Energy Proceedings
Vol 30, 2023
ISSN 2004-2965

An Empirical Investigation of Apartment Typologies and Building Energy Use in Seoul#

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ABSTRACT

This study adopts an urban form typology approach to better understand the energy performance of apartment complexes in Seoul. Apartment complex typologies were identified using the Gaussian mixture model (GMM), an unsupervised learning method, and annual, summer, and winter building electricity uses were compared with the Analysis of Variance (ANOVA) and Games–Howell post hoc test. Monthly electricity use patterns were then identified with k-shape clustering for different apartment complexes, and their correspondences with apartment typologies were analyzed. The results show that Seoul has three apartment typologies (flat-type low-density typology, flat-bent-type mid-density typology, tower-mixed-type high-density typology) and three electricity use patterns (summer-peak-month dominant pattern, summer-dominant pattern, winter-dominant pattern). Among apartment typologies, the tower-mixed-type high-density typology has the highest electricity consumption and the highest ratio of the summer-peak-month dominant pattern compared to other typologies. Flat-bent-type mid-density typology has the lowest electricity consumption and the lowest ratio of summer-peak-month dominant pattern compared to other typologies. The findings from this research could help urban planners and designers better understand the relationship between apartment form types and building energy use patterns to develop energy-efficient urban forms.

Keywords: urban morphology, apartment typology, building energy use, Gaussian mixture model, urban planning

1. INTRODUCTION

The effects of urban form on building energy use and microclimate have been extensively researched in the last decade [1]. Many studies have indicated how urban form factors influence building energy use in different climate zones, such as density, the surface to volume ratio, sky view factor, building orientation, housing type, building shape, building age, and aspect ratio [2-5]. However, most studies are parametric-based, which is difficult to imply in practice. To provide planners with better information and better interpretation techniques, it is necessary to consider urban form in its entirety.

The typology approach could be used to distinguish different urban form patterns and generalize similar urban form characteristics. Moreover, urban form typology is generated through the long urban development and implies morphological character and human activities. A few studies have noticed that the urban form typology has different building energy performance in real urban contexts [4, 6, 7]. Quan, Wu [6] compare nine neighborhoods in Shanghai. They indicate that when only considering the geometry, the density is negatively correlated with energy use intensity; however, their relationship changes when considering urban form typology. Li, Song [7] also find similar results. They compare 46 neighborhoods' electricity uses in Ningbo, China. They indicate that different neighborhood typologies have a contradictory density-energy relationship. Density and electricity use in summer is positively correlated with slab and tower apartment types, while single-family houses are negatively correlated.

Studies have also explicitly compared urban form typologies and energy consumption in a real context. Salat [8] compare three residential urban fabric typologies in heating energy use in Paris. The author finds the contemporary urban form typology consumes the least heating energy, and the not too new nor very old one consumes the most heating energy among the three typologies. Later, Salat, Bourdic [9] compare five residential urban fabric typologies for heating energy uses in Paris. They also find that contemporary urban form typologies use the least heating energy, and neither too new nor very old use the most.

Previous studies have focused on the form-energy relationship. However, it is far from clear which urban form typology is more energy efficient, how much urban form typology affects energy use, and the differences in energy use patterns due to an unclear definition of urban form typology, a lack of statistical methods applied, and consideration of energy use patterns. This study aims to fill these research gaps by systematically identifying urban form typologies, statistically comparing energy use, and linking typology to energy use patterns.

2. RESEARCH SCOPE AND DATA

2.1 Study area

Seoul is the capital of the Republic of Korea and is approximately 605 km^2. The city is surrounded by mountains and the Han river crosses the city. Seoul has a humid continental climate with harsh dry winters and scorching summers. The typical air temperature range is from -6 °C to 30 °C, and August is the hottest month.

