Exploring the Carbon Emission Impact of Community Life Circle Shared Clusters: A Case Study of Nanjing, China

Qingxin YANG, Zhihan ZHANG, Yuyue HUANG, Xun ZHANG, Junyan YANG
Affiliation: Southeast university
Email: qingxinyang@seu.edu.cn

Abstract
Aligned with global sustainability goals, this study examines how facility service and sharing structures influence urban carbon emissions. Using Nanjing as a case, a multi-scale system is developed across four facility types: education & health, culture & sports, convenience & utility, and commercial & leisure. Shared community clusters are identified via isochrone analysis and strongest-link mapping. Carbon emission impacts are evaluated using both univariate and multivariate regressions. Results reveal type-specific differences in spatial sharing patterns and emission sensitivities, with cultural facilities showing the strongest effects. A carbon-oriented planning strategy is proposed, advocating differentiated configurations of self-sufficient and shared facilities based on facility-type characteristics and spatial service structures.

Keywords: community life circle; facility sharing; cluster identification; carbon emissions

1.Introduction

Driven by sustainability goals, developing low-carbon spatial governance models has become a vital strategy for urban development. As the fundamental spatial unit of everyday life, the community life circle plays a critical role in shaping activity distribution, mobility patterns, and service efficiency, making it a key focus in low-carbon urban research (Hong et al., 2020)it is necessary to reduce energy use and associated greenhouse gas emissions in buildings through energy conservation and efficiency improvements. Computational tools empowered with rich urban datasets can model performance of buildings at the urban scale to provide quantitative insights for stakeholders and inform their decision making on urban energy planning, as well as building energy retrofits at scale, to achieve efficiency, sustainability, and resilience of urban buildings. Designing and operating urban buildings as a group (from a city block to a district to an entire city. By integrating essential services—such as education, healthcare, commerce, and cultural amenities—within walkable or short-travel distances, life circles encourage more compact, efficient, and greener lifestyles, thereby contributing to city-wide carbon reduction efforts (Bruno et al., 2024)in particular, heralded a new vision for cities where essential services must be easily accessible. Despite its undoubted merit in stimulating discussion on new organization of cities, the 15-minute city cannot be applicable everywhere, and its very definition raises a few concerns. Here we tackle the feasibility and practicability of the 15-minute city model in many cities worldwide. We provide a worldwide quantification of how close cities are to the ideal of the 15-minute city. To this end, we measure the accessibility times to resources and services, and we reveal strong heterogeneity of accessibility within and across cities, with a pivotal role played by local population densities. We provide an online platform (https://whatif.sonycsl.it/15mincity/

Most existing studies on community life circles emphasize internal completeness, focusing on service sufficiency, accessibility, or equity within individual communities. However, in practice, significant service overlap and facility sharing exist between communities. These shared connections form interconnected clusters, where multiple life circles are functionally linked through shared facilities (Pan, 2023)ΔSuch clusters often transcend administrative or physical boundaries, reflecting more complex patterns of service coverage and functional interdependence. While this configuration may enhance facility utilization and spatial flexibility, its systemic implications for mobility, service reliance, and local carbon emissions have yet to be fully understood or quantified (Chai and Li, 2019)Δ

As cities become more polycentric and resource allocation more distributed, the structure of these shared clusters may play a key intermediary role in shaping urban carbon emissions. Identifying these clusters and clarifying their impact mechanisms is crucial—not only for refining life circle planning, but also for advancing precision carbon governance at the community scale. The lack of integrated models that combine spatial structure, facility interaction, and environmental outcomes remains a critical gap in current literature.

This study takes Nanjing, China as a case to examine how spatial accessibility and facility sharing patterns influence carbon emissions at the local level. First, a multi-scale life circle system is constructed based on 5-, 10-, and 15-minute isochrones, covering four essential service categories: education & health, culture & sports, convenience & utility, and commercial & leisure. Second, based on accessibility and spatial overlap, functionally connected shared clusters are identified through a strongest-link network approach. Third, service intensity (number of accessible facilities) and sharing intensity (the share of facilities engaged in cross-community use) are used in univariate regression models to evaluate their individual effects on carbon emissions. Finally, a multivariate regression model incorporates the combined characteristics of multiple facility types to reveal potential synergistic or compensatory effects on emissions.

This research addresses the following questions:

- How do facility configuration and inter-community sharing jointly shape shared cluster structures?
- How do service and sharing intensities across different facility types influence carbon emissions?
- Do multidimensional sharing patterns lead to synergies or trade-offs in emission outcomes?

