771.42kg/sqm for Nonresidential building, 244.12kg/sqm for Single-familiy House, and 620.07kg/sqm for Multi-family house were multiplied by the total floor area.

국문초록

총체적인 관점에서 도시의 에너지 소비를 분석하고, 도시계획과 도시개발에서 더욱 정보에 입각한 의사결정을 하기 위해서는 도시의 내재에너지와 도시 형태의 관계에 대한 연구가 시급하다. 이 논문은 도시 형태의 두 가지 주요 요소인 도시 밀도, 토지 이용이 도시의 내재에너지에 어떤 영향을 미치는지를 탐구한다. 그에 따라 네 가지의 주요 연구 질문을 설정하였고 각 질문에 대한 답을 찾는 방식으로 연구를 진행하였다. 네 가지의 주요 연구 질문은 다음과 같다: 1) 도시 밀도가 내재에너지에 어떤 영향을 미치는가? 2) 토지 이용이 내재에너지에 어떤 영향을 미치는가? 3) 도시 밀도, 토지 이용 및 기타 변수들이 내재 에너지에 공동으로 어떤 영향을 미치는가? 4) 어떻게 연구 결과가 도시 에너지 소비 저감을 위한 종합적 전략에 기여할 수 있는가? 이다. 본 논문은 주요 연구 질문에 답하기 위해 도시 환경의 내재에너지를 추산하기 위한 모델을 새롭게 개발하여 가상 환경과 실제 도시 환경이라는 두 가지 유형의 실험 환경에 적용하였다. 그 결과 첫 번째 연구 질문에 대한 답으로 고밀도의 도시 환경이 내재 에너지 측면에서 유리하다는 일부 선행 연구에서 내렸던 판단을 지지하는 결과를 얻었다. 하지만 이 연구에서는 단지 고밀도의 도시환경이 내재 에너지 측면에서 유리하다는 결과를 확인하는 것으로 그치지 않고, 대표적인 도시개발 규제 도구로 사용되는 용적률과 건폐율을 도시 밀도의 변수로 선정하여 각 변수의 측면에서 영향력과 내재 에너지를 절감하기 위한 효과적인 범위에 대해 논하였다. 두 번째 질문인 토지 이용과 관련해서는 가상의 도시 환경 실험에서 토지 이용의 변화가 내재 에너지에 유의미한 차이를 만들어 내는 것을 확인하였으며, 그 영향력을 정량적으로 평가하였고 그 이유에 대해서 논하였다. 그러나 실제 환경에 대한 실험에서는 산업 용도의 토지이용 비율을 제외하고는 다른 모든 토지 이용 관련 변수들이 내재에너지에 유의미한 영향을 미친다는 증거를 찾지 못했다. 세 번째 연구 질문과 관련하여 실제 도시 환경에서 다양한 변수들의 영향력을 고려하기 위하여 다변량 선형 회귀분석을 실시하였으며 공간적 자기 상관을 고려하기 위하여 Ordinary Least Squares 방법과 Geographically Weighted Regression 방법을 모두 사용하였다. 선정된 변수 중 상대적 중요도는 용적률이 가장 컸고, 산업 용도의 토지이용 비율이 가장 낮았다. 마지막으로 도시 에너지 소비

저감을 위한 종합적 전략의 측면에서, 본 연구에서 수행한 두 가지 환경에 대한 실험 결과는 도시환경에서 에너지 소비의 세 가지 요소인 교통에너지, 운용에너지, 내재에너지가 지속가능한 개발을 위해서 균형 있게 고려되어야 한다는 것을 시사한다.

키워드: 내재 에너지, 도시 밀도, 토지 이용, 도시 형태, 지속가능한 개발, Life Cycle Assessment

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