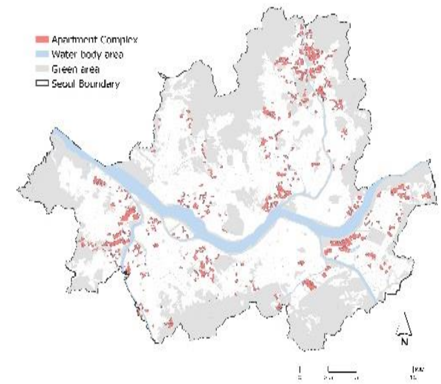

Fig. 1. Spatial distributions of Seoul's apartment complexes in the study.

2.2 Unit of analysis and data collection

The unit of analysis is a plot, and each apartment is one plot. The data is based on the year 2019. A total of 649 apartment complexes with information on electricity use and composed of more than two buildings were selected (Fig. 1). The National Geographic Information Institute provides urban geometry data, such as building geometry and elevation. The Seoul Metropolitan Government provided the socio-economic data, such as the population and land price. The study focuses on electricity. The energy use intensity (EUI) was calculated as the electricity energy consumption divided by total

Table 1. Urban form indicators for apartment complexes.

Division	Urban form indicator	Measure target	Unit	Description	Mean	Std.	Min.	Max.
Urban context	Number of buildings	Apartment complex	N/10000 m^2	The number of buildings per 10000 square meters in the apartment complex	3.00	1.00	1.00	21.00
	Building coverage ratio		n/a	Total building footprint area / apartment complex area	0.20	0.05	0.09	0.61
	Length-to-width ratio		n/a	The long side of a minimum bounding box / short side of a minimum bounding box of the apartment complex	1.72	0.66	1.00	6.17
	Elevation difference		m	Difference between maximum and minimum elevation in the apartment complex	12.83	15.52	0.00	82.44
	Average building height	Building	m	Average building height in the apartment complex	16.83	5.10	5.00	46.00
	Average building length-to-width ratio		n/a	The long side of a minimum bounding box / short side of a minimum bounding box of building	3.05	1.34	1.02	9.30
	Average building orientation		degree	The angle of the longest axis of the minimum bounding box. Orientation is calculated clockwise with 0 at north	86.25	24.77	2.70	178.60
	Average building compactness		n/a	The apartment complex area / minimum bounding box area	0.76	0.14	0.35	1.00
Social-economic	Apartment complex age	Apartment complex	years	The apartment complex age	21.85	8.69	3.00	66.50
	Population density		N/100 m^2	Population at 3 am and 3 pm per 100 square meters in the apartment complex	8.00	4.00	0.00	29.00
	Land price		1000 won/m^2	The land price per square meters of the apartment complex	4701.33	2549.14	2170.00	32400.00

floor areas in apartment complex. The Ministry of Land, Infrastructure, and Transport provides the electricity use data.

3. METHODS

This study followed three steps. First, apartment typologies were identified using GMM, an unsupervised learning algorithm, with the apartment complex measured with eight urban contexts and three social and economic indicators (Table 1) derived from urban design and planning parameters. Second, the ANOVA Games–Howell post hoc test was used to compare pairwise differences in EUIs among apartment typologies [10]. Third, the typical electricity use patterns were identified using k-shape clustering based on Euclidean distance.

Python 3.8.5 was used for GMM implementation with the sklearn.mixture [11] and for k-shape clustering with the tslearn package [12]. SPSS was used to conduct ANOVA and post hoc tests. Tableau, Rhino, and Grasshopper were used for data visualization.

4. RESULTS

4.1 Apartment complex typologies

Three apartment typologies are identified in Seoul and named based on their features (Table 2). Typology 1 is the most common type, called the flat-type low-density apartment. Typology 2 is the flat-bent-type mid-density apartment. Typology 3 is the tower-mixed-type high-density apartment with the largest number of buildings and population density (Fig. 2).