The findings provide new insights into the functional logic linking urban facility networks and emission patterns, offering evidence-based guidance for carbon-oriented planning and optimized life circle service configurations. The proposed framework contributes to both academic understanding and practical strategies for managing the spatial-energy nexus in future sustainable cities.

2.Methodology

This study focuses on the central urban area of Nanjing and develops an analytical framework that links facility types and accessibility, sharing structures, and carbon emission impacts. Using multi-scale isochrone analysis, community-specific facility access was identified to define facility bundles for each neighborhood. Based on the overlap between these bundles, sharing relationships were established to construct facility sharing networks and delineate shared clusters. Finally, integrating community-level carbon emission data, the analysis evaluates how service intensity and sharing intensity influence emission outcomes.

2.1Classification of Facility Types and Definition of Facility Bundles

The appropriate composition of facilities within community life circles has been widely discussed in prior research. Frameworks for defining such systems typically consider two key dimensions: accessible travel time (He et al., 2024; Logan et al., 2022, p. 10; Staricco, 2022) and facility type (Liu et al., 2024; Moreno et al., 2021)there is a lack of comprehensive measures and an overall understanding of the 15-minute city status. By using the latest population census data and POI data in Hong Kong, this study proposes a 15-minute city index that holistically measures the 15-minute city status by incorporating the accessibility, which is measured by a modified two-step floating catchment area (2SFCA. Based on daily living needs, this study establishes a facility system comprising four core service functions: education & health, culture & sports, convenience & utility, and commercial & leisure. Building upon this classification, 5-, 10-, and 15-minute isochrones are introduced to define three levels of service space—self-sufficient (5-minute), neighborhood-level (10-minute), and shared (15-minute) life circles. Each level corresponds to a different spatial scale of facility provision and is associated with a set of representative facility types. The detailed facility composition is as follows (Table1):

Table 1 Facility Composition Across Life Circle Scales and Service Categories

	5min (Self-Sufficient)	10min (Neighborhood)	15min (Shared)
Commerce & Leisure (C&L)	Restaurants	Dessert shops, beverage stores Teahouses, mahjong clubs, karaoke Pet and plant markets Bathhouses, salons	Cinemas, theaters Shopping malls, amusement parks
Education & Health (E&F)	Pharmacies	Kindergartens Primary schools Clinics, specialty hospitals	General hospitals Middle schools
Culture & Sports (C&S)	Small public spaces	Cultural store Gymnasium	Museums, art galleries, cultural centers Parks, squares, stadiums Scenic spots, zoos, aquariums
Convenience & Utility (C&U)	Parcel stations Public transport (bus/metro) Convenience stores Parking lots	Telecom service centers Charging stations Wet markets	Postal services Banks Gas and fueling stations Elderly care centers

Specifically, the education & health category includes various levels of medical and educational facilities, reflecting the progressive expansion of basic healthcare and compulsory education services. The culture & sports category spans from small public spaces and local sports venues to parks, squares, and museums, covering both everyday and occasional cultural and recreational needs. The convenience & utility category comprises parcel stations, convenience stores, public transport (bus/metro), parking lots, charging stations, banks, wet markets, gas stations, and elderly care centers, addressing daily goods acquisition and mobility support. Lastly, the commerce & leisure category ranges from local entertainment facilities—such as restaurants, dessert shops, and teahouses—to cross-community consumption venues including cinemas, shopping malls, and amusement parks.

Subsequently, 5-, 10-, and 15-minute isochrones were generated for each community using central point locations and the Mapbox API. Through spatial overlay analysis, all reachable facilities within each time threshold were identified. This resulted in a multi-scale dataset of community facility bundles, recording the number and types of accessible facilities—across the four service categories—for each community at each isochrone level.

2.2 Identification of Shared Community Clusters

Based on the constructed facility bundles, sharing relationships between communities were identified by examining the overlap of accessible facilities. If two communities shared one or more facilities within the same isochrone threshold, they were considered to have a facility-sharing connection. This sharing logic was applied across two dimensions: three isochrone levels (5, 10, and 15 minutes), and four facility categories (education & health, culture & sports, convenience & utility, and commerce & leisure), resulting in a set of multi-dimensional facility sharing networks.

In each network, nodes represent communities and edges represent facility-sharing links, with edge weights indicating sharing intensity (e.g., number or proportion of overlapping facilities). To capture the most significant sharing relationships, each community's strongest sharing partner—the community with the highest sharing intensity—was identified. These links were used to construct a strongest-link sharing network, from which shared community clusters were delineated. Each cluster comprises communities that are directly or indirectly connected via their strongest facility-sharing ties.

