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Urban Form Typology and Building Energy Use: Empirical Investigation in Seoul

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ABSTRACT

Urban form play an important role in influencing building energy use. Previous empirical studies on urban form and building energy mostly represented urban form as separate indicators of form components and socio-economic conditions. However, urban form is a complex system that consists of different components and interactions. Thus, simply considering urban form as an aggregation of their components and properties often suffers from strong correlations among these factors and the confounding effect as in previous studies. To better understand the energy performance of complex urban form, this study identifies urban form typologies in Seoul using unsupervised learning and examines the energy performance of those typologies. The Gaussian mixture model (GMM), a widely used clustering method, is adopted to identify 16 urban form typologies based on 10 common urban form and population distribution factors. Electricity use and gas use in different typologies in 2019 are collected and compared using the Brown Forsythe ANOVA and Games Howell post hoc test. Results suggest that urban form typologies reflect energy efficiency to a certain degree, and the difference in energy efficiency across urban form typologies is more significant in gas than in electricity because of occupant behavior differences in their use. Among the urban form typologies, high-rise high-density urban form type is the most efficient, and the high-rise mixed type is the least efficient. The findings from this research could help urban planners and designers to understand the relationship between complex urban form and building energy better to support planning and design toward an energy-efficient urban form.

Keywords: urban morphology, clustering, building energy consumption, Gaussian mixture model, urban planning

1. INTRODUCTION

Cities accounted for about 75% of global energy use and approximately 60% - 70% of carbon emissions [2, 3]. Building energy use accounts for the largest proportion of urban energy consumption [4, 5], accounting for approximately 40% of total primary energy consumption [6]. In the age of climate change, cities need to increase energy efficiencies in buildings and reduce carbon emissions. The urban geometry affects building energy use through solar access, shading effects and microclimate [7, 8]. Thus, understanding urban form typologies in terms of building energy use can help achieve energy-efficient urban forms in cities.

A growing number of research examine the relationship between urban form and building energy use. In the empirical approach. Li, Song [9] described the impact of urban form on residential electricity consumption by using a multilevel regression model on survey data from 534 households in 46 neighborhoods. At the housing unit, the urban form is described as a single-family house, a slab apartment, and a tower apartment. At the neighborhood level, FAR, street layout, and proximity to natural water features are specified. Chen, Matsuoka [10] found the connection

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among urban form factors and household energy use by analyzing 231 communities with multiple linear regression. The urban form is defined by 11 urban form factors, which include four building characteristics and three demographic indicators. They found the population density as the most important urban form factors. In Seoul, You and Kim [11] showed that architectural, land-use and urban design affect residential energy efficiency. The study analyzed four housing types (e.g., Single-family house, Multi-family house, Multi-unit housing I, and Multi-unit housing II) and their surrounding morphological characters for 400 buildings. Oh, Jang [2] found surface-to-volume ratio and obstruction angles were important to energy consumption through correlation coefficient analysis.

Empirical research has validated many theoretical hypotheses and shown a strong link between urban form and building energy use. It remains, however, difficult to apply in urban planning and design practice with following two issues. First, urban form is defined as housing types or building characters. Other essential components of a city, such as blocks, plots, roads, green areas, and water bodies, nor ~~are~~ their interrelationships, are not included. Second, the urban form indicators are usually based on building characters or on thermal-related criteria. Thus, interpreting and implementing the results in urban planning and design practice are difficult.

These issues could be addressed via study on the relationship between urban form typologies and building energy use. First, studies on urban form typology could define urban form as the commonly used units in planning. This study describes urban form as a block that considers the plots, buildings, greens, and water bodies. Second, urban form measurements are selected on the basis of widely-used parameters in urban planning. Thus, the results are easily interpreted by urban planners. Third, typologies refer to the clustering of the current urban forms in cities.

The typology approach is used to classify similar urban form patterns. These urban form typologies imply the history of the city and the development of human activities. Urban form typologies reflect real-world conditions. Therefore, this research identifies urban form typologies for the entire city using Gaussian mixture model (GMM) and examines their energy efficiency accordingly by analyzing variance (ANOVA) post hoc test. The research question is whether urban form typologies reflect energy efficiency in urban planning practice.

2. RESEARCH SCOPE AND DATA

The study area is Seoul, which is the capital and most populated city in the Republic of Korea, covering approximately 605 km^2 and has a population density of approximately 16,000 people per km^2. Seoul is composed of various urban form typologies developed over hundreds of years.

