Identification and optimization analysis of urban building space use characteristics by integrating POI and GIS

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Abstract. Aiming at the problems of single function and unbalanced use efficiency of urban architectural space, this study integrates POI data and GIS technology to construct a full chain analysis framework of "data acquisition-feature recognition-optimization simulation", aiming at revealing the use characteristics of architectural space and proposing optimization strategies. In this paper, POI data is obtained through API and business hours information is supplemented. Combined with building outline GIS data, a three-dimensional database of "Building -POI- Time" is constructed after spatial cleaning and topology correction. The spatio-temporal activity index (STAI) model is used to quantify the dynamic use characteristics of building space, and the spatial mismatch problem is diagnosed by the functional supply-demand ratio (FSR), and the multi-objective functional reorganization scheme is generated by NSGA-III multi-objective genetic algorithm. Taking Nanshan District of Shenzhen as an empirical research area, the results show that there is a significant difference between day and night in the office activity of science and technology park, with the STAI reaching 0.85 at 9 am and dropping to 0.12 at night; There is an imbalance between functional supply and demand in different regions, such as the gap of catering service at noon on weekdays in the office area of Science and Technology Park (FSR=0.63) and the surplus of commercial leisure facilities at night in Xili Community (FSR=1.87). The comparison of optimization schemes shows that although the transformation cost of vitality priority scheme is 610 million yuan, the STAI is increased by 53% and the functional mixing entropy is 3.02, and the effect is the best. This study provides scientific methods and practical references for spatial optimization of smart cities, and enriches the theoretical system of urban spatial optimization.

Keywords: POI; GIS; urban building space; use characteristics; STAI; FSR.

1. Introduction

As the main carrier of human activities, urban architectural space faces some outstanding problems, such as single function and unbalanced use efficiency. The tidal phenomenon of "office gathering during the day and vacant at night" generally exists in the central area of first-tier cities, while the large commercial complexes in the suburbs are crowded on weekends and deserted on weekdays due to the separation of work and residence; At the same time, the vacancy rate of a large number of inefficient industrial plants and community businesses in old urban areas continues to rise. These phenomena reflect that the traditional "static planning" model is difficult to adapt to the dynamic space use demand, and it is urgent to reveal the deep characteristics of architectural space use through data-driven methods.

Traditional urban space research relies on structured data such as planning documents and statistical yearbooks, which has the problems of coarse granularity of time and space and lagging function identification, and it is difficult to reflect the actual use situation such as flexible use patterns or emerging business changes [1]. With the integration and application of POI data and GIS technology, these problems have been solved in a new way. POI data provides high spatial-temporal resolution and semantic richness, and can capture minute-level updates, functional labels of buildings and other detailed information, making it possible to conduct micro-scale spatial analysis, such as identifying night economic active areas by analyzing the night distribution of catering POIs [2-3]. GIS technology uses spatial analysis algorithm to reveal the spatial relationship between POI distribution pattern and building function, which provides a scientific basis for optimizing urban spatial allocation [4].

This study breaks through the discipline barriers of urban planning, geographic information science and data science, and constructs a full chain analysis framework of "data acquisition-feature recognition-optimization simulation", which provides a new paradigm for smart city research; By introducing the temporal and spatial attributes of POI data, the dynamic evolution law of architectural space use is revealed, which makes up for the lack of traditional research on "space life course"; Combining multi-objective optimization algorithm with GIS visualization technology, this paper puts forward the strategy of building function reorganization based on spatial mismatch index, which enriches the theoretical system of urban spatial optimization.

2. Research methods and technical routes

2.1. Data acquisition and preprocessing

Data acquisition and preprocessing include the processing flow of POI data and building outline GIS data (Figure 1). The spatial cleaning of POI data removes redundant coordinates and duplicate entries, while the geometric errors of building outline data are repaired by topological correction, and the two are superimposed in the spatio-temporal correlation step to construct the "building -POI-time" three-dimensional database [5-6]. The whole process relies on key preprocessing technologies to improve data accuracy and applicability.

