

Article

Exploring the Spatiotemporal Heterogeneities in Urban Vitality Through Scalable Proxies from Mobile Data

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Abstract: Jane Jacob's concepts of urban vitality and diversity have become prevailing urban planning philosophies in most countries for making cities more livable. Recent changes in demographics and the impacts of COVID-19 have exacerbated the economic and social challenges that cities commonly face, particularly spatiotemporal heterogeneities. Being able to understand these heterogeneities in scalable approaches is fundamental to tackling these challenges in cities. Therefore, this article aims to provide a new form of scalable estimation of urban vitality by using the de facto population. Instead of merely adopting static statistical information such as morphological characteristics in areas, we leverage dynamic factors such as internal mobility flows and energy use intensity as proxies for the spatiotemporal dynamics of indoor and outdoor behaviors of crowds. In this way, we combine dynamic attributes and static features to describe the patterns of urban vitality, which are directly related to spatiotemporal dynamics in urban places. We utilize GNSS-based mobile data and building energy usage intensity as dynamic proxies along with static data such as land use mix and age distribution. To better capture spatial heterogeneity, we use a Multiscale Geographically Weighted Regression (MGWR) model to identify the relationships between the de facto population and the dynamic and static factors. Drawing from the factors determining urban vitality, this article provides policy implications for alleviating spatiotemporal urban imbalances. These data-driven implications can fill the technical knowledge gaps in establishing planning strategies for achieving urban sustainability while enhancing overall subjective livability.



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Keywords: urban vitality; de facto population; spatiotemporal urban dynamics; subjective livability; spatial heterogeneity

1. Introduction

A city's vitality is reflected in the diversity of its spaces and the dynamic interactions that occur within them. Jane Jacobs's concept of urban vitality emphasizes the diversity that can be achieved by harmonizing three dynamic functions: intensity, variability, and consistency [1]. These three dynamic functions generally show heterogeneous spatiotemporal variations in cities linked to the mobility flows. Thus, effective urban planning and policy require a dynamic quantitative model of urban vitality that captures these functions. When cities become denser and highly populated, spatiotemporal dynamics become more complicated. Increased complexity in urban spaces brings both opportunities and challenges at the same time. Recently, urban demographic challenges such as low fertility rates and an increase in the aging population have become pressing issues in most developed countries, which increase burdens on government and society. The stringent controls resulting from COVID-19 also accelerate the reshaping of usual patterns and behaviors in cities.

Since Jacob's concepts of vitality and diversity have become prevailing urban planning philosophies in most countries for achieving urban sustainability goals, a new form of scalable approach to urban vitality is fundamental for establishing urban master plans. According to Jacobs' idea, having "eyes on the street" strongly affects the vibrancy of urban places while continuously maintaining the spatial and temporal dynamics of crowds in

places. In particular, the dynamic elements representing the diversity and vitality of cities show high heterogeneity across space and time. Accurately quantifying the dynamics of vitalities in places can be challenging when merely using static statistical information. Therefore, the level of vitality of a location should incorporate not only static attributes (e.g., morphological characteristics) but also dynamic attributes (e.g., temporal infrastructure usage patterns).

Previous studies have conducted quantitative analyses by using independent indices to measure urban vitality, e.g., floating population [2], diversity of land use [3], supermarket sales [4], mobility patterns [5], and the spatial distribution of businesses by sector [6]. Nonetheless, previous studies have been limited to accounting for harmonizing dynamic and static information. This is partly because the data used in these studies was collected through quasi-experimental observations with surveys, mostly including static attributes. To account for spatiotemporal dynamics, researchers have used sensor-based data as proxies for urban vitality. Fine-grained mobility datasets [2,7–9], such as smart cards and mobile app-based data, have been adopted to investigate urban vitality. Spatial business and economic statistics can be another example to be adopted as proxies for investigating the relationships between urban morphology and vitality. Nonetheless, sensor-based datasets collected from independent silos are yet limited to harmonizing various factors affecting urban vitality.

To better understand and quantify urban vitality under interdependent silos, the Seoul Metropolitan Government recently introduced the concept of “de facto population” by using sensor-based data (e.g., Global Positioning System (GPS) and Global Navigation Satellite System (GNSS) data). Specifically, the de facto population includes the behavior of crowds, providing hourly, gender, and age-specific population and trip estimates within specific spatial units, capturing residents as well as visitors for diverse trip purposes [10]. Therefore, the de facto population as a scalable proxy for urban vitality is publicly accessible data representing the population dynamics in an area at a given time.

The de facto population is not an entirely novel concept [3,11,12]. Cao et al. [13] analyzed the urban decline and vitality characteristics of administrative neighborhoods in Busan, which has been experiencing population decline since its incorporation into Gijang County in 1995, by typifying changes in the registered population and de facto population at the administrative neighborhood level over time and space. Kamata and Nam [14] examined the decrease in urban residents’ activities and sensitivity changes during the COVID-19 spread based on the de facto population. Hwang and Jang [15] analyzed the impact of the COVID-19 pandemic on urban vitality using the de facto population as an indicator of urban vitality. Additionally, studies have quantitatively analyzed factors affecting urban vitality based on the de facto population. Yun and Choi [3] aimed to understand the impact of the relationship between the de facto population and land use characteristics, and Eom et al. [16] analyzed factors affecting the changes in de facto population numbers in the southeast quarter of Seoul at the superblock level.

Nonetheless, these previous studies are limited to merely investigating the relationships between static factors and urban vitality. Since urban vitality implies the dynamics of space at a given time and associated mobility flows, it is crucial to consider the dynamics of mobility and associated activities in addition to the static characteristics of places. Therefore, this article offers a new scalable approach to meticulously investigate the relationships between urban vitality and spatiotemporal dynamic and static factors. In particular, the present study differentiates itself from previous research by incorporating the aspect of activity, which the limitations of static analyses have often overlooked.

By adopting a dynamic perspective, this article provides a more comprehensive and scalable understanding of urban dynamics and further identifies factors affecting urban vitality. In particular, GNSS-based mobile data collected by KT (Korea Telecom) is used to extract the internal trip flows within administrative districts to incorporate mobility dynamics affecting urban vitality. In addition, the intensity of building energy usage is measured as a proxy for the spatiotemporal dynamics of indoor. For static factors, we

collect and merge land use mix, official land prices, age diversity, and average age data into spatial units of analysis. All information used in this article is publicly accessible.

This article adopts multi-level analytical flows to provide technical insights into investigating urban vitality by alleviating spatial heterogeneity issues (see Figure 1). First, spatial heterogeneities in urban areas are recognized by analyzing Morans' I and Getis–Ord G_i^* analysis. Furthermore, the de facto population is segmented into four different time frames to incorporate temporal imbalances of urban vitality. Multiscale Geographically Weighted Regression (MGWR) is adopted to estimate the relationships between urban vitality and dynamic and static factors by capturing the impacts of different spatial scales. In addition, micro-analysis using time series clustering is conducted to provide policy implications for temporal imbalances in urban vitality. Consequently, the results of MGWR are compared with the “Seoul Master Plan” to derive macro- and micro-level policy recommendations regarding spatial and temporal conditions.

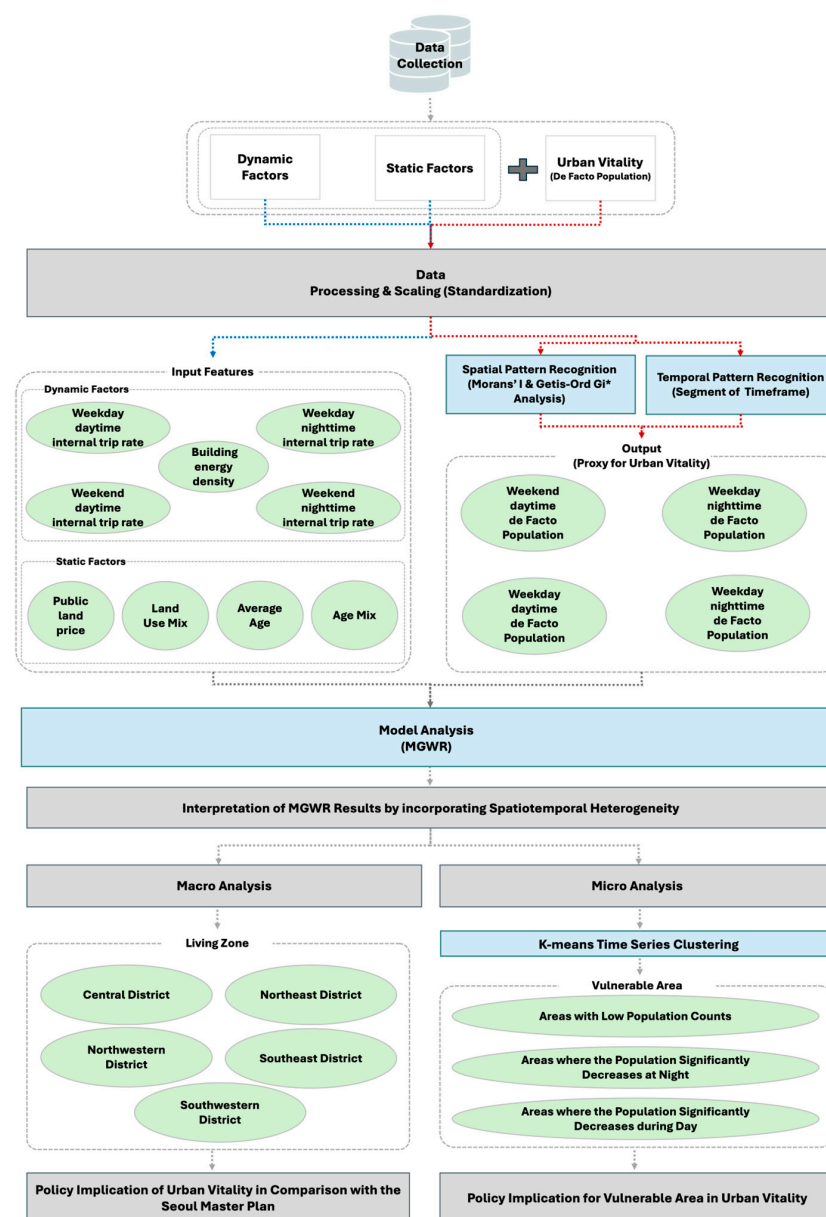


Figure 1. Research design and analytical flow. The blue arrows represent the analytical flows of independent features, including static and dynamic features, while the red arrows indicate the flow for urban vitality variables. The gray arrows show the overall analytical flow.