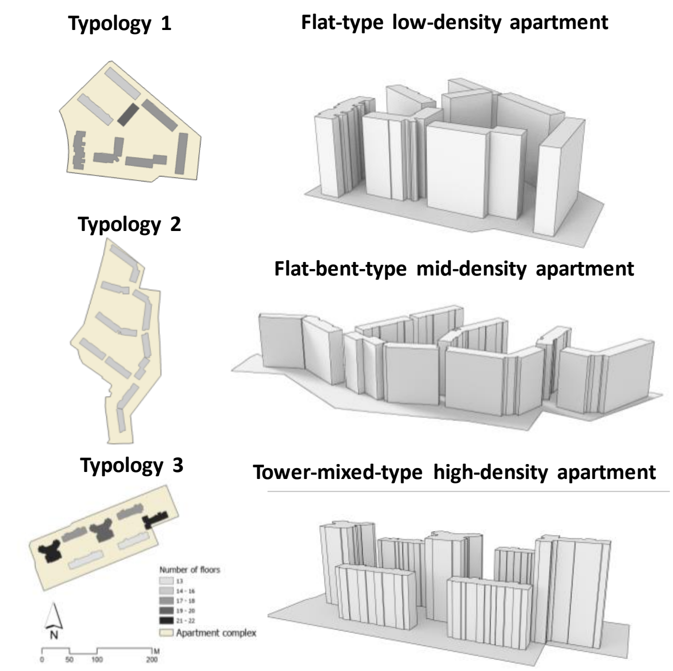

Fig. 2. Representative apartment complex in three typologies.

4.2 Comparisons of EUI

Electricity use varies among apartment typologies (Fig. 3). The EUI of apartment typologies differs more in summer than in annual and winter consumption (Table 3). The tower mixed-type high-density typology consumes more electricity than other typologies, especially in summer.

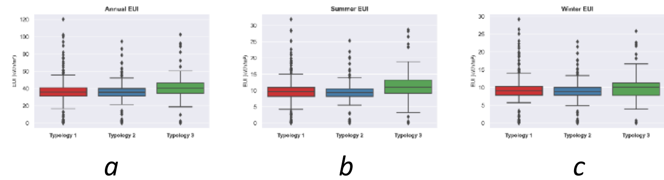

Fig. 3. Box plots of EUI in three typologies: a) annual; b) summer; c) winter.

4.3 Electricity use patterns

The results show that apartments have three major patterns of electricity use. Pattern 1 is the summer peak month dominant pattern. It is the most common pattern with 365 apartments, and the hottest month consumes the most energy. Pattern 2 is the summer dominant pattern with 210 apartments. The summer season consumes more energy without significant peak time. Pattern 3 is the winter dominant one with 74 apartments (Fig. 4). The summer-peak month pattern is prevailing in all three typologies (over 50%). Summer-dominant is the second prevailing pattern, with 29% in flat-type low-density, 39% in flat-bent-type mid-density, and 24% in tower-mixed-type high-density (Fig. 5).

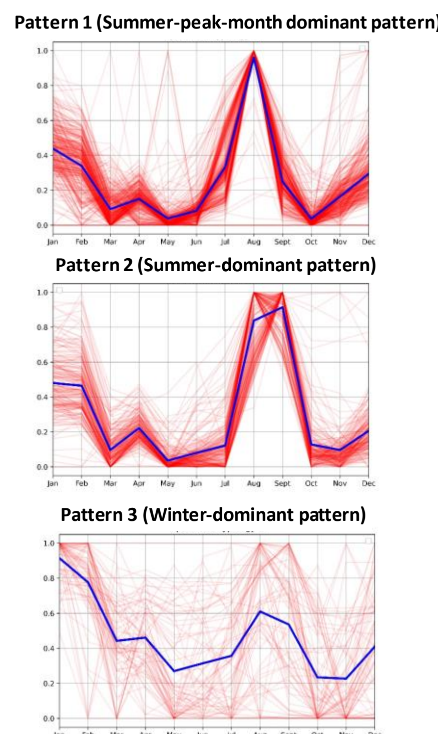

Fig. 4. Three electricity use patterns in apartments.

Table 2. Mean value of urban form indicators in typologies.