Each facility-specific network yields a corresponding set of Shared Community Clusters, reflecting the spatial sharing structure and functional distribution of that facility type across the city. These clusters not only reveal patterns of inter-community service reliance, but also serve as the fundamental spatial units for the subsequent analysis of carbon emission impacts.

2.3 Carbon Emission Patterns under Facility Service-Sharing Structures

Following the identification of shared community clusters, this study incorporates community-level carbon emissions data and conducts a two-level regression analysis to systematically evaluate the impact of service and sharing characteristics on carbon outcomes. The analysis includes:

- Univariate regression analysis (cluster level): Each analysis unit corresponds to a set of shared community clusters derived from one specific facility type. The average carbon emission of all communities within each cluster is calculated. Two explanatory variables are extracted: the service intensity (total number of facilities within the cluster) and the sharing intensity (proportion of shared facilities). Linear regression is employed to assess the direction and significance of emissions impact across different facility types, revealing the emission patterns associated with single-type sharing structures.
- Multivariate regression analysis (community level): Each individual community serves as the unit of analysis. A multidimensional vector of service and sharing intensities is constructed, encompassing all four facility types. A multiple linear regression model is applied to evaluate the composite influence of different facility types within the overall sharing network, exploring whether their effects on carbon emissions are synergistic, complementary, or substitutive.

To enhance interpretability, the model incorporates standardized variables and controls for multicollinearity. This analytical framework facilitates a macro-level understanding of how facility sharing structures shape urban carbon emissions, while also uncovering the complex interactions among multiple services at the micro (community) level.

3.Results

3.1Shared Facility Structures in Community Life Circles

Figure 1 illustrates the facility sharing network structures across communities in Nanjing's central urban area, differentiated by isochrone thresholds (5, 10, and 15 minutes) and facility types. From the perspective of overall sharing networks, inter-community connections intensify significantly as the time radius expands. In the 5-minute life circle, only 574 sharing edges are observed, with an average degree of 0.94, indicating that most facility use is confined within individual communities. In contrast, the number of sharing edges increases to 2,517 and 7,346 in the 10- and 15-minute networks, with corresponding average degrees rising to 4.12 and 12.02, respectively. This reflects a transition from "local self-sufficiency" to "regional sharing," with a progressively higher level of spatial integration.

Facility-specific sharing networks also exhibit clear variations in network connectivity and cluster configuration. The culture & sports (C&S) network shows the highest average degree (18.77), indicating the strongest and widest sharing pattern. The commerce & leisure (C&L) and convenience & utility (C&U) networks also show relatively high degrees of connectivity (15.61 and 15.86, respectively). In contrast, the education & health (E&H) network has a lower average degree of 11.77, suggesting weaker inter-community ties and a more localized pattern of service provision.

The red edges in the figure highlight each community's strongest sharing connection, further revealing the diversity of shared community cluster structures. Across different facility types, the same community often links to distinct target communities, resulting in divergent cluster affiliations in each facility-specific network. This indicates a functional divergence in sharing behavior: communities exhibit varying patterns of cooperation and service coupling depending on the facility category. Such differentiation reflects the complexity of multi-dimensional sharing structures in urban space and lays the groundwork for analyzing how different types of facility sharing influence carbon emissions.