This article aims to provide a profound understanding of spatiotemporal imbalances in urban vitality and identify how these characteristics change over time and in each region. In addition, the findings from this scalable modeling about urban vitality using publicly accessible datasets can fill technical knowledge gaps in scalable investigating urban vitality by adopting publicly accessible datasets while alleviating spatial and temporal heterogeneous issues. Thus, this research can provide useful insights into comprehensively understanding and analyzing the complex factors related to urban vitality, which is one of the crucial factors for enhancing the vibrancy of cities. This is anticipated to substantially contribute to practitioners and policymakers' establishing customized strategies for each region through a scalable understanding of urban vitality and its determining factors.

This study contains four sections. After the literature review, the Material and Methods (Section 2) present the variables that describe the characteristics of a region, explores the spatial autocorrelation of de facto population, an indicator of urban vitality, and describes the MGWR algorithm chosen for this article. The Results section (Section 3) describes the results of the analysis and presents macro-level (living zone-based) implications of the model analysis results. The Conclusion section (Section 4) wraps up the article.

Literature Review

Urban vitality is one of the crucial urban indices that emerge from interactions between people and their surrounding environments in urban spaces. A high level of urban vitality enhances the quality of life for city residents and promotes sustainable urban development [17]. Theorists such as Jacobs [1], Lynch [18], and Montgomery [19,20] have broadly conceptualized urban vitality. Montgomery emphasized that urban vitality is a fundamental component of vibrant urban life. Ravenscroft [21] viewed dynamic activities in urban centers as a measure of urban vitality. Delclòs et al. [8] argued that understanding where and when urban activities occur can aid in comprehending urban vitality. Jacobs, especially in her book *"The Death and Life of Great American Cities"*, defined urban vitality from the perspective of street space, diversity of land use, architectural environment arrangement, populations with various backgrounds and resources, and the actual presence of people as key drivers.

In this context, urban vitality is not limited to a specific time of year but must be maintained continuously. The environment of streets and diverse land use must be mixed and well-distributed, acting as core elements in enhancing urban vitality. Creating street spaces where activities occur continuously across various times is crucial for increasing social capital in the city and reducing potential crimes [1]. This aligns with Jacobs' concept of "eyes on the street", which emphasizes the importance of urban vitality by always keeping a certain population level. In this sense, scalable analysis of the dynamics of the population can be a promising indicator for understanding urban vitality. Based on scalable analysis, practitioners and policymakers can fill the technical knowledge gaps in enhancing urban space vitality, which is vital for promoting economic, social, and cultural prosperity in the city.

Recently, many studies have been conducted to understand urban vitality by leveraging information from population statistics. Sulis et al. [2] meticulously measured the spatial and temporal variations of urban vitality in central London using smart card data from public transportation. This study revealed the spatial distribution of London's vitality and identified the most vibrant areas through spatial visualization. Delclòs et al. [8] analyzed conditions for urban vitality in Barcelona by combining data extracted through smartphone tracking apps with Jacobs' ideas. Xia et al. [9] measured daytime and nighttime urban vitality using small-scale catering businesses and nighttime lighting data, analyzing the spatial relationship between land use intensity and urban vitality. Kang et al. [10] analyzed urban vitality in Wuhan, China, using human mobility data and crowdsourcing data. The authors interpreted the relationships between population concentration, activity, time, and spatial diversity while confirming that these diversities are essential components of urban

vitality and providing an expandable methodology for understanding urban vitality in various geographic, social, and economic contexts.

In South Korea, studies have investigated the effects of land use mix and the physical environment of streets on factors like floating population and sales, impacting urban vitality [22–25]. Yun and Choi [3] applied the Geographically Weighted Regression (GWR) model to understand the relationship between the spatial pattern of the floating population and land use characteristics, analyzing the spatial autocorrelation of the floating population and its interactions with land use and transport features. Kim et al. [12] utilized KT mobile phone data to compare the changes in floating populations in Daegu and Seoul university areas before and after the COVID-19 pandemic, identifying how the spread of the virus and urban characteristics influenced floating population patterns.

Recent efforts in South Korea aim to introduce a new population concept to enhance regional vitality, moving beyond traditional concepts like the resident and daytime populations. The daytime population, calculated by adding the commuting and schooling population inflowing from other areas to the nighttime residential population and subtracting the outflowing population, does not necessarily accurately reflect actual population movements and demand [12,26]. To address this, Seoul introduced the “de facto population” concept [11], utilizing big data from KT mobile data. This concept provides hourly, gender, and age-specific population estimates within spatial units, capturing not only residents but also visitors for work, tourism, medical, education, and other purposes [11]. Thus, the de facto population represents all individuals present in each district of Seoul at any given time.

De facto population data has various advantages. First, it is not limited by location or time [15] and can explain the distribution differences between specific population groups’ nighttime residences and daytime living spaces [13]. It also provides spatial distribution information by gender and age over time. Additionally, the data are distinctive from traditional demographic data such as census and resident registration populations due to the short time lag of only five days from creation to publication. Due to these characteristics, de facto population data plays a very important role in understanding the demand for human activity within spaces and urban vitality.

Recently, many studies have used the concept of de facto population as an indicator of urban vitality. Kamata and Nam [14] analyzed the urban decline and vitality characteristics of administrative neighborhoods in Busan, which has been experiencing population decline since its incorporation into Gijang County in 1995, by typifying changes in registered population and de facto population at the administrative neighborhood level over time and space. Hwang and Jang [15] examined the decrease in urban residents’ activities and sensitivity changes during the COVID-19 spread based on the de facto population. Eom et al. [16] analyzed the impact of the COVID-19 pandemic on urban vitality using the de facto population as an indicator of urban vitality. Additionally, studies have quantitatively analyzed factors affecting urban vitality based on the de facto population. Yu [4] aimed to understand the impact of the relationship between the de facto population and land use characteristics, and Cho and Jun [27] analyzed factors affecting the changes in de facto population numbers in the southeast quarter of Seoul at the superblock level. Previous studies that analyzed quantitative factors of urban vitality and those that examined quantitative factors of the de facto population typically measured urban vitality indicators in detail based on environmental and infrastructure characteristics, such as commercial areas, industry, living facilities, and population characteristics. Nonetheless, these approaches had limitations in sufficiently considering the dynamic nature of urban vitality.

2. Materials and Methods

Dynamic and static factors of urban places are collected and meticulously scaled to investigate the relationships between the de facto population and both factors. The study area was Seoul, as it is the only region with available open data on the de facto population at the time of writing this article. When it comes to dynamics in urban mobility, internal

trip rates within administrative districts in November 2022 were selected using KT mobile data. Building power consumption density per administrative district was calculated using November 2022 electrical energy data from the Building Data Open System. As static factors, the land use mix per administrative district was calculated using data from the National Spatial Information Portal's 'Land Characteristics Spatial Information' as of November 2022, and the average officially assessed land value was determined. Additionally, the population per administrative district was extracted from the Seoul Open Data Plaza to calculate the average age and age diversity. The dependent variable, de facto population, was also derived from the Seoul Open Data Plaza, using data from November 2022 per administrative district.

2.1. Dynamic Factors for Urban Vitality

2.1.1. Urban Mobility Dynamics

De facto population and internal trip rates exhibit distinct spatiotemporal heterogeneity by area and time. Thus, separate analyses are required for four different times of day, e.g., weekday daytime (8 a.m. to 7 p.m.), weekday nighttime (8 p.m. to 7 a.m.), weekend daytime (8 a.m. to 7 p.m.), and weekend nighttime (8 p.m. to 7 a.m.). Therefore, this analysis will contribute to a better understanding of the factors influencing the dynamics of the de facto population and offer insights into the development of more effective urban planning and management strategies in Seoul.