The unit of analysis is a block. Block is the district planning and urban redevelopment unit in the Republic of Korea. A block is defined as an island surrounded by 8 m wide roads in this study. The Building Act stipulates that the minimum width of roads to be 4 meter. However, there are no explicit provisions for the definition of the block. This study uses an 8 m wide road rather than a 4 m wide road to define the block to reduce the standard deviation of the block size. The study is based on the data from 2019. The National Geographic Information Institute (NGII) provides data about urban geometry, including streets, buildings, green spaces, rivers, and information on building ages. The Seoul Metropolitan Government (SMG) offers de facto population of Seoul. The Ministry of Land, Infrastructure, and Transport (MLIT) provides monthly gas and electricity use, and plot information.

Table 1. Urban form measures for the block

Division	Name	Unit	Description	Source
Urban geometry factor	Number of plots	N/m^2	Total number of plots / block area	MLIT
	Average plot size	m^2	Average plot area in a block	MLIT
	Number of buildings	N/m^2	Total number of buildings / block area	NGII
	Average building height	m	Average building height in a block	NGII
	FAR	n/a	Total floor area / block area	NGII
	Building coverage ratio	n/a	Total building footprint area / block area	NGII
	Green area ratio	n/a	Total green area / block area	NGII
	Waterbody area ratio	n/a	Total waterbody area / block area	NGII
Socio-economic factor	Average building age	year	Average building age in a block	MLIT
	Population density	N/m^2	Average population at 3 am and 3 pm / block area	SMG

The urban form indicators are 10 widely-used urban planning parameters (Table 1): number of plots, average plot size, number of buildings [10], average building height [10], FAR [9], building coverage ratio [12, 13], green area ratio, waterbody area ratio, average building age [10], and population density [10].

3. METHODS

The research question is whether urban form typologies reflect energy efficiency in urban planning practice. To answer the research question, the study followed two steps. First, this study identifies Seoul's urban form typologies using 10 urban form indicators with GMM to classify various urban form typologies. Second, the ANOVA test is used to determine the differences in energy efficiency across urban form typologies. The Brown–Forsythe ANOVA and Games–Howell post hoc tests are used to compare energy efficiency.

The sklearn package in Python was used to implement GMM in Python 3.8.5. The ANOVA test was conducted in the SPSS (statistic software). The outputs were further analyzed and visualized in ArcGIS pro.

3.1. Identification of urban form typology

The study area is the built environment in Seoul. Thus, the blocks that have more than 0.95 of the natural environment ratio (e.g., green and waterbody area) are excluded as a non-built environment. The total number of blocks in the final study is 4424, which covers 65% of Seoul. Moreover, to minimize bias in clustering results, the study areas are divided into two groups. One group is blocks with water and green areas. The other group is blocks without water and green areas.

The GMM algorithm was used to cluster urban forms and define urban typologies. GMM is a soft version of k-means, which estimates the statistical probability of cluster memberships. This method is extensively used across different fields. It models a given dataset as a certain number of clusters with Gaussian distributions, which approximates urban form better than the k-means method. Performance is quantified by using the Bayesian information criterion (BIC), which is a penalized log-likelihood estimate. The initial mean vectors in the case with k-means, are selected randomly from features. Clustering quality is highly dependent on the starting circumstances [14, 15]. As a result, restarts are required to randomize starting centers. In this research, GMM is repeated 50 times and iterates up to 1000 times for each run.

3.2. Calculation of EUI in a block

A total of 42% of blocks contain electricity data, and only 26% have gas data. Thus, electricity and gas are examined, respectively. Building energy intensity (EUI) is building energy use divided by its total floor area. EUI of a block is the sum of the average monthly EUI of buildings within the block. To reduce outliers, this study analyzes EUI between the 5th and 95th percentiles of all blocks .

3.3. Comparison of energy efficiency

The ANOVA test is used to examine the statistical significance of variations in EUI across urban typologies. A post hoc test is used to analyze the mean differences in details by providing pairwise comparisons. The Brown–Forsythe ANOVA with Games–Howell post hoc test was used for the unequal variances and sample sizes of blocks in urban form typologies [16].

4. RESULTS

4.1. Urban form typologies

The GMM results indicate that Seoul has 16 urban form typologies. Fig 1 shows the spatial distribution of typologies in Seoul. The minimum Mahalanobis distance in typologies is represented as a typical urban form.