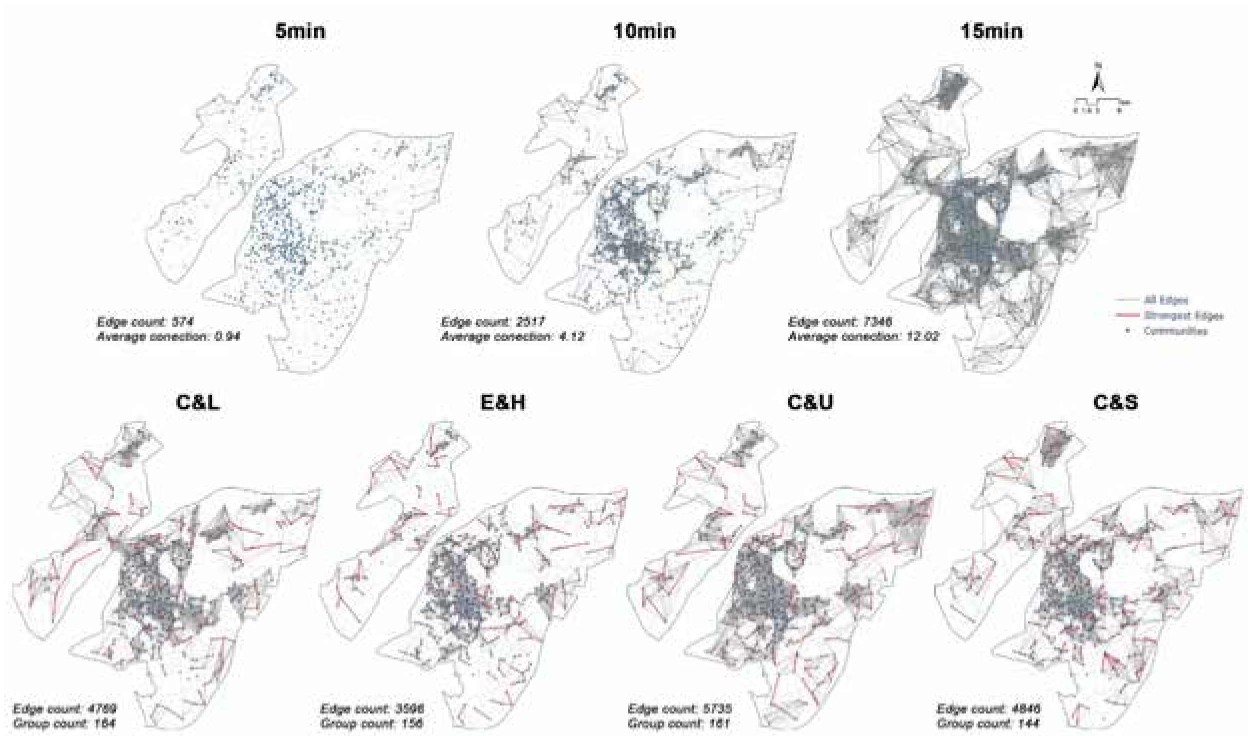


Figure 1 Community facility sharing networks under different time scales and facility types

Building upon the constructed sharing networks, two key indicators—service intensity and sharing intensity—were calculated for each community (or shared community cluster) across different facility types (Figure 2).

In terms of service intensity (left panel), the four facility categories exhibit substantial variation in spatial distribution. Commercial & leisure (C&L) facilities are markedly more abundant and widespread than the other types, with service intensity exceeding 3,000 in some communities, indicating a high-density clustering pattern. In contrast, the median and upper quartile values for education & health (E&H), culture & sports (C&S), and convenience & utility (C&U) are consistently lower, reflecting compact distributions with generally low intensity. This suggests these facilities are more evenly distributed across the city but exhibit lower localized density.

As for sharing intensity (right panel), all four categories present broadly similar distribution patterns, yet subtle differences emerge. Culture & sports (C&S) and convenience & utility (C&U) facilities show slightly higher sharing intensities, implying a greater propensity for overlapping usage across communities and stronger sharing potential. By contrast, education & health (E&H) exhibits lower sharing intensity overall, with some communities showing near-zero sharing proportions—suggesting spatially confined service areas with limited cross-community reach. Despite the high service intensity of commercial & leisure (C&L) facilities, their sharing intensity is more dispersed, indicating strong shared usage in some regions while remaining locally concentrated in others. Collectively, service intensity captures the spatial density of different facility types, while sharing intensity reflects their potential for inter-community connectivity. The combination of these metrics provides a quantitative basis for characterizing the shared facility structures within urban life circles and supports the subsequent analysis of their association with carbon emissions.