To account for the dynamic characteristics of urban mobility, the internal trip rate for every administrative district was used as a proxy scalable index for mobility dynamics in spaces. Mobile sensor-based data were used, including location and user characteristics. In particular, KT mobile data consists of the following information (e.g., the volume of departures and arrivals, date, time, gender, and age). Especially for the internal space vitality, the internal trip rate for every administrative district was used as a variable to determine the vitality of the administrative districts. This data exhibits spatial and temporal heterogeneity, necessitating its segmentation into weekday daytime, weekday nighttime, weekend daytime, and weekend nighttime for analysis. Figure 2 represents the internal movement rates by time of day for each administrative district in Seoul. It illustrates that the movement characteristics of people on the streets differ spatially and according to the time of day, indicating the existence of spatiotemporal heterogeneity.

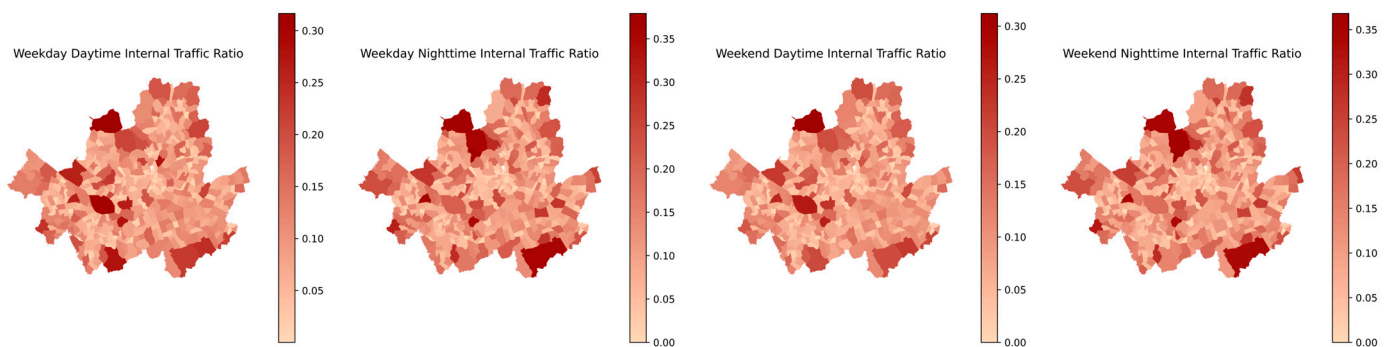


Figure 2. Visualization of the internal trip ratio by the time of day by the administrative district of Seoul.

2.1.2. Energy Use Intensity Dynamics

In addition to outdoor vitality, people's movement indoors can be another critical factor affecting urban vitality, especially for urban areas with a high floor-area ratio. As an indicator of urban indoor vitality, the study obtained monthly average electrical energy data for buildings nationwide from the Building Data Open System. This data enabled the construction of a building energy density metric for each administrative district in Seoul. The building energy density was calculated by dividing the total power consumption

of buildings in an administrative district by the area of the district, using the following Equation (1):

$$\text{Building_Energy_Density} = \frac{\sum_{i=1}^n B_i}{A} \quad (1)$$

where A refers to the administrative district areas, n is the number of buildings per administrative district, i is the number of buildings in the administrative region, and B_i represents the energy consumption of buildings.

Figure 3 represents the number of buildings and the building energy density by administrative district in Seoul. Because the number of buildings varies by region, building energy density was calculated by dividing the total building energy consumption by the number of buildings to represent the dynamic characteristics of urban interiors.

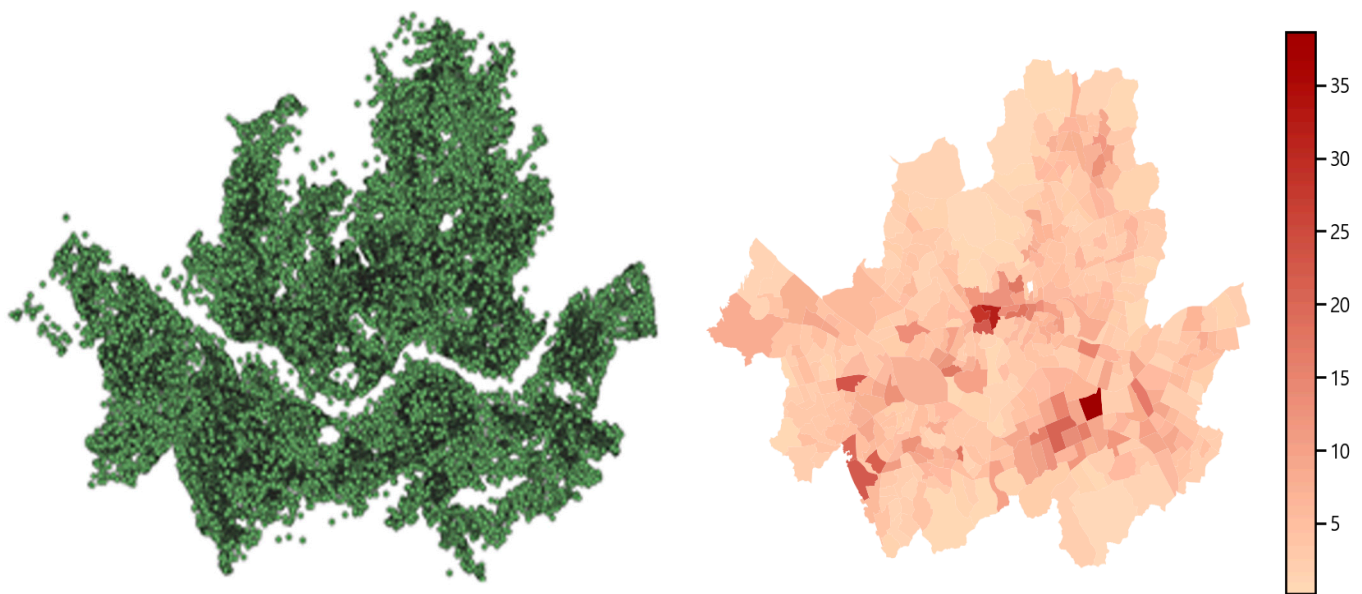


Figure 3. Visualization of the number of buildings in Seoul (**left**) and building power usage by administrative district (**right**).

Other indicators representing building density include the plot ratio and the floor area ratio. The plot ratio, which is the ratio of the building's floor area to the total land area, does not account for the height of buildings, which is a limitation. On the other hand, the floor area ratio, which represents the ratio of the total floor area of a building to the land area and includes building height, is calculated excluding areas such as basements, parking spaces, and communal facilities. Therefore, it was determined that this ratio lacks a deep connection with urban vitality. Given these limitations, this study redefined building energy density by dividing the total building power consumption in each administrative district of Seoul by the area of the district. This new metric was then utilized to measure urban vitality.

2.2. Static Factors for Urban Vitality

In addition to the dynamic factors, it is crucial to consider static variables that do not change over short periods. These static regional characteristics, such as demographic data and morphological (e.g., land-use) characteristics, provide a stable foundation for understanding the underlying factors influencing urban vitality. Reflecting these variables is essential as they represent long-term and consistent elements of the urban environment, making them suitable for evaluating the composition of the de facto population. Static regional characteristics in this study were represented using demographic data and land characteristic data.

2.2.1. Morphological Characteristics: Land Use Mix and Land Value

Land use mix and real-estate values are adopted as proxies for incorporating morphological characteristics. In considering the de facto population and urban vitality, as emphasized by Jane Jacobs and the New Urbanism movement in the United States, the diversity of land use facilitates interactions among local people and enhances the potential for organic development. This is seen as an essential element for efficient and sustainable urban planning that transcends the separation of work and leisure. The concept of land use mix (LUM) was applied in this study, a measure commonly used in previous research. LUM, based on entropy, is used to measure how uniformly various land types such as residential, commercial, green spaces, industrial, and others are distributed or how high the proportion of a particular use is relative to others [4]. The land use mix can be represented as Equation (2).

$$LUM = - \sum_{i=1}^n \frac{p_i \times \ln p_i}{\ln n} \quad (2)$$

where n refers to the total number of land uses, p_i is the percentage of the i -th land use area.

The map on the left panel in Figure 4 represents the spatial distribution of land use in Seoul, where green denotes green spaces, brown denotes residential areas, blue denotes commercial areas, and purple denotes semi-industrial areas. The right panel in Figure 4 shows the level of land use mixture based on the information from the left panel. The area with darker colors implies a higher-level mixture of land use.