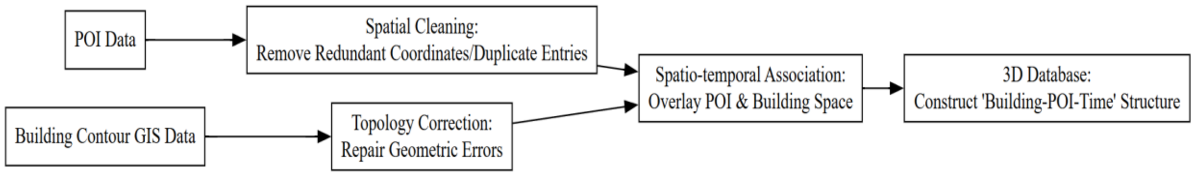

Figure 1. Data type and processing flow.

Among them, POI data supplements business time information through API, and establishes time weight function to distinguish the use intensity of different time periods; For the unification of spatial scale, the Dasymetric mapping method is adopted, and the POI point data are allocated to 10m×10m× three-dimensional grid units according to the building area, so as to realize the fusion expression of multi-source data on the unified spatial scale [7].

2.2. Key technical methods

2.2.1. Dynamic use of feature recognition model

In order to deeply describe the dynamic use characteristics of architectural space, the "spatio-temporal activity index" (STAI) was studied and constructed, which comprehensively considered the activity degree and spatial influence of different functional types of POI in the building [8]. The calculation formula of STAI is as follows:

$$STAI_{b,t} = \frac{\sum_{i=1}^{n}(A_i W_{t,i} F_i)}{S_b} \tag{1}$$

Among them, A_i represents the functional intensity coefficient of i POI, such as 1.2 for business, 1.0 for office and 0.8 for residence, which reflects the difference in the contribution of different types of facilities to spatial activity; $W_{t,i}$ is the corresponding time weight function, which distinguishes the spatial use potential of the POI in different time periods; F_i is the correction factor of facility scale, which combines the area ratio and human flow parameters to reflect its actual influence scope more accurately; S_b represents the total effective use area of the target building, which is used for normalization to make different buildings comparable.

By quantifying the functional activity level of buildings in different periods, the model can effectively identify the periodic fluctuations and irregular changes in space use, such as the difference in the use of office buildings on weekdays and weekends, or the operation mode of shared space adjusted with seasons.

2.2.2. Spatial mismatch diagnosis technology

Spatial mismatch diagnosis technology aims to identify the matching degree between urban building function and actual demand, and the core index is "functional supply-demand ratio" (FSR). This ratio is revised by comparing the actual service capacity of POI with the potential demand reflected by the regional population heat map, and combining with the accessibility coefficient, so as to quantify the rationality of functional allocation in a certain region [9]. Among them, the accessibility coefficient is determined by the walking distance from the building to the nearest public transport station, and it is calculated by exponential attenuation model. Different regional types use different attenuation parameters β to reflect the influence of traffic convenience on functional adaptation more truly. This technology can effectively identify spatial units with excessive or insufficient functions, such as "cold business district" with dense commercial facilities but low flow of people, or "function-missing area" with high residential density but lack of supporting services. Through the spatial visualization analysis of FSR indicators, it can provide accurate suggestions for urban planners to adjust their functions and improve land use efficiency and residents' quality of life.

2.2.3. Multi-objective optimization simulation

Through mathematical modeling and intelligent algorithm, the optimal solution of urban spatial function allocation is sought. The model sets three core objective functions: one is to minimize the total deviation Z_1 between the actual STAI and the ideal STAI, so as to improve the use efficiency of buildings in different time periods; The second is to minimize the product sum Z_2 of vacancy rate and renovation cost, so as to control the urban renewal cost on the premise of ensuring space reuse; The third is to maximize the mixed entropy Z_3 of functions, encourage multi-functional integrated layout, and enhance the flexibility and adaptability of space. These goals jointly promote the evolution of architectural space in the direction of high efficiency, economy and pluralism.