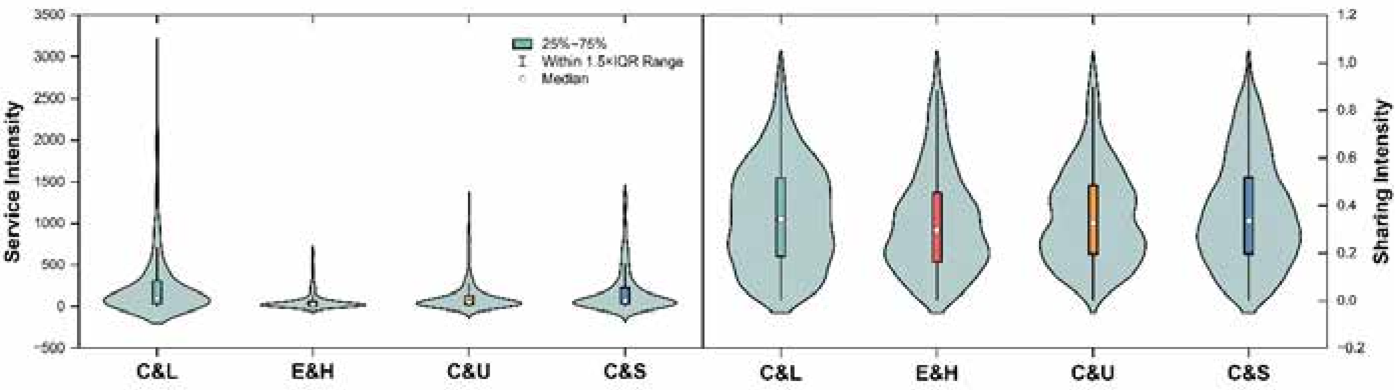


Figure 2 Distribution of service intensity and sharing intensity across facility types

3.2 Carbon Emission Patterns across Single-Type Sharing Clusters

Figure 5 presents the spatial distribution of carbon emissions at both the community level and the shared cluster level. The left panel illustrates carbon emissions at the community level, derived by overlaying ODIAΔC gridded data with community boundaries(Tomohiro Oda and Shamil Maksyutov, 2015). The results reveal a clear spatial pattern of "high in the center, low in the periphery" across Nanjing's central urban area. The emission values are right-skewed and spatially asymmetrical, aligning with the concentration of population and built-up intensity in the urban core.

The four maps on the right display carbon emissions aggregated by shared community clusters for each facility type: commercial & leisure (C&L), education & health (E&H), culture & sports (C&S), and convenience & utility (C&U). These cluster-based maps reveal notable differences in emission distribution. Clusters derived from C&L and C&S sharing networks tend to reinforce carbon concentration in central areas, indicating strong overlap of high-emission communities within their shared structures. In contrast, clusters based on E&H and C&U display more dispersed carbon emission values, suggesting a broader spatial distribution of functional dependencies and a weaker centralizing effect.

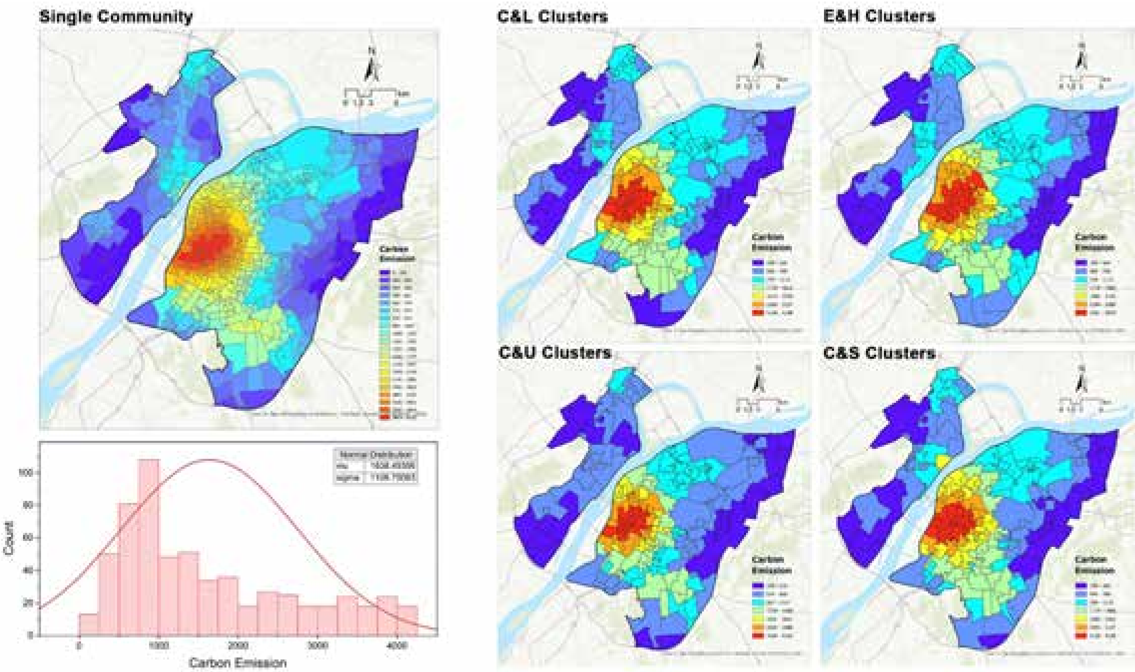


Figure 3 Spatial distribution of carbon emissions at the single community level and facility-based sharing cluster level

To further quantify the carbon implications of different facility sharing structures, Figure 6 presents the results of univariate linear regression models using service intensity (left) and sharing intensity (right) as independent variables. All four facility categories exhibit a statistically significant positive correlation with carbon emissions ($p < 0.001$), but differ notably in both explanatory power and marginal impact.