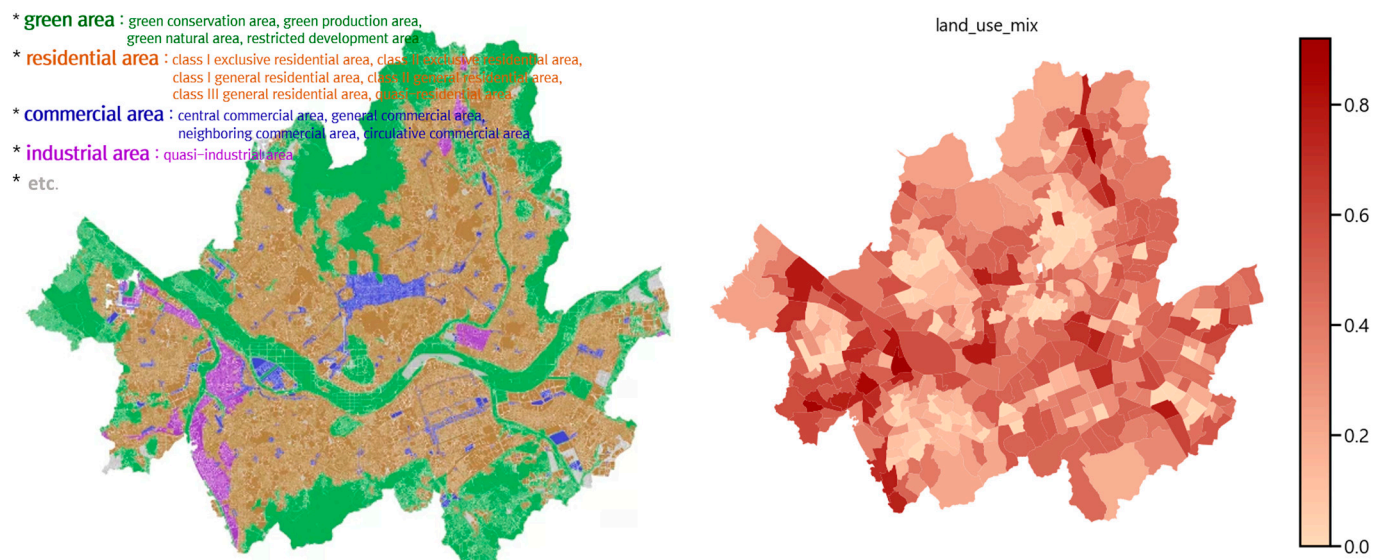


Figure 4. Visualization of Seoul's land use map (left) and land use mix (right).

Officially assessed land values (i.e., real estate appreciation) represent the officially evaluated price of land and buildings and are used as an important indicator of a city's economic vitality. High officially assessed land values reflect economic prosperity in an area, indicating a favorable environment for investment and development. This can lead to increased business activity, expanded employment opportunities, and improvements in commercial services and infrastructure, which are closely related to the overall vitality of the city. Therefore, in this study, the average officially assessed land value per administrative district was utilized as an independent variable representing the static characteristics of the de facto population. Figure 5 visualizes the officially assessed land values by the administrative district in Seoul, with darker colors indicating higher values.

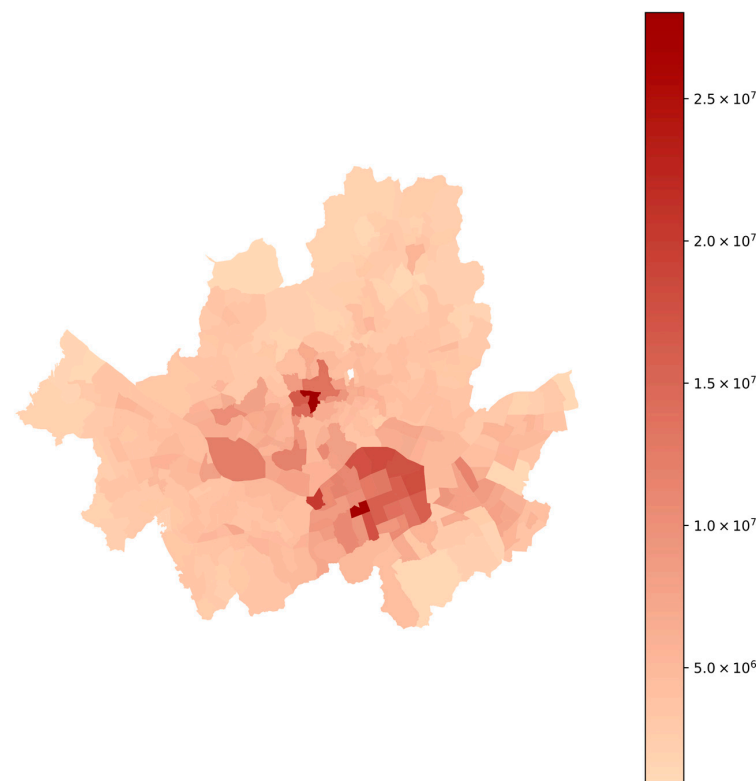


Figure 5. Visualization of public land price by the administrative district of Seoul.

2.2.2. Spatial Distribution of Population Age

Regarding demographic characteristics, this study focused on the age structure of each administrative district to analyze its impact on urban vitality. Diversity in age groups within a city enhances social interaction, economic activity, and cultural richness. Therefore, age diversity is considered an important element for sustainable urban development, fostering intergenerational exchange and the transfer of knowledge, thereby increasing social capital. The calculation of age diversity was performed using a formula like that used for calculating land use mix (see Equation (3)).

$$age_mix = -\sum_{i=1}^n \frac{p_i \times \ln(p_i)}{\ln(n)} \quad (3)$$

where n refers to the number of total age groups (in 10-year increments), p_i is the percentage of the population in the i -th age group. Average age is also an indicator of the age structure of the urban population and plays a crucial role in understanding the demand for economic activities and social services. A lower average age typically reflects a higher birth rate and the presence of a younger workforce, indicating economic vitality and potential for growth in the city. Conversely, a higher average age suggests an aging population, presenting challenges such as increased demand for medical care, housing, and pension systems. The figure on the left panel in Figure 6 visualizes the age diversity by administrative district in Seoul, showing that most areas have a coexistence of various age groups. The second image visualizes the average age, with darker colors indicating higher average ages.

The descriptive statistics of the variables used in this study are shown in Table 1. The Variance Inflation Factors (VIF) are used to measure the correlation among independent variables in a multiple regression model, and a VIF exceeding 10 indicates the presence of multicollinearity. The VIF for all independent variables is below 10. Therefore, it can be concluded that there is no multicollinearity among the independent variables [28]. Additionally, since neighboring areas have similar population distributions, it is feasible to apply a multivariate spatial regression model.

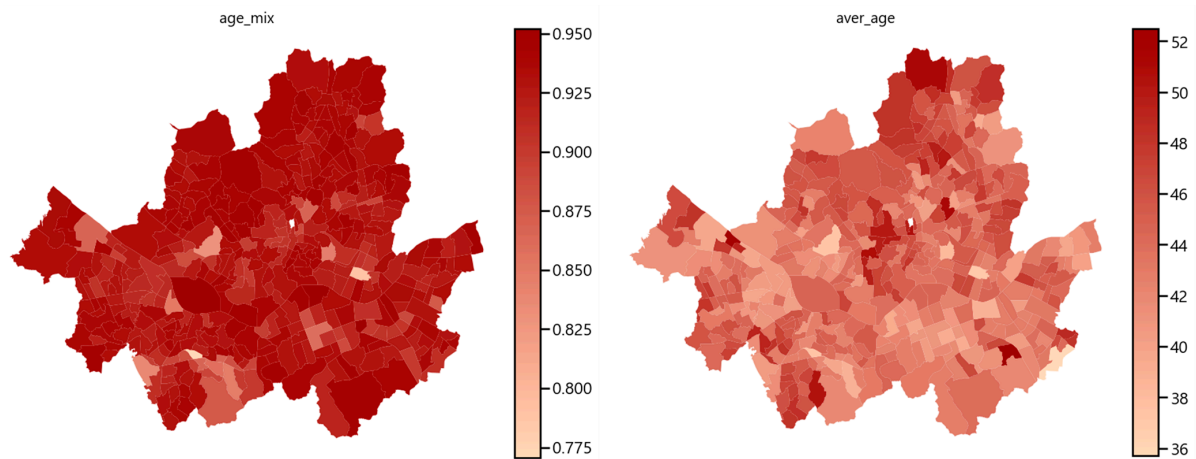


Figure 6. Visualization of age mix (left) and average age (right) by administrative district in Seoul.

Table 1. Descriptive statistics of variables used in the analysis.

	Variables	Mean	Std	Min.	Max	VIF	Source
Feature	Weekday daytime internal trip rate	0.084	0.056	0	0.317	1.40	KT Data
	Weekday nighttime internal trip rate	0.105	0.072	0	0.379	1.29	
	Weekend daytime internal trip rate	0.078	0.051	0	0.312	1.43	
	Weekday nighttime internal trip rate	0.10	0.069	0	0.368	1.31	
	Building energy density	5.19	4.600	0.177	38.62	1.59	Open Building Data System
	Public land price (KRW 1000)	4940	3440	956	28,030	1.72	National Spatial Information Portal's
	LUM	0.335	0.223	0	0.921	1.06	
	Age Mix	0.926	0.021	0.771	0.952	1.08	Seoul Open Data Plaza
	Average age	44.33	2.65	52.5	35.7	1.31	

2.3. Segmentation of De Facto Population

2.3.1. Temporal Heterogeneities in De Facto Population

Spatiotemporal heterogeneity is an inevitable aspect of the de facto population, which can lead to biased interpretations. Spatiotemporal heterogeneous issues are required to be addressed somehow to understand the factors affecting urban vitality.

Given that urban vitality varies over time [29], the 2022 de facto population data were used to observe urban vitality trends across different times, distinguishing between weekdays and weekends, and day and night. By segmenting the data temporally, this approach allows for a finer understanding of population flows and activity patterns within the city. For example, the de facto population during weekday daytimes is mainly related to routine activities such as work and school, while during weekday nights, the population distribution can be observed in residential areas or entertainment facilities. On weekend days, there is an active movement of people involved in leisure activities, shopping, and visiting tourist attractions, and during weekend nights, changes in the population distribution occur due to cultural activities and dining out. This temporal segmentation not only highlights the dynamic nature of urban vitality but also provides valuable insights for urban planning and policymaking aimed at the sustainable development of the city and the improvement of citizens' quality of life.

