

Building Characteristics, Urban Contextual Form and Energy Use in Seoul—A Local Climate Zones Typology Approach

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ABSTRACT

The influence of urban contextual form in the studies on the relationship between built form and building energy has been attracting increasing attention. However, most emerging studies on this idea adopted form indicators on the basis of urban planning conventions and researchers' expertise to measure the urban contextual form. This indicator approach often suffers from confounding effects in research and lacks a clear connection to urban energy policy. With the understanding that urban form is often self-organized and self-adapted as a complex system, this study takes a typology approach to measure urban contextual form. Particularly, the local climate zone (LCZ) is used as the typology framework, which has been developed in the urban climatology field to establish standard urban form typologies on the basis of thermal performance. The LCZ typologies connect the individual buildings to their contextual areas through mutual shading and microclimate pathways, which are among the major mechanisms behind the relationship between built form and building energy use. With the LCZ approach, this study investigates how urban contextual forms as typologies influence building energy use in Seoul. The research is divided into two steps. In the first step, an LCZ map for Seoul is created using a GIS-based LCZ mapping method. In the second step, the linear mixed model is employed to examine how individual building characteristics and urban contextual form defined by LCZ classes influence annual building energy use in Seoul in 2018. Results show that LCZ classes significantly influence building energy use both directly and indirectly. The findings suggest a promising application of

the LCZ framework in urban energy policies, in addition to its application in microclimate-oriented urban management.

Keywords: sustainable urban form, urban form typology, linear mixed model, urban energy planning, residential energy

1. INTRODUCTION

Urban areas account for a large share of energy consumption, with an estimated 71%–76% of total CO₂ being produced by cities [1]. Within cities, buildings are major energy consumers, which on average utilize 34% of total energy [2]. Although the energy efficiency of individual buildings has been extensively researched to develop design codes, the impact of urban form on building energy consumption has received limited attention. Urban form provides the urban context of a building where heat exchange, mutual shading, and shared influence of urban form and individual building on microclimate exist. The urban context influence can be significant on building energy use. Ratti, Baker [3] found that the urban contextual form (also called urban geometry), by the pathway of mutual shading, can explain 10% of the variance observed in building energy consumption for the same dimensions and use of the building. When mutual shading and microclimate effects are considered, different urban contextual forms can lead to the variation of building energy use of –7.7%–16.6% [4]. To improve building energy efficiency within cities, policy and design decisions must be taken not only at the scale of individual buildings, but also at the scale of urban form.

How to measure this urban contextual form for urban energy policy? According to Quan and Li [5], urban form can be measured by indicators or as typologies. Compared to the indicator approach, the typology approach finds good balances for urban form measurement between being general and unique and between being abstract and detailed. Particularly, typology regards urban form as a complex system comprising complex interactions rather than a group of simple indicators. Given its capability to reflect the complexity of urban form, in urban planning and design practice, urban form typologies have been widely adopted [6]. In the field of urban form and building energy, three main typology approaches were adopted: housing type, Martin and March's form prototypes [7], and classification of urban form with respect to certain urban factors [5]. Studies based on housing type, such as Li, Song [8], and those based on form prototype are often overly generic to apply to complex urban forms in a large urban area [4]. Studies based on classification of urban form often focused on a few urban area samples, lacking the definition of criteria for classifying a larger area or even an entire city into typologies [9]. Furthermore, they often lack or only have a weak connection to pathways linking urban typology to building energy consumption.

The search for an appropriate classification of urban form types has already been intensively studied in the field of urban climatology, but with the goal of reflecting microclimate. One of the most recent and influential developments in that field, the Local Climate Zone (LCZ) framework [10], provides a standardized urban form database as LCZ classes. The framework's objective is to develop urban and natural form classification for urban heat island studies, which is universal and agnostic to local conditions and differences in perceived definitions of urban form terminologies. It comprises 17 classes divided into two categories. Built type LCZ comprises 10 LCZ classes labeled from LCZ 1 to 10. Land cover type LCZ comprises six LCZ classes labeled from LCZ A to G. Each LCZ class is defined by seven geometric parameters and three thermal parameters [10].