In the service intensity models, culture & sports (C&S) and convenience & utility (C&U) demonstrate the highest model fit ($R^2 = 0.351$ and 0.336, respectively), indicating their facility counts have the strongest explanatory power for community-level emissions. Education & health (E&H), in contrast, shows the steepest regression slope (22.276), meaning each additional unit of service intensity contributes the most to carbon emissions, reflecting a stronger marginal emission effect. Commercial & leisure (C&L) performs moderately in both R^2 (0.258) and slope (2.261).

In the sharing intensity models, overall explanatory power is slightly lower (highest $R^2 = 0.204$ for C&S), but the gradient of impact across facility types remains clear. E&H and C&S exhibit the steepest slopes (632.992 and 540.703), suggesting their cross-community usage significantly amplifies emissions—likely due to increased travel distances or facility aggregation effects. In contrast, C&L and C&U show weaker slopes and lower R^2 values, implying a more limited marginal effect, potentially constrained by their proximity-based service characteristics. In summary, service intensity reflects the facility provision baseline and acts as the primary determinant of carbon emissions, while sharing intensity captures the spatial extension of facility usage and contributes a type-dependent marginal modulation effect.

From a planning perspective:

- In areas with facility oversupply or high density, uncontrolled expansion of E&H and C&S facilities should be avoided, especially where local service is sufficient but sharing value is low, to mitigate marginal carbon impacts.
- For C&L and C&U, which exhibit weaker carbon implications, improving sharing efficiency through strategic coordination can help avoid redundant investments and spatial inefficiencies.
- New infrastructure should prioritize local self-sufficiency for foundational services like E&H, reducing inter-community trips.
- In contrast, C&L and C&S may benefit from enhanced sharing configurations, where well-placed nodes promote broader service coordination without compromising emission control.

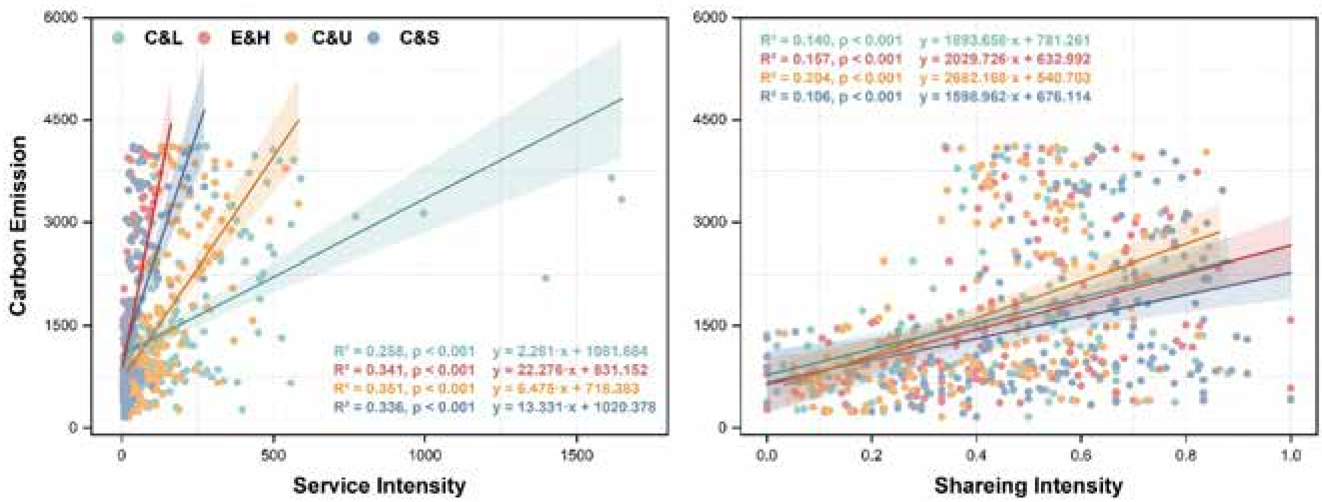


Figure 4 Univariate regression between service/sharing intensity and carbon emissions across facility types

3.3 Carbon Emission Patterns under Multi-Dimensional Sharing Structures
To further evaluate the joint effects of different facility types across both dimensions—service intensity and sharing intensity—Figure 7 presents standardized coefficients and 95% confidence intervals from a multiple linear regression model. Compared with the previous univariate results, the multivariate model controls for cross-variable interactions and reveals a more structured mechanism of carbon emission drivers.