2.3.2. Spatial Heterogeneities in the De Facto Population

In addition to addressing temporal heterogeneity, it is equally important to consider spatial heterogeneity to fully capture the complexities of urban vitality. The variables employed in this study are based on the administrative districts of Seoul, necessitating an analysis of spatial patterns. Specifically, Moran's I was employed to quantify the global spatial autocorrelation of the de facto population. This technique assesses the spatial similarity among neighboring units, with values ranging from -1 to 1 , indicating the degree of spatial autocorrelation (see Equation (4)). The results, as shown in Table 2, indicate a significant positive spatial autocorrelation at the 0.1% level, although the correlations are relatively weak (ranging from 0.15 to 0.22). This finding corroborates the existence of spatial dependencies within the de facto population distribution, thereby reinforcing the necessity for urban planning strategies that are nuanced and consider both spatial and temporal dynamics.

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n (x_i - \bar{x})(x_j - \bar{x})}{W \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4)$$

where n is the number of geographic units, x_i is the attribute of region i , x_j is the attribute of region j , $\bar{x}$ is the average value and W is the weight.

Table 2. Autocorrelation coefficients and p -values for independent variables.

Urban Vitality Variables	Moran's I	p -Value
Weekday daytime de facto population	0.22	0.001
Weekday nighttime de facto population	0.17	0.001
Weekend daytime de facto population	0.15	0.001
Weekend nighttime de facto population	0.17	0.001

Furthermore, the Getis–Ord G_i^* analysis was conducted to understand how spatial autocorrelation manifests regionally. Getis–Ord G_i^* is one of the Local Indicators of Spatial Association (LISA) techniques, utilizing standardized scores (z-scores) of observed data (Equation (5)). This method calculates high and low G_i^* values within a specified range around a point, statistically identifying clusters of high values (hotspots) and low values (cold spots). Figure 7 presents the results of the Getis–Ord G_i^* analysis performed to analyze the regional spatial autocorrelation of the de facto population.

$$G_i^* = \frac{\sum_{j=1}^n w_{ij} x_j - \bar{X} \sum_{j=1}^n w_{ij}}{S \sqrt{\frac{n \sum_{j=1}^n w_{ij}^2 - (\sum_{j=1}^n w_{ij})^2}{n-1}}} \quad (5)$$

where S represents the standard deviation, w_{ij} denotes the elements of the spatial weight matrix, and n stands for the total number of cases. i and j indicate individual spatial units (or locations). If two spatial units are defined as neighbors, $w_{ij} = 1$, otherwise, $w_{ij} = 0$. Each unit is considered a neighbor to itself. Hence, $w_{ii} = 1$. The expected value of this statistic is 0, and its variance is nearly 1. Therefore, the significance test of this statistic is almost identical to that of the standardized score, assuming a normal distribution.

2.4. Methodologies for Alleviating Spatial Heterogeneities

Spatial regression analysis is based on Tobler's (1970) [30] First Law of Geography, which states, "Everything is related to everything else, but near things are more related than distant things". This methodology analyzes the relationships between dependent and independent variables that vary regionally, allowing for the incorporation of spatial similarities. A prominent method of spatial regression analysis is Geographically Weighted Regression (GWR), which was initially proposed by [31].

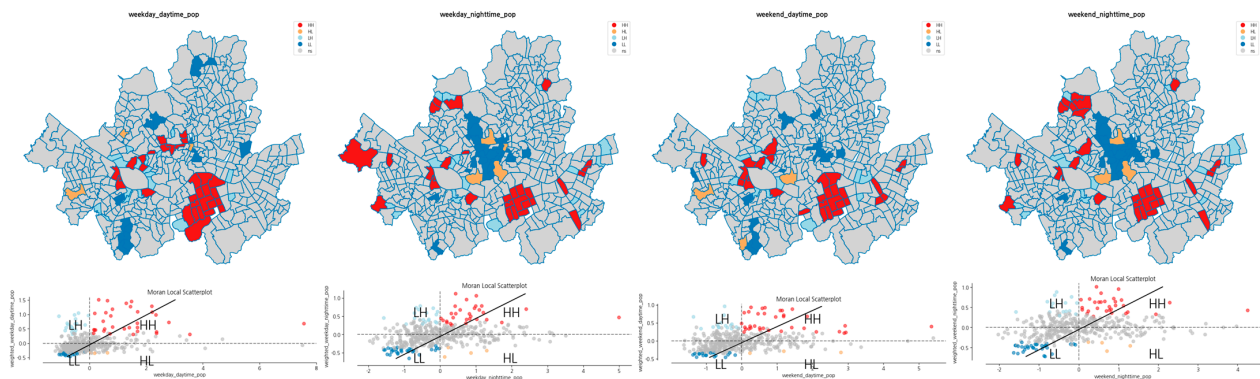


Figure 7. Visualization of Getis-Ord Gi* analysis results for Seoul's de facto population by time of day.

GWR assumes Tobler's First Law to analyze the relationships between locally varying dependent and independent variables. However, there is research indicating that GWR tends to overestimate or underestimate the results because it recognizes surroundings with the same bandwidth for each variable [32]. MGWR emerged as an improvement of GWR, where individual bandwidths are set for each variable, thus providing more refined values than GWR [32]. Therefore, this study utilized MGWR to predict the de facto population, reflecting the similarities among proximate areas and deriving accurate results. This model explores the potential to enhance proactive capabilities in responding to various changes in urban vitality. The formula for MGWR is as Equation (6):

$$y_i = \beta_0(u_i, v_i) + \sum(j \times \beta_{bwj}(u, v_i) \times x_{ij}) + \varepsilon_i \quad (6)$$

where, $\beta_0(u_i, v_i)$ is the intercept, and β_{bwj} is the bandwidth used for calibration of the j -th conditional relationship.

MGWR addresses spatial heterogeneities by allowing multiscale analysis through variable-specific bandwidths, offering a more refined examination of spatial patterns and crowd dynamics. By adjusting the bandwidth for each variable, MGWR enhances the ability to model urban spatial complexities, providing a more precise depiction of spatial heterogeneity than GWR, which uses a single bandwidth for all variables. This approach captures the varying spatial influences of different factors across multiple scales, offering deeper insights into urban environments.

3. Results

3.1. Results for MGWR

Table 3 presents the prediction results of the Multiscale Geographically Weighted Regression (MGWR) model, with the minimum adjusted R^2 value of 0.663, indicating robust reliability. Figure 8 visualizes the MGWR results, illustrating the heterogeneous impact of each variable across different spatial and temporal contexts. The analysis covers four distinct times of the day: weekday daytime, weekday nighttime, weekend daytime, and weekend nighttime. The variables examined include the intercept, internal movement rate within administrative districts, officially assessed land values, building energy density, land use mix, age diversity, and average age.

Table 3. MGWR analysis results.

Independent Variables	Adjusted R^2	Bandwidth						
		Constants	Internal Trip Ratio	Land Price	Building Energy Density	Land Use Mix	Age Mix	Average Age
Weekday daytime	0.861	172	421	422	143	422	96	422
Weekday nighttime	0.663	76	422	417	54	422	170	422
Weekend daytime	0.733	132	78	422	65	422	170	422
Weekend nighttime	0.698	76	422	412	64	422	170	422