Typologies 1, 2, and 3 have an average building height of 12 m, and have high building density, population density, and building age, thereby referred as mid-rise compact residential area (Table 2). Typologies 4 and 12 imply a high-rise, high-density area with a small number of plots and large plot sizes. Typology 5 is a high-rise mixed apartment neighborhoods with high building height, high building coverage ratio, and high population

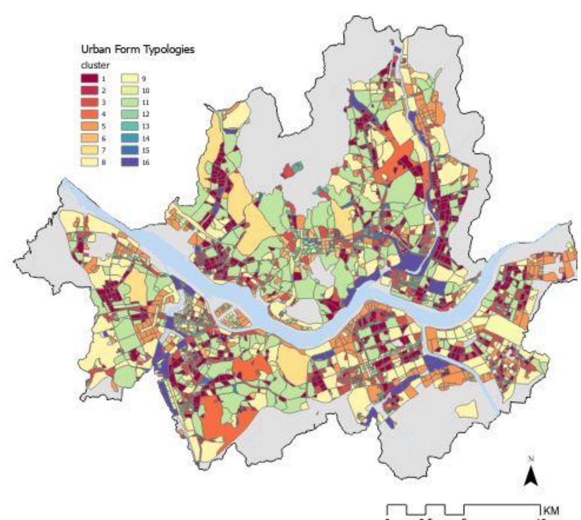

Fig 1. Mapping of urban form typologies in Seoul.

density. Typologies 6 and 9 have the highest FAR and population density, thereby referring to high-rise, high-density apartment areas. Typology 7 is the most prevalent urban typology, accounting for 22.63% of urban areas (Table 3). Typology 7 is a low-rise, high-density area with small plots' sizes and low building height. Typologies 8 and 10 have a high FAR and medium building coverage ratio. Typologies 13 and 15 are large plots with low building density and population, thereby suggesting the riverside mixed area. Typology 16 is large green areas with high building height.

4.2. Comparisons of energy efficiency

The Brown–Forsythe ANOVA test demonstrates that the electricity and gas use intensity vary among typologies. However, in the Games–Howell post hoc tests, the results show that not all EUI vary across pairwise comparisons. Tables 4 and 5 provide the statistically significant pairwise findings. In electricity, seven typologies are statistically significantly different from the rest. The remaining six typologies are homogenous, consisting of Typologies 2, 4, 8, 10, 13, and 14. The maximum difference is 52.46 kWh/m^2 between Low-rise compact typology (Typology 1) and High-rise high-density apartment typology (Typology 6). The minimum difference is 30.26 kWh/m^2 between Mid-rise high-density mixed apartment typology (Typology 5) and Mid-rise low-density typology (Typology 11). In gas, more typologies are significantly different from others in pairwise comparisons. EUI in eleven typologies are statistically different from the rest. The remaining five typologies are Typologies 9, 12, 13, 14, and 15. The maximum difference is 55.24 kWh/m^2 between High-rise low-density typology (Typology 4) and High-rise high-density apartment typology (Typology 6). The minimum difference is 23.06 kWh/m^2 between Low-rise compact area (Typology 1) and High-rise low-density typology (Typology 4).

Table 3. Number of typologies and availabe energy data

Typology	Number of blocks (N)	Pct. of typologies in total (%)	Pct. of blocks with electricity energy data (%)	Pct. of blocks with gas energy data (%)
1	456	10.30%	37%	22%
2	417	9.40%	43%	24%
3	645	14.60%	39%	18%
4	9	0.20%	56%	22%
5	419	9.50%	44%	18%
6	228	5.20%	38%	11%
7	1001	22.60%	42%	30%
8	5	0.10%	60%	40%
9	46	1.00%	52%	11%
10	281	6.40%	32%	15%
11	814	18.40%	47%	32%
12	3	0.10%	33%	0%
13	32	0.70%	38%	19%
14	57	1.30%	44%	14%
15	2	0.10%	50%	0%
16	9	0.20%	44%	22%
Total	4424	100%	42%	24%

Pct.: percentage.

Table 2. Mean value of urban form indicator in typologies

Typologies	Number of Plots (N/m2)	Average Plot Size (m2)	Number of Buildings (N/m2)	Average Building Height (m)	FAR (n/a)	Building Coverage Ratio (n/a)	Green Area Coverage Ratio (n/a)	Water Body Area Coverage Ratio (n/a)	Average Building Age (year)	Population density (N / m^2)
1	0.007	146.777	0.004	7.656	1.204	0.426	-	-	36.132	0.026
2	0.001	1087.553	0.001	18.194	1.715	0.206	-	-	23.815	0.006
3	0.003	354.500	0.002	10.753	1.310	0.323	-	-	29.727	0.026
4	0.000	16723.436	0.000	20.682	1.300	0.181	-	-	32.934	0.003
5	0.002	619.750	0.001	17.012	2.615	0.334	-	-	30.267	0.032
6	0.001	2329.745	0.000	37.607	4.169	0.282	-	-	22.445	0.025
7	0.004	234.324	0.003	9.549	1.425	0.406	-	-	27.602	0.009
8	0.000	14718.030	0.000	40.776	4.001	0.195	-	-	22.084	0.014
9	0.012	98.694	0.004	8.163	2.436	0.439	-	-	48.777	0.033
10	0.000	5187.292	0.000	30.124	1.797	0.158	-	-	26.459	0.004
11	0.003	396.187	0.002	11.196	1.653	0.310	-	-	27.512	0.006
12	0.000	23187.549	0.000	29.051	2.429	0.285	-	-	31.094	0.009
13	0.001	1198.119	0.000	12.457	0.790	0.111	0.186	0.183	27.485	0.003
14	0.004	332.043	0.002	13.961	1.618	0.299	0.139	0.000	36.424	0.020
15	0.000	7431.963	0.000	41.829	1.692	0.107	0.108	0.000	22.055	0.001
16	0.000	3336.047	0.000	17.045	0.677	0.094	0.123	0.277	22.469	0.001