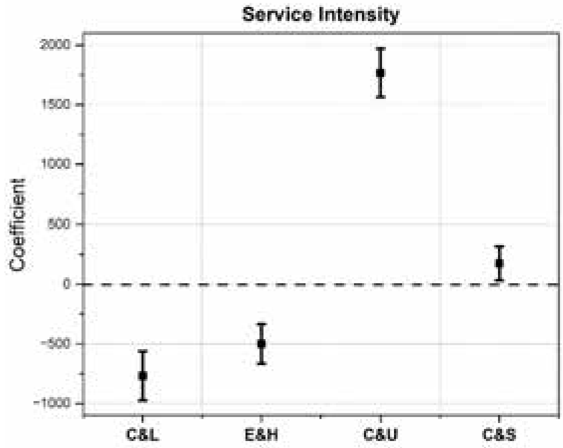
On the service intensity dimension, culture & sports (C&S) and convenience & utility (C&U) facilities continue to show significant positive effects. Notably, C&S holds the highest coefficient, suggesting that even after adjusting for other facility types, the service density of C&S facilities remains one of the strongest drivers of carbon emissions. In contrast, commercial & leisure (C&L) and education & health (E&H) show significant negative coefficients in the multivariate model—opposite to their positive trends in the univariate analysis. This suggests that, once the effects of C&S and C&U are accounted for, higher service intensity of C&L and E&H may actually correlate with reduced carbon emissions, potentially indicating a substitution effect or mixed-use efficiency in highly integrated facility zones that mitigates marginal emission pressure.

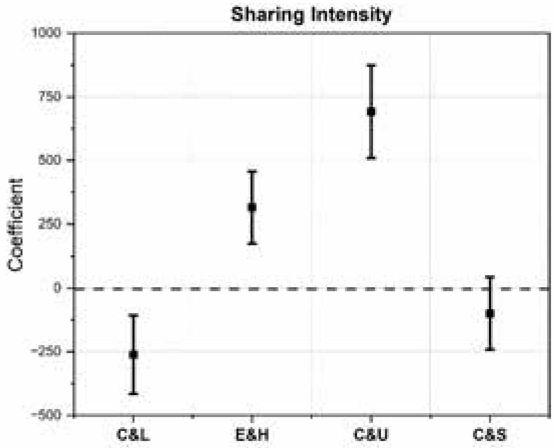
On the sharing intensity dimension, C&S again emerges with the strongest positive effect, reaffirming its high-emission association through cross-community usage. E&H also maintains a positive effect, albeit with lower magnitude. C&U shows no significant impact in the multivariate model, while C&L retains its negative association, suggesting that over-sharing in some cases may result in inefficient trips due to redundant facility usage.

Overall, the multivariate model reveals differentiated roles and interactions among facility types:

- C&S facilities contribute to increased emissions in both service and sharing dimensions, highlighting them as critical intervention targets in low-carbon facility planning.
- E&H facilities show a duality—while sharing may raise emissions, enhancing localized service capacity could yield mitigation benefits, supporting a “proximity-based” planning logic.
- C&L facilities exhibit negative marginal contributions in the multivariate context, indicating that concentrated deployment with efficient sharing could improve carbon performance.
- C&U facilities show relatively mild carbon impacts, suggesting that optimizing sharing coverage may enhance system-level efficiency without large emission trade-offs.

These findings underscore the need to avoid one-size-fits-all expansion strategies. Instead, urban planning should adopt a type-sensitive approach by aligning facility density, sharing structure, and carbon responsiveness in a coordinated framework—guiding community-scale infrastructure development toward greater efficiency, lower emissions, and structural synergy.