LCZs have great potential as urban contextual form typologies in building energy studies because of their thermal related nature of urban form classification. The pathways of heat exchange, mutual shading and microclimate in urban form–building energy relationships can be well captured by the definition of LCZs. Therefore, many scholars have explored the application of LCZ framework in urban building energy studies. Quan, Dutt [11] have suggested that LCZs can be

deployed as an urban form identifier to measure the influence of urban context on building energy consumption. Wu, Sharifi [12] made progress in this direction in their study of carbon emissions from building energy consumption. Although their study showed emissions intensity differences between LCZ classes, it did not consider any other covariates to isolate the impact of urban form on carbon emissions.

This study aims to contribute to this direction of research by utilizing LCZs as urban contextual form typologies to examine the relationship between building form, urban form, and building energy use. The study focuses on the case area of Seoul.

2. METHODOLOGY

2.1 Study Scope

Seoul is the capital and largest city in South Korea, with a total area of 605 KM². Water bodies occupy roughly 10% of the area, and 25% of land falls under the green belt. Despite intense real estate pressure for development, many sparsely developed areas exist within the city's boundary. A mix of compact low-rise housing, open slab style apartments, and tower style office building along with natural features makes for a widely diverse and irregular urban pattern within the city. In this study, building energy use intensity (EUI) (energy use per floor space) for residential buildings in the year of 2018 is simply calculated as the sum of electricity and gas usages for exploratory analysis.

2.2 Data Collection and Processing

Residential building energy consumption and building characteristics dataset for Seoul were collected from the government portal [13]. Building energy consumption data comprises monthly electricity and gas consumption of multi-unit residential buildings. Building characteristics data comprises building footprint and its attributes. Buildings missing building energy consumption information for any of the months were removed from the dataset.

The number of buildings was 11,892 after filtering. Building level parameters; cover ratio, height, real estate price, and building age were calculated and organized. Table 1 provides the summary statistics. Cover ratio and height are primary zoning regulations that buildings must comply with. Another related parameter is floor area ratio, but it was excluded due to multicollinearity issues. Building age was included given that it often relates to the thermal efficiency of a building. Real estate price was used as an indicator for economic status, which is an

Table 1. Descriptive Statistics ($n = 11,886$)

Variable Type	Variable	Mean	SD	Min	Max	Unit	Description
Dependent Variable	Annual EUI	263.30	80.37	46.02	602.76	kWh/m ²	Sum of electricity and gas use intensity for the whole year (2018).
Level-1 Independent Variable (Building)	Cover Ratio	39.99	12.19	6.44	81.29	%	Building footprint area/Plot area * 100
	Height	31.57	12.36	6.03	102.70	M	Estimated from floors for some buildings
	Real Estate Price	34.55	15.31	4.06	112.03	100,000 KRW/m ²	Total price of plot/Total floor area
	Building Age	25.48	11.46	0	59	Years	In the year 2020
Level-2 Independent Variable (Urban Form)	LCZ Class	N/A	N/A	N/A	N/A	N/A	LCZ class of grid in which the building is located.

important covariate of EUI.

2.3 LCZ Classification

To prepare the LCZ map of Seoul, the city was divided into 400 m X 400 m grids and LCZ parameters were calculated for each grid. Terrain roughness class and thermal parameters were not considered due to their subjective nature and difficulty in accurately measuring them [14]. Additionally, given that detailed location and height of trees were not available, LCZ A–D (dense tree, scattered tree, bush or scrubs, and low plants) were combined to LCZ green. An attempt was made to classify each grid on the basis of parameter ranges specified by Stewart and Oke [10]. For grids that did not satisfy all parameter ranges for any of the LCZ classes, Random Forest was used to identify the closest LCZ class. The LCZ class of grid in which a building is located was identified.

LCZ large low rise had only six buildings with complete building energy data and thus was excluded from the analysis. Thus, the final sample size was 11,886, with LCZ open high rise having the highest number of observations (2,430) and LCZ sparse having the smallest number of observations (521).

2.3 Model Specification

Linear Mixed Model (LMM) was used in this study to model inter-group and intra-group dependency together [15]. LMM was used on the basis of statistical tests and the nested nature of data. First, intraclass correlation was 33.78% ($p < 0.01$), indicating a moderate amount of variance in annual EUI can be attributed to LCZ classes. Conceptually, the buildings are spatially nested within the LCZ grid, justifying the use of this kind of specification.