5. DISCUSSIONS AND CONCLUSIONS

The research question is whether urban form typologies reflect energy efficiency in urban planning practice. To answer this question, this study first identifies urban form typologies in Seoul by applying the GMM method. Second, the energy efficiency of urban form typologies is compared through ANOVA post hoc test.

Do urban form typologies reflect energy efficiency in urban planning practice? The results show that not all 16 urban form typologies identified have different EUI. Instead, urban form typologies could be grouped into three subgroups. The most energy-efficient urban form typologies are Typologies 2, 8, 10, 13, and 14, referring to high-rise high-density types. The moderately energy-efficient urban typologies are Typologies 1, 3, 7, and 9, referring to low-rise, compact types. The least energy efficient ones are Typologies 4, 5, and 6 or the high-density mixed types.

EUI varies significantly between specific urban form typologies. For electricity, the maximum difference is 52.46 kWh/m2 and urban form typology with the highest EUI (Low-rise compact typology) consumes 2.3 times of urban form typology with the lowest EUI (High-rise high-density apartment typology). For gas, the maximum difference is 55.24 kWh/m2 and urban form typology with the highest EUI (High-rise low-density typology) consumes 10.7 times of urban form typology (High-rise high-density apartment typology).

The number of urban form typologies which have significant statistical difference was much higher in gas than electricity. This is because the gas is mainly used for heating. In contrast, electricity is used mainly for cooling and appliances. For heating, urban form directly influences the shading effect and solar access to the building, impacting building's heating gain and loss. Additionally, buildings in the same urban form typology are generally built during the same period and follow the insulation material regulations of that period. Therefore, buildings in the same urban form typology show similar gas usage during cold weather.

In the case of cooling using electricity, like gas, it is affected by solar access and shading effect due to the influence of urban context. However, daily home appliances are generally unaffected by changes in the external physical environment and maintain their primary daily usage. Hence electricity is less sensitive to urban form typology.

The limitation of this study is that the empirical energy data contain a large number of outliers. For

Table 4. Urban typology comparisons (I-J) in EUI of electricity.

(I) Typology	(J) Typology	Mean Difference (I-J)	*p*-value
1	5	-45.02*	0.00
	6	-52.46*	0.00
3	5	-40.33*	0.00
	6	-47.77*	0.00
5	1	45.02*	0.00
	3	40.33*	0.00
	7	40.06*	0.00
	9	37.99*	0.00
	11	30.26*	0.02
6	1	52.46*	0.00
	3	47.77*	0.00
	7	47.50*	0.00
	9	45.43*	0.01
7	5	-40.06*	0.00
	6	-47.50*	0.00
9	5	-37.99*	0.00
	6	-45.43*	0.01
11	5	-30.26*	0.02

*. *p*-value < 0.05.

Table 5. Urban typology comparisons (I-J) in EUI of gas.

(I) Typology	(J) Typology	Mean Difference (I-J)	*p*-value
1	4	23.06*	0.00
2	4	28.48*	0.00
3	4	27.29*	0.00
4	1	-23.06*	0.00
	2	-28.48*	0.00
	3	-27.29*	0.00
	5	-40.49*	0.00
	6	-55.24*	0.00
	7	-24.04*	0.00
	10	-26.83*	0.00
	11	-29.54*	0.00
5	4	40.49*	0.00
	8	33.59*	0.01
	16	35.16*	0.00
6	4	55.24*	0.00
	8	48.34*	0.02
	16	49.92*	0.02
7	4	24.04*	0.00
8	5	-33.59*	0.01
	6	-48.34*	0.02
10	4	26.83*	0.00
11	4	29.54*	0.00
16	5	-35.16*	0.00
	6	-49.92*	0.02

*. *p*-value < 0.05.

example, in some months, energy consumption suddenly increased or decreased. It is not informed whether this is a result of human behavior or an error by manual recording. Thus, a more rigorous data cleaning method is required. Further studies could investigate the temperature sensitivity of energy loads in urban form typologies. This study could help urban planners and designers in developing a more energy-efficient urban form.

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