Effect Summary

Source	LogWorth	PValue	VIF
Commerce & Leisure	12.1054	< 0.0001	11.6195
Education & Health	8.2963	< 0.0001	7.5318
Culture & Sports	1.7792	0.0166	5.5329
Convenience & Utility	52.8774	< 0.0001	11.2914

Summary of Fit

R-Squared	0.5288
Adj. R-Squared	0.5257
Root Mean Square Error	759.0711
Mean of Response	1638.4936
Durbin-Watson	1.0344
Observations	611

Analysis of Variance

Source	DF	SUM of Squares	Mean Square	F Ratio
Model	4	395135748.84	98783937.21	170.04
Error	606	352051394.53	580942.89	Prob > F
C. Total	610	747187143.37		0.0000

Effect Summary

Source	LogWorth	PValue	VIF
Commerce & Leisure	3.0213	0.0010	4.8739
Education & Health	4.8493	< 0.0001	4.0755
Culture & Sports	0.7643	0.1721	4.1725
Convenience & Utility	12.4846	< 0.0001	6.7935

Summary of Fit

R-Squared	0.3706
Adj. R-Squared	0.3664
Root Mean Square Error	877.3189
Mean of Response	1638.4936
Durbin-Watson	1.0296
Observations	611

Analysis of Variance

Source	DF	SUM of Squares	Mean Square	F Ratio
Model	4	276907524.86	69226881.21	89.2054
Error	606	470279618.51	776038.97	Prob > F
C. Total	610	747187143.37		0.0000

Figure 5 Regression coefficients of service and sharing intensity on carbon emissions in a multivariate model

4.Discussion

Using Nanjing as a case study, this research systematically constructed the facility sharing network structure across communities and examined the impact mechanisms of different facility types on community-level carbon emissions through the dual dimensions of service intensity and sharing intensity. The network was established by delineating isochrone-based service areas and identifying the strongest shared facility edges between communities, forming functionally connected structures. These were further categorized into four shared community clusters, each dominated by a specific facility type. Spatial analysis revealed significant differences in emission patterns among cluster types: clusters dominated by commercial & leisure (C&L) and culture & sports (C&S) facilities exhibited dense emission hotspots in central areas, while education & health (E&H) and convenience & utility (C&U) clusters showed more dispersed distributions.

Regression analyses further highlighted the heterogeneous impacts of service and sharing intensity across facility types. In the univariate models, service intensity consistently exhibited stronger explanatory power for carbon emissions than sharing intensity, confirming facility density as a primary driver. Nonetheless, sharing intensity showed significant positive effects in C&S and E&H types, suggesting that shared facility usage may increase inter-community travel and energy consumption under certain conditions. In the multivariate models, some variables (e.g., service intensity of E&H, sharing intensity of C&L) reversed direction, indicating that spatial substitution and functional coupling among different facility types can mediate carbon outcomes.

These findings provide important implications for low-carbon urban facility planning. First, C&S facilities, which significantly contribute to emissions in both dimensions, should be key targets for emission control—through capacity regulation, spatial optimization, and managed sharing mechanisms. Second, E&H facilities are better suited for self-sufficient local provision, minimizing reliance on inter-community travel. Lastly, C&L and C&U facilities demonstrate carbon-efficient sharing potential, and should be enhanced through regional coordination strategies to maximize service efficiency and resource utilization.

In sum, the impact of facility sharing structures on urban carbon emissions is structural and multidimensional. Effective planning must adopt type-specific strategies that align facility density, sharing patterns, and carbon responses, enabling synergistic control toward more efficient and sustainable urban living environments.

5.Conclusion

This study proposes an integrated analytical framework that combines isochrone analysis, facility sharing network construction, and carbon emission response evaluation to investigate how the sharing structures of different facility types within community life circles influence urban carbon emissions. Using Nanjing as a case study, we constructed cluster structures based on facility types and sharing intensity, quantified the dual-dimensional contributions of service intensity and sharing intensity, and employed both univariate and multivariate regression models to reveal differentiated impact patterns across facility types. The main conclusions are as follows:

- Facility sharing networks exhibit clear spatial and typological variations, with clusters dominated by different facility types displaying distinct emission concentration patterns;
- Service intensity acts as a key driver of carbon emissions, particularly for culture & sports and convenience & utility facilities, while the effect of sharing intensity is more type-sensitive, with culture & sports and education & health showing significant positive associations;
- Multivariate models reveal interaction effects and sign reversals among facility types, suggesting that the regulatory role of sharing structures on carbon emissions is complex and structural;
- Low-carbon urban planning should adopt type-specific strategies: fostering self-sufficiency where appropriate, and promoting shared usage where beneficial, to advance low-carbon and synergistic optimization of community life circles.

This research provides an empirical basis for understanding the intrinsic relationship between urban spatial structure and carbon emissions, offering concrete typological guidance for urban facility allocation and emission mitigation policies. Future studies may incorporate dynamic mobility behaviors, big-data-based flow metrics, and lifecycle emission accounting to develop more refined models of urban carbon response.

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