A relatively simpler alternative with a more intuitive interpretation would be separate Ordinary Least Square (OLS) regression for each LCZ class. Separate OLS provides the influence of building level parameter in different LCZ classes. However, measuring the direct

impact of LCZ would not be possible, and the different sample sizes of each model could be an issue, especially for LCZ classes with a smaller number of observations. Additionally, as Steenbergen and Jones [15] described, although OLS with LCZ as the dummy variable interacted with the predictor can be used as an alternative to LMM, this would be problematic for multiple reasons. Observations within the same LCZ would generally be more similar than observations in other LCZs, violating the assumption of independent observation. Additionally, such dummy variables would only indicate LCZ class difference but not explain why model parameters vary across LCZ classes [15].

Thus the LMM used here is:

Level 1 (Building level):

$$Y_{ij} = B_{0j} + B_{1j}CR + B_{2j}HT + B_{3j}REP + B_{4j}Age + r_{ij}.$$

Where Y_{ij} is the annual EUI of building i in group j , B_{0j} is the intercept, $B_{1j}, B_{2j}, B_{3j}, B_{4j}$ are the slope for cover ratio, height, real estate price, and building age for group j , respectively, and r_{ij} is the error component. i and j refer to individual building and LCZ class. The Level 1 equation looks highly similar to OLS multiple regression except for j subscript. The j subscript indicates that different coefficients are estimated at Level 1 for each of Level 2 units (LCZ classes).

Level 2 (Urban form level):

$$B_{0j} = \gamma_{00} + u_{0j}$$

$$B_{1j} = \gamma_{10} + u_{1j}$$

$$B_{2j} = \gamma_{20} + u_{2j}$$

$$B_{3j} = \gamma_{30} + u_{3j}$$

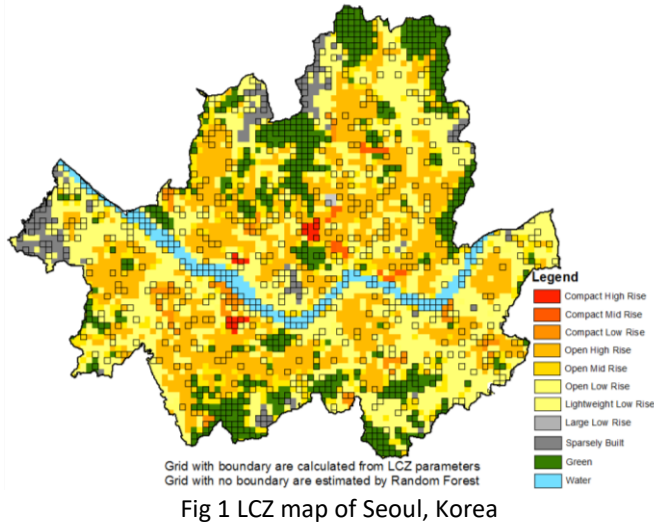
$$B_{4j} = \gamma_{40} + u_{4j}.$$

Where γ_{00} is the overall intercept., and $\gamma_{10}, \gamma_{20}, \gamma_{30}, \gamma_{40}$ are the fixed effects for cover ratio, height, real estate price, and building age. u_{0j} is the random intercept. $u_{1j}, u_{2j}, u_{3j}, u_{4j}$ are the random slopes for cover ratio, height, real estate price, and building age, respectively.

3. RESULTS

3.1 LCZ Classification Results

Figure 1 shows the LCZ map of Seoul. In total, 22.45% of grids were identified following the classification method on the basis of the LCZ parameters, meanwhile the rest were identified using the Random Forest classification algorithm.



3.2 Model Results

Table 2 shows the results of the fixed effects. Intercept and four coefficients are significant at the 99% confidence interval. Significance calculation in LMM differs from OLS regression due to uncertainty associated with calculating the degree of freedom [16] but retains the same interpretation. Cover ratio, building age, and real estate price are positively related to EUI, whereas height is negatively related. Although this is in line with general expectation, as Quan and Li [5] showed, the direction of the relationship could vary on the basis of the climatic region and even with study methodology.

The marginal R^2 of the model was 0.411, whereas the conditional R^2 of the model was 0.525. Marginal R^2 is variance explained by the fixed factors, whereas conditional R^2 is variance explained by fixed and random factors [17]. Thus, LCZs explained 11.4% variance in EUI, in line with several previous studies [5].