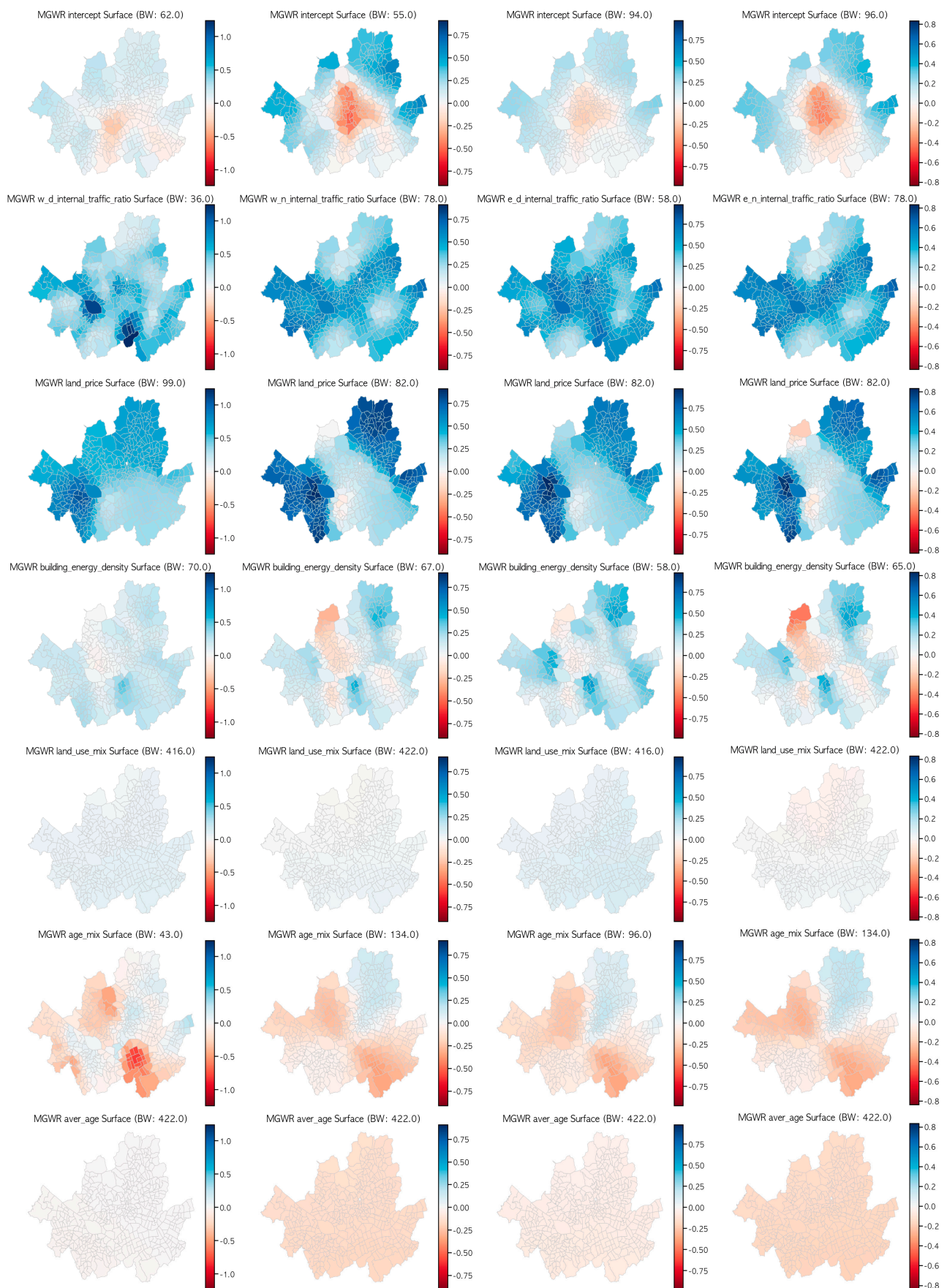


Figure 8. Visualization of Seoul MGWR results.

In Figure 8, deeper shades of blue signify a positive correlation with the de facto population, while deeper shades of red indicate a negative correlation. The coefficient values reveal that administrative districts in closer proximity exhibit stronger relationships compared to more distant ones. Specifically, the internal trip rate within administrative districts consistently shows a positive correlation with the de facto population across all time periods, suggesting that higher internal mobility enhances urban vitality. Conversely, the average age consistently exhibits a negative correlation, indicating that younger populations contribute more significantly to urban vitality. The land use mix demonstrates minimal to no correlation, suggesting that diversified land use does not uniformly influence population dynamics. Additionally, higher official land prices correlate positively with economic vibrancy, while building energy density shows varying correlations, with a negative relationship during nighttime in certain regions like Yongsan, indicating potential impacts of new residential developments.

These findings imply that enhancing urban vitality in Seoul can be effectively achieved by increasing internal mobility and attracting younger populations. The spatiotemporal heterogeneity of other variables necessitates region-specific urban planning strategies, as different areas exhibit unique patterns of influence on urban vitality.

3.2. Policy Suggestions for Spatial Heterogeneities in Urban Vitality

3.2.1. Importance of Urban Vitality in the Seoul Master Plan

Urban master plans are pivotal in directing long-term development and shaping the future urban landscape. This study examines the “Seoul 2040 Urban Comprehensive Plan”, evaluating its policies aimed at enhancing urban vitality and assessing their impact on Seoul’s urban space and residents. This empirical approach facilitates an understanding of the effectiveness of urban planning and provides strategic directions to bolster Seoul’s vitality.

The latest “Seoul Master Plan” aspires to realize the vision of “A livable my Seoul, everyone’s Seoul” through seven major projects [33]. These initiatives focus on improving quality of life by creating self-sufficient living areas with daily walking zones where citizens can reside, work, and enjoy leisure activities. Additionally, the plan seeks to transform urban waterfronts into pleasant cultural hubs, addressing Seoul’s rail-centered transportation issues by developing three-dimensional infrastructure and new urban spaces. To enhance competitiveness, the plan promotes deregulation, regional connections, and innovation in central functions, while introducing new transportation modes and mobility hubs to strengthen Seoul’s global standing. Furthermore, the plan targets the development of a carbon-neutral, safe city by reducing greenhouse gases, advancing eco-friendly technologies, and adopting a flexible urban planning system with multifunctional complexes. These efforts are geared towards sustainable growth, improving citizens’ quality of life, and enhancing urban vitality.

Seoul operationalizes these initiatives through living zone plans, categorized into large living zones and local living zones. The city is divided into five major large living zones—central, northeast, northwest, southwest, and southeast—based on natural environments, growth patterns, land use, and demographics. Local living zones consist of 3–5 neighborhoods with approximately 100,000 residents, aligned with the previous 2030 plan and adjustable by districts. This categorization allows for customized urban planning and policies that reflect the unique characteristics of each region, as illustrated in Figure 9.

The living zone plan aims to optimize urban space usage and enhance daily life, which is crucial for Seoul’s long-term development. It addresses regional imbalances through targeted public investments and maintenance, adopting the compact city and 30-min city models to ensure essential services are within a short commute. The plan emphasizes high-density, mixed-use developments, efficient public transportation, and walkable, bike-friendly environments, promoting convenience and health. Resident involvement in the planning process ensures that community needs are met, thereby improving quality of life. Additionally, the integration of green spaces and eco-friendly infrastructure supports

environmental sustainability. Overall, the living zone plan is essential for managing Seoul efficiently, fostering balanced growth, and ensuring equitable access to services, serving as a model for future urban planning in other cities.

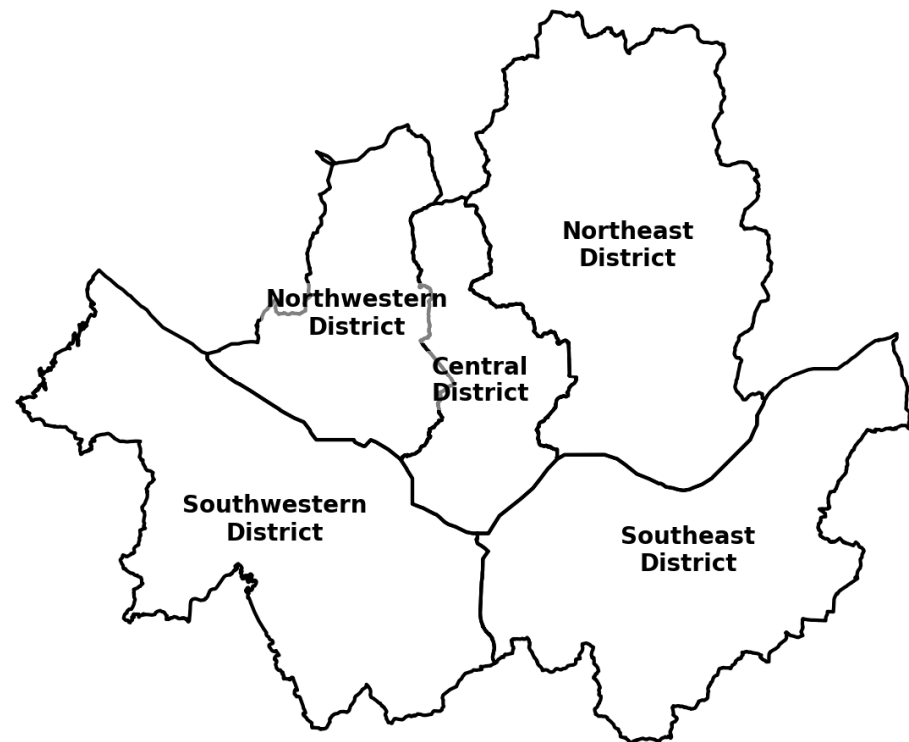


Figure 9. Visualization of five major regions.

3.2.2. Policy Suggestions for the Central District

According to the Seoul Master Plan, the central district (Jongno-gu, Jung-gu, Yongsan-gu) is set to develop as “a renaissance of a future city where tradition and innovation coexist”. The goal is to strengthen the roles of Seoul Station and Yongsan as domestic and international hubs through comprehensive development, transforming these areas into new national symbols. Plans include improving residential environments, preserving historical characteristics, undergrounding the Gyeongbu railway line with parks above, creating pedestrian-friendly eco-friendly transportation systems, expanding living logistics facilities, and restoring Yongsan Park’s identity and history. A positive correlation between internal trip rate and the de facto population suggests enhancing urban vitality, while land use mix indicates functional specialization may be more effective. Higher official land prices correlate with economic vibrancy, and a negative correlation between building energy density and nighttime population in Yongsan indicates the potential impacts of new residential developments. The need to attract younger populations is also highlighted. These insights guide practical strategies and policy directions for realizing the coexistence of tradition and innovation in Seoul’s 2040 Urban Comprehensive Plan.