Typology	No. of complex	No. of bldg. (N/10000 m²)	Avg. bldg. height (m)	Bldg. area coverage ratio (n/a)	Complex length to width ratio (n/a)	Elevation difference (m)	Bldg. length to width ratio (n/a)	Avg. bldg. orientation (degree)	Bldg. Compactness (n/a)	Population density (N/100 m²)	Complex age (years)	Land price (1000 won/m²)
1	338	3.00	16.62	0.18	1.49	5.05	3.32	83.03	0.79	7.00	23.52	4879.51
2	245	3.00	16.73	0.20	1.95	25.9	2.56	90.3	0.71	8.00	19.41	3826.70
3	66	4.00	18.08	0.26	1.98	4.21	3.48	86.39	0.79	10.00	22.70	7008.00

Table 3. Apartment typology comparisons (I-J) in EUI.

Dependent Variable	Typology (I)	Typology (J)	Annual		Summer		Winter	
			Mean Difference (I-J)	Std.	Mean Difference (I-J)	Std.	Mean Difference (I-J)	Std.
EUI (kWh/m²)	Flat-type low-density	Flat-bent-type mid-density	0.64	1.33	0.25	0.36	0.24	0.33
		Tower-mixed-type high-density	-5.89	2.92	-1.93*	0.83	-1.22	0.73
	Flat-bent-type mid-density	Tower-mixed-type high-density	-6.53*	2.90	-2.18**	0.82	-1.46	0.73

* p-value < 0.1, ** p-value < 0.05, Std.: Standard deviation.

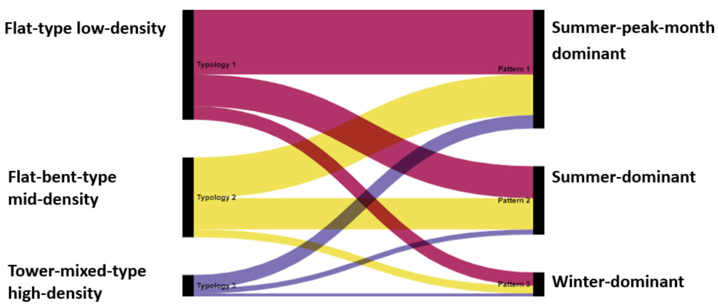

Fig. 5. Sankey diagram of electricity use patterns in apartment typologies.

5. DISCUSSION

The research question is whether different apartment typologies have different EUIs and patterns. Unlike the previous parametric-based form-energy studies, this study investigates the urban form, building electricity energy use, and energy use pattern with a typology approach that considers the urban form as an entirety. Among the comparisons, the tower-mixed-type low-density typology consumes more electricity compared to other typologies, especially in the summer and annually. Moreover, tower-mixed-type high-density has the highest ratio of summer-peak month dominant pattern at 62% and the lowest summer-dominant pattern at 24%. The flat-bent-type mid-density has the lowest electricity consumption in summer and annual. This typology has the lowest summer-peak month dominant pattern and highest summer-dominant pattern, which are close to balance.

6. CONCLUSION

This research investigates urban form typology and building electricity use and patterns in three steps. First, this study identified apartment typologies based on 11 urban form indicators using GMM. Second, the study compared EUIs among apartment typologies with ANOVA and post hoc test. Third, the electricity use patterns were identified based on k-shape clustering. The results indicate that Seoul has three apartment typologies: flat-type low-density typology, flat-bent-type mid-density typology, and tower-mixed-type high-density typology, as well as three electricity use patterns: a summer-peak-month dominant pattern, a summer-dominant pattern, and a winter-dominant pattern. The tower-mixed-type high-density typology has the highest electricity consumption and the highest ratio of summer-peak month dominant pattern compared to other typologies. Flat-bent-type mid-density has the lowest electricity consumption and lowest summer-peak month dominant pattern compared to other typologies.

The results of this study are more interpretable and instructive for urban planners and policymakers than parametric-based form-energy studies. The study has the limitation that apartment typologies were identified within the energy data available in apartment complexes in Seoul. The findings of this study may contribute to the development of a sustainable urban development strategy that is energy-efficient and climate-sensitive.

ACKNOWLEDGEMENT

This work was supported by the Creative-Pioneering Researchers Program through Seoul National University (SNU), the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. 2018R1C1B5043758; No. 2022R1C1C1004953), and the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Education) (No. 5120200113713).

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