3.3 Statistical Model Diagnostics

According to Zuur, Ieno [18], the main assumptions of LMM are as follows. First, the linearity of relationship. Second, the normality of residuals. Third, the homogeneity of residuals. The three assumptions can be visually tested using the Q-Q plot, residual distribution curve plot, and category wise residual boxplot,

respectively. All four Level 1 variables did not show deviation from linearity. However, a slight violation of the assumption of normality and homogeneity of residuals was observed. However, the violation in both cases appears to be minor and should not cause major issues with model estimation or interpretation [18].

Table 2 Model Results

Fixed Effect					
Variable	Coef	SE	t value	Sig [#]	
Intercept	184.79	7.51	24.42	***	
Cover Ratio	1.65	0.13	12.94	***	
Height	-2.61	0.10	-24.35	***	
Building Age	0.81	0.09	9.48	***	
Real Estate	2.04	0.11	17.81	***	
# ***p<0.01.					
Random Effect					
LCZ	Intercept	CR	Height	Age	REP
Compact High	5.56	-0.26	-0.24	0.03	-0.03
Compact Mid	7.26	-0.29	0.13	-	-0.16
Compact Low	8.5	-0.31	0.17	-	-0.3
Open High	-4.56	0.12	-0.26	-0.1	0.45
Open Mid Rise	-1.8	0.06	-0.05	0.08	-0.22
Open Low Rise	0.12	-0.01	-0.13	0.05	0.17
Lightweight	2.66	-0.06	0.17	-0.1	-0.12
Sparsely Built	3.7	-0.22	0.55	0.12	-0.32
Green	-6.68	0.34	-0.25	0.14	0.19
Water	-14.69	0.57	-0.1	0.02	0.37

4. DISCUSSIONS

The results in Table 2 indicate that the urban form defined by LCZ classes directly influences annual EUI and changes the magnitude of the impact of building characteristics commonly used for regulating urban development. The significant nature of building level parameter and large random effect shows model specification's strength in measuring the impact of urban form on EUI when LCZ classes are used to specify the urban form. The typology-based approach where typologies are defined by parameters directly related to underlying pathways allows for a simplified but comprehensive way to model effects compared with utilization of generic urban form indicators.

To quantify the impact of LCZ, LCZ sparse is used as the baseline scenario. Given that building in LCZ sparse generally lack any urban context, its intercept and coefficient serve as a contrast to determine the relative impact of other LCZ classes.

The intercepts explain how LCZ classes directly influence an individual building's annual EUI. Assuming LCZ sparse as a baseline condition, LCZ compact high, mid, low rise increases EUI by 1.86, 3.56, 4.8 kWh/m²,

respectively. LCZ open high, mid, low, and lightweight low rise decrease EUI by 8.26, 5.5, 3.58, 1.04 kWh/m², respectively. This indicates that in urban areas, when a building context is densely built, its EUI increases compared with a building located in a sparsely built area. The magnitude of effect increases with a decrease in context's height. However, when the building context is openly built, its EUI decreases compared with a building located in a sparsely built area. The magnitude of effect decreases with a decrease in context's height.

The random slopes explain how LCZ classes affect building characteristics' influence on its annual EUI. For cover ratio, LCZ compact high, mid, and low rise have smaller coefficients than open high, mid, and low rise. This indicates that the increase in cover ratio in already compact areas has a smaller influence on annual EUI than the increase in cover ratio in relatively open areas. This broadly indicates that the as the urban contextual area becomes more compact, the magnitude of influence that building cover ratio exerts over the building EUI decreases.

For height, building age, and real estate price, although LCZ changes coefficients, no clear trend is observed. However, marginal plots (Fig. 2) provide the ability to analyze random intercept and coefficient together. For simplicity, the focus is on major build area LCZs (compact/open-high/mid/low) where residential buildings are concentrated. Figure 2a indicates that below 40% cover ratio, for all six LCZs, annual EUI increases with the increase in cover ratio and all LCZ have lower annual EUI than LCZ sparse. Post 40% cover ratio, LCZ compact high, mid, and low rise have higher annual EUI than LCZ sparse. Figure 2b indicates that for all six LCZs, annual EUI decreases with the increase in height. When height increases beyond 28 M, all six LCZs have lower annual EUI than LCZ sparse. Figure 2c indicates that for all six LCZs, annual EUI decreases with the increase in real estate price. At a relatively lower real estate price, all six LCZs have lower annual EUI than LCZ sparse. However, at relatively higher real estate price, only two compact LCZs have lower annual EUI than LCZ

sparse. Figure 2d indicates that for all six LCZs, annual EUI increases with building age, and most of LCZs have lower EUI than LCZ sparse.