3.2.3. Policy Directions for the Northeast District

According to the Seoul Master Plan, the northeast district (Seongdong-gu, Seongbuk-gu, Gwangjin-gu, Gangbuk-gu, Dongdaemun-gu, Dobong-gu, Jungnang-gu, Nowon-gu) aims to promote balanced development by becoming new growth and transportation-economic hubs. Cheongnyangni and Wangsimni will be enhanced as major transport and economic hubs, while Chang-dong and Sanggye will be developed into future industry and culture-based economic hubs. The plan includes improving residential environments, integrating roads and railways, enhancing transport connectivity, creating water-friendly spaces, establishing a green network, developing cultural hubs, utilizing university in-

frastructures for knowledge clusters, and upgrading urban manufacturing with smart technologies. These initiatives aim to make the northeast district a new growth hub and promote balanced economic and transportation development. The analysis shows a positive correlation between intra-district transit rates and de facto population, indicating enhanced connectivity is effectively boosting mobility and socio-economic activities. The negative correlation between average age and de facto population reflects high activity levels among the youth attracted by new industry hubs. The negligible correlation between land use mix and de facto population suggests that concentrated and specialized development boosts economic vitality. The strong positive correlation between official land prices and de facto population indicates vibrant economic activities in areas with higher property values, and the positive correlation between building energy density and de facto population shows urban centers as hubs for various activities, contributing to urban vitality. These insights demonstrate that the development projects in the northeast district are successfully energizing the local economy.

3.2.4. Policy Directions for the Northwestern District

According to the Seoul Master Plan, the goal for the northwest district (Eunpyeong-gu, Seodaemun-gu, Mapo-gu) is to “build a hub of creative culture by strengthening regional connectivity and fostering specialized industries”. The plan aims to develop Sangam and Susaek as international creative culture centers, utilize Nanji Island and the Western Driver’s License Test Center area to expand the metropolitan transportation network, and provide youth-centered housing and rational public housing projects considering regional characteristics. By optimizing available land through three-dimensional integration techniques, creating waterfront living spaces, and establishing green networks, the district aims to leverage culture, publishing, and creative industries to boost tourism. The positive correlation between intra-district transit rates and de facto population indicates that enhanced connectivity and accessibility increase urban vitality. The negative correlation between average age and de facto population highlights the contribution of youth to urban vitality, while the negligible correlation between land use mix and de facto population suggests that specialized development is more effective. The positive correlation between official land values and de facto population reflects high economic activity and urban vitality, and the positive correlation of building energy density at night in Mapo-gu indicates active cultural and media activities. This analysis supports the northwest district’s goal of becoming a creative cultural hub and achieving balanced development.

3.2.5. Policy Directions for the Southwestern District

According to the ‘Seoul Master Plan’, the developmental direction for the southwestern district (Yangcheon-gu, Yeongdeungpo-gu, Gangseo-gu, Dongjak-gu, Guro-gu, Gwanak-gu, Geumcheon-gu) is centered on “innovation based on educational and cultural resources to establish a new industry foundation”. Yeouido and Yeongdeungpo enhance urban competitiveness through integrated spatial structures, while Gasan Digital Complex and Magok develop as bases for new and knowledge-based industries. The plan includes improving residential environments with diverse housing types, enhancing convenience facilities, and solving regional discontinuities through three-dimensional integration and enhanced connectivity. The green space sector aims to enhance waterfront accessibility and connect north–south green axes, while educational and cultural axes are utilized to foster specialized areas in culture, publishing, and creative industries. These plans aim to comprehensively integrate transportation, culture, and residential environments, thereby activating economic activities and promoting new industries. The positive correlation of intra-district transit rates with de facto population suggests that smooth local transit and accessibility directly link to economic activities, indicating that integrated transportation systems positively impact urban vitality. The consistent negative correlation of average age with the de facto population highlights the significant role of the young population in the local economy, aligning with efforts to provide youth-centered living spaces. The

lack of a significant correlation between land use mix and de facto population suggests that concentrating on specific industries or functions may be more impactful than diversity in land use. The strong positive correlation between official land values and de facto population reflects high economic activity in areas with high real estate values. The negative correlation of building energy density with de facto population at night in some areas indicates decreased economic activities or different activity patterns. This analysis reveals that the development plans for the southwestern district are closely linked to transportation accessibility, youth activities, and specialized industry development, with educational and cultural resources expected to enhance economic vitality further.

3.2.6. Policy Directions for the Southeast District

According to the ‘Seoul Master Plan’, the southeastern district (Seocho-gu, Gangnam-gu, Songpa-gu, Gangdong-gu) focuses on “Enhancing Global Competitiveness and Strategic Management of Existing Residential Areas.” Critical areas like Gangnam, Jamsil, Suseo, and Munjeong are developed as international business hubs, with expansions in metropolitan transport networks and large land developments. Residential management is enhanced in conjunction with the waterfront network, and planned management aims to improve aging residential environments. Major regional centers are enhanced as future-oriented complex cities focusing on youth culture and innovation. The transportation goal is to improve accessibility through metropolitan and international links, and plans for parks and green spaces include connecting north–south green axes and creating waterfront-friendly spaces. Regional specialization focuses on strengthening historical and cultural content linked to international business and fostering the tourism industry. The southeastern district’s development strategy emphasizes boosting global competitiveness and strategically managing existing residential areas. Analysis shows a positive correlation between intra-district transit rates and de facto population, indicating high economic activity and accessibility. The negative correlation between average age and de facto population suggests vigorous economic activity in regions with a higher proportion of young people. The lack of a significant relationship between land use mix and de facto population reflects diverse economic activities that are not overly concentrated in specific industries. The positive correlation between official land values and de facto population reaffirms bustling economic activities in high real estate value areas like Gangnam and Seocho. The strong positive correlation of building energy density in Seocho suggests high urban vitality through residential, office, and commercial activities. The negative correlation between age diversity and de facto population indicates lower urban vitality in areas with diverse age groups, especially in family-centric districts like Gangdong and Songpa. These analyses confirm that the southeastern district’s development plans align with strategies to leverage existing strengths for greater global competitiveness and appeal.

3.3. Policy Suggestions for Temporal Heterogeneities in Urban Vitality

By analyzing the correlations between variables related to the de facto population of Seoul, a macroscopic approach by region becomes possible. To enhance the overall urban vitality in Seoul, designed strategies for a certain group of places are required by considering the spatiotemporal heterogeneous characteristics of each region. This is because some regions display little difference in vitality between day and night, resulting in balanced areas, while others show significant differences, leading to social disparities. This study has identified three different groups, necessitating the designated strategies for urban vitality enhancement: (1) areas with low population counts, (2) areas where the population significantly decreases at night, and (3) areas where the population significantly decreases during the day.

Figure 10 presents the results of k-means time series clustering based on the rate of change in the population at different times of the day. Areas with minimal change are shown in gray, areas with a slight decrease in population at night are shown in sky blue,

areas with a decrease in daytime population are shown in red, and areas with a significant decrease in population at night are shown in blue.

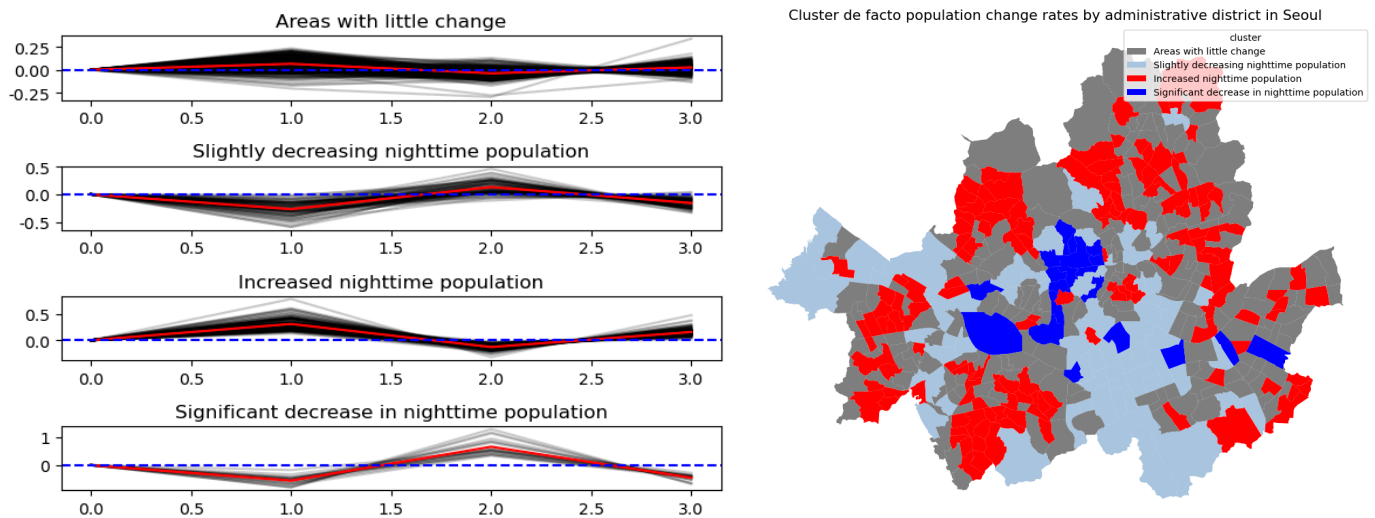


Figure 10. Results of time series cluster analysis of de facto population by administrative district in Seoul.

According to the results, areas that require the enhancement of vitality can be classified as follows: (1) areas with low average populations (Samcheong-dong, Muak-dong, Sinwol 6-dong) were selected based on the daily average de facto population, (2) areas with significant decreases in daytime population (Yongmun-dong, Donam 2-dong, Cheongryim-dong) were selected as the top three most extreme from the clustering results, and (3) areas with significant increases in nighttime population (Jongno 1·2·3·4 ga-dong, Sogong-dong, Huihyeon-dong) were also selected as the top three most extreme from the clustering results. In addition, MGWR models for each vulnerable area are estimated to investigate the determinant factors affecting urban vitality, as presented in Table 4. For the urban vitality vulnerable areas, we tried to draw implications based on the land characteristics of each area in relation to the MGWR coefficient values. Table 5 shows the results of the land characteristics of the vulnerable areas.