Objective function:

$$\begin{cases} minZ_1 \sum_{k=1}^{K} \left|STAI_{\text{actually },k} - STAI_{\text{Ideal },k}\right| \\ minZ_2 \sum_{m=1}^{M} \text{ vacancy rate }_m \times \text{ reconstruction cost }_m \\ minZ_3 \sum_{n=1}^{N} \text{ Functional mixed entropy }_n \end{cases} \tag{2}$$

In order to ensure that the optimization results meet the requirements of realistic planning, the model introduces a number of constraints, including the building floor area ratio should not exceed the statutory upper limit, the proportion of main functions should meet the scope restrictions of urban control regulations, and the functional change rate of historical protected buildings is zero, so as to ensure the continuity of urban context. In the optimization process, NSGA-III multi-objective genetic algorithm is adopted, which can search Pareto frontier solution set under complex constraints and realize the trade-off and cooperation among multi-objectives. The final result is displayed visually through the space-time cube constructed by ArcGIS Pro, and the dynamic simulation is carried out by combining with CityEngine, which helps decision makers to intuitively understand the spatial evolution trend and support scientific planning.

2.3. Technical route implementation process

The implementation process of technical route is shown in Figure 2, which includes three modules: data layer, analysis layer and optimization layer. In the data layer, the integration of POI spatio-temporal data, building GIS and BIM data, and mobile phone signaling or heat map data realizes the fusion of multi-source heterogeneous information; After entering the analysis layer, STAI modeling, spatial mismatch index calculation and functional reorganization sensitive area identification are carried out in turn to gradually reveal the space use characteristics and potential optimization space;

Finally, a multi-objective functional reorganization scheme is generated in the optimization layer, and its feasibility and effectiveness are evaluated through benefit simulation, and finally it is output to the decision support platform, which provides technical support for the whole process of refined urban space update and management.

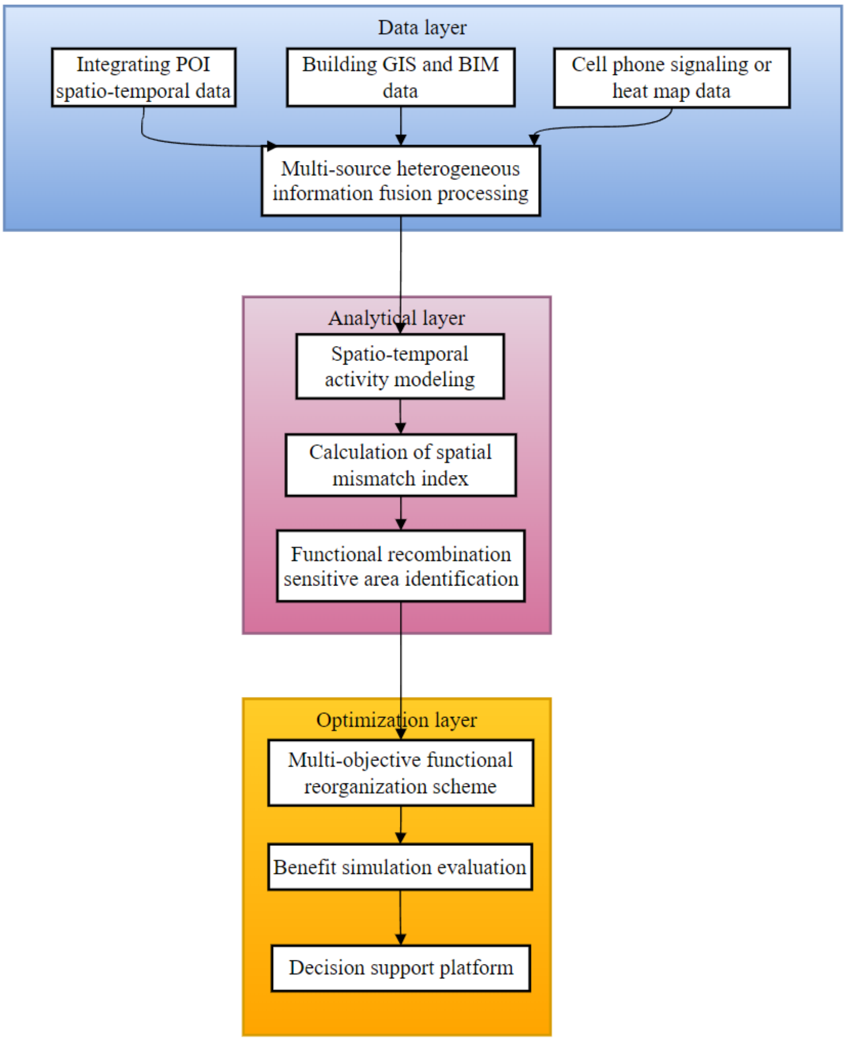

Figure 2. Technical route implementation process.

3. Empirical research design

3.1. Research area and data acquisition

The research focuses on Nanshan District, Shenzhen, covering CBD, Shekou old industrial zone and Xili residential group, and supports spatial analysis and optimization through multi-source data collection. The data list includes 12,568 POI data in the second quarter of 2023 obtained from Gaode Map API; Outline information of 1,842 buildings in 2023 provided by Shenzhen Municipal Bureau of Planning and Self-Administration; Unicom Smart Footprint's daily average of 1.2 million mobile phone signaling data from April 10 to 16, 2023; And the vacancy of rents in 32 business districts in the first quarter of 2023 reported by dtz.

3.2. Analysis process and key results

Through the analysis of the time series changes of typical office buildings in the Science Park area, it is found that their activity fluctuates obviously day and night, reaching a peak of 0.85 at 9: 00 a.m. and dropping to 0.12 at night, reflecting the characteristics that the use intensity of office space changes significantly with time (Figure 3).

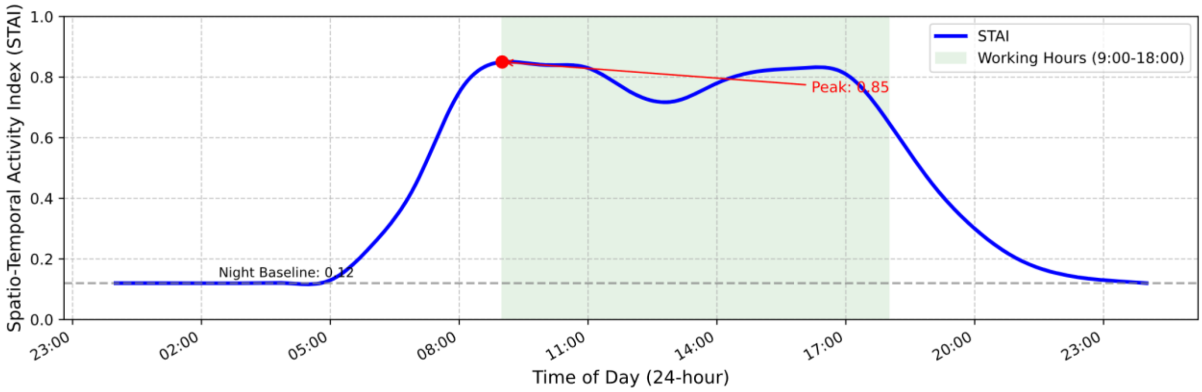

Figure 3. Time series change of STAI in office building A of Science Park (working day).

The diagnosis results of spatial mismatch in Table 1 show that there are significant differences between functional supply and demand in different regions and time periods. The gap of catering service in the office area of science park is obvious at noon on weekdays, with an average FSR of 0.