5. CONCLUSIONS AND POLICY IMPLICATIONS

This study uses the large and detailed electricity and gas dataset to study the influence of urban form on residential building energy consumption in Seoul, Korea. Unlike previous studies, which often ignored the urban contextual form or deployed a subjective list of indicators to measure the urban contextual form, this study uses LCZ classes, which are closely related to thermal properties of built environment to measure the complex urban contextual form. The LCZ typologies are supposed to connect the individual buildings to their surrounding areas through mutual shading and microclimate pathways, which are among major mechanisms by which urban form influences building EUI [5].

LMM is used to explain the annual EUI of residential buildings in Seoul on the basis of building level parameters and urban contextual form typologies. Using building level parameters, cover ratio, height, real estate price, and building age as well as urban form level parameter of LCZ class, the direct and indirect impact of urban contextual form on EUI is explored. The results suggest that on the one hand, urban contextual form typology defined as LCZ classes directly influences the annual EUI of residential building, and on the other hand, it changes how building characteristics impact the building EUI. Based on intercepts of the model, in Seoul, LCZs compact high rise, compact mid-rise, and compact low rise increase EUI directly, whereas LCZs open high rise, open mid-rise, open low rise, and lightweight low rise decrease EUI directly. Additionally, by the pathway of modifying the impact of building's characteristics, LCZ indirectly also influences EUI, but no consistent pattern across LCZ classes is observed. Although the overall nature and magnitude of the impact of LCZ on building EUI would depend heavily on the region's weather and building characteristics, the study provides preliminary

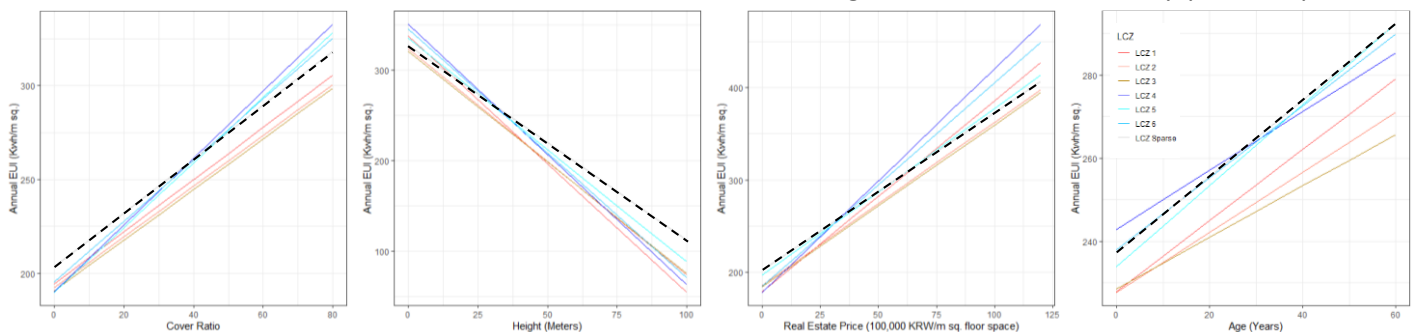


Fig 2 Marginal plots for cover ratio(a), height(b), real estate price(c) and building age(d) (left to right)

evidence on the suitability of LCZ as a measure of urban contextual form for urban building energy studies.

The methodology assumes that urban form's influence on EUI is fully explained by area within a grid. Although the grid size used in this study is based on the minimum size suggested by Stewart and Oke [10] to ensure upwind stabilization, it is not necessarily the optimal basic spatial unit of urban form typology. Additionally, the urban form of a building is defined by the building's location in a predefined grid. Thus, a building located at the center or near the center of the grid has a relatively more accurate urban form definition than a building close to a grid's boundary.

This study presents a promising application of the LCZ framework for urban energy management policies, in addition to its straightforward application in microclimate oriented urban management. However, how to integrate the LCZ framework that is based on thermal properties of urban form into conventional zoning and land-use controls in planning requires further research [14, 19]. Furthermore, other urban factors, including socio-economic and cultural factors, can be introduced to extend the definitions of LCZ typologies to measure the urban contextual form that is complex and multi-dimensional. The future study will also consider electricity and gas usage separately.

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