Table 4. MGWR coefficient values for urban vitality vulnerable areas.

Areas with Weak Urban Vitality	Time Zone	Constant	Internal Trip Ratio	Land Price	Building Energy Density	Land Use Mix	Age Mix	Average Age
Jongno 1·2·3·4 ga-dong	weekday night time	−0.431	0.46	0.18	−0.052	−0.003	−0.094	−0.145
	weekend night time	−0.361	0.486	0.142	−0.086	−0.026	−0.072	−0.151
Sogong-dong	weekday night time	−0.39	0.451	0.162	−0.115	0.003	−0.196	−0.148
	weekend night time	−0.377	0.469	0.123	−0.142	−0.019	−0.188	−0.152
Huihyeon-dong	weekday night time	−0.401	0.51	0.151	−0.117	0.006	−0.181	−0.15
	weekend night time	−0.383	0.535	0.113	−0.144	−0.016	−0.173	−0.155
Yongmun-dong	weekday daytime	−0.167	0.552	0.46	−0.016	0.074	−0.19	−0.013
	weekend daytime	−0.181	0.63	0.251	−0.033	0.075	−0.236	−0.066
Donam 2-dong	weekday daytime	0.103	0.362	0.649	0.213	0.055	0.078	−0.001
	weekend daytime	0.019	0.497	0.445	0.217	0.065	0.081	−0.055
Cheongryim-dong	weekday daytime	−0.164	0.286	0.247	0.095	0.085	−0.017	−0.019
	weekend daytime	−0.057	0.321	0.055	0.029	0.088	−0.063	−0.075
Samcheong-dong	weekday daytime	0.107	0.471	0.594	0.119	0.054	−0.48	−0.002
	weekday night time	−0.431	0.232	0.21	−0.024	−0.006	−0.157	−0.143
	weekend daytime	−0.138	0.528	0.338	0.096	0.058	−0.174	−0.053
	weekend night time	−0.328	0.215	0.169	−0.054	−0.029	−0.139	−0.148

Table 4. Cont.

Areas with Weak Urban Vitality	Time Zone	Constant	Internal Trip Ratio	Land Price	Building Energy Density	Land Use Mix	Age Mix	Average Age
Muak-dong	weekday daytime	0.177	0.32	0.561	0.032	0.06	−0.355	−0.005
	weekday night time	−0.275	0.28	0.185	−0.135	0.	−0.252	−0.145
	weekend daytime	−0.079	0.526	0.305	−0.007	0.059	−0.257	−0.055
	weekend night time	−0.248	0.268	0.144	−0.16	−0.02	−0.248	−0.15
Sinwol 6-dong	weekday daytime	0.149	0.332	0.841	0.162	0.069	−0.285	−0.021
	weekday night time	0.33	0.594	0.751	0.125	0.019	−0.077	−0.159
	weekend daytime	0.215	0.469	0.74	0.208	0.062	−0.169	−0.068
	weekend night time	0.283	0.55	0.529	0.111	0.007	−0.1	−0.16

Table 5. Land characteristics in urban vitality vulnerable areas.

Group	Areas with Vulnerable Urban Vitality	Industrial Area	Green Area	Commercial Area	Residential Area
Nighttime Vitality Reduction Areas	Jongno 1-2-3-4 ga-dong	0.000	0.242	0.596	0.162
	Sogong-dong	0.000	0.001	0.584	0.415
	Huihyeon-dong	0.000	0.060	0.294	0.646
	Yongmun-dong	0.000	0.039	0.000	0.961
Daytime Vitality Reduction Areas	Donam 2-dong	0.000	0.001	0.000	0.999
	Cheongryim-dong	0.000	0.000	0.000	1.000
	Samcheong-dong	0.000	0.613	0.005	0.382
Areas of absolute lack of vitality	Muak-dong	0.000	0.795	0.000	0.205
	Sinwol 6-dong	0.000	0.129	0.000	0.871

Commercial areas such as Jongno 1-2-3-4 ga-dong, Sogong-dong, and Huihyeon-dong, which have a high proportion of commercial activities as shown in Table 5, exhibit a consistent trend in the MGWR results: higher internal trip rates, higher publicly stated property values, lower building energy densities, lower age mixing rates, and lower average ages correlate with increases in population. This suggests a need for more youthful activities and the introduction of cultural and social programs to stimulate local engagement. Additionally, the diversity and density of indoor activities negatively impact vitality, suggesting that reducing building density might foster better urban vitality, possibly through enhanced outdoor activities. Strategies to improve urban vitality include enhancing connectivity between buildings and outdoor spaces, integrating indoor and outdoor areas, and promoting mixed-use developments. Designing pedestrian-friendly environments, providing outdoor activity areas, and incorporating green spaces can also significantly contribute to increased urban vitality.

Areas including Yongmun-dong, Donam 2-dong, and Cheongryim-dong, primarily residential, experience population declines during the day. Thus, policies should focus on enhancing local activities and opportunities for daytime consumption within the areas rather than developing new residential areas. For instance, Donam 2-dong shows a strong correlation between economic activity and population vitality, suggesting that stimulating both outdoor and indoor activities could enhance local vitality.

Lastly, areas with low average vitality, such as Samcheong-dong, Muak-dong, and Sinwol 6-dong, are mainly residential and green areas. For example, Samcheong-dong, which shows a positive correlation between property values and population vitality during the day, suggests that tourism enhancement could attract younger people and boost urban vitality. In contrast, Muak-dong and Sinwol 6-dong might benefit from policies aimed at enhancing residential features and encouraging youth inflow, alongside utilizing local green spaces to foster family-oriented outdoor activities. This approach can potentially increase

urban vitality through mixed land use that supports diverse and vibrant community activities.

4. Discussion

This article emphasized the role of the de facto population as a proxy of urban vitality, leveraging a mix of sensor-based dynamic features and static statistics. By providing a segmented analysis of factors affecting urban vitality, it examines dynamic human activities both outdoors and indoors, along with static factors such as land use intensity and the age mixture index. This new form of scalable approach enables a comprehensive understanding of various aspects of the city, offering a solid foundation for an in-depth exploration of the factors influencing urban vitality.

Understanding the spatiotemporal heterogeneity of the de facto population is essential for accurately understanding urban vitality, which can be a proxy measure for subjective livability. Temporal heterogeneity captures how population dynamics shift across different times—weekday daytime, weekday nighttime, weekend daytime, and weekend nighttime—offering insights into the varying urban activity patterns. This segmentation provides a precise understanding of how urban vitality fluctuates throughout the day and week. Additionally, spatial heterogeneity is crucial as it considers the influence of geographical proximity on urban vitality. By applying the MGWR model, this study adheres to Tobler’s First Law of Geography, acknowledging that “everything is related to everything else, but near things are more related than distant things”. This approach enables a detailed analysis of how spatial factors impact urban vitality, ensuring a comprehensive understanding of the underlying dynamics.

The analysis yielded policy implications for enhancing urban vitality based on the “Seoul 2040 Urban Comprehensive Plan”, identifying correlations between the de facto population and various variables. It also enabled the clustering of temporal patterns of de facto population, identifying vulnerable areas with low nighttime population, regions with sharp decreases at night, and areas with sharp increases, thus facilitating discussions on necessary policy measures for these areas. By proposing tailored strategies that consider the characteristics of each area, this research contributes to enhancing urban vitality and supporting vulnerable populations.

The methodologies and findings of this study are not limited to Seoul and can be applied to various urban environments. By adjusting the model to reflect the unique characteristics and conditions of different cities, this research opens possibilities for effectively analyzing population trends and urban vitality across diverse urban settings, providing foundational data for addressing various urban challenges and pursuing balanced and sustainable development. The insights from this study can serve as crucial reference material for urban planning and policymaking processes, contributing to a comprehensive understanding of urban population dynamics and related complex factors.

Nonetheless, this study has several limitations that could inform future research directions. First, the reliance on de facto population data limited to Seoul restricts the generalizability of the findings. The absence of nationwide de facto population data constrained the scope to a broad analysis reflective of various regional characteristics, limiting the research to Seoul. Second, the minimum unit size of the Origin–Destination (OD) information in the used telecommunication data is set at 500 m × 500 m, which poses challenges in analyzing finer movement patterns within administrative neighborhoods. This limitation impacted the precision in capturing detailed movement patterns and dynamics, particularly in smaller areas. Third, the monthly provision of building power usage data presented constraints in time series analysis, preventing the capture of daily or hourly fluctuations, which is crucial for analyzing dynamic characteristics like urban vitality.

Recognizing these limitations, future research should aim to expand the data scope, acquire higher resolution data, and secure additional data sources that enable more detailed time series analyses. Such improvements would allow for more precise and extensive analyses, enhancing the generalizability and accuracy of research outcomes.

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Data Availability Statement: Anyone with minimal experience in statistical modeling should be able to use the ML models used in this study easily by using Python 3.11 or most other libraries available in Python and in other computer languages (e.g., R). The Python codes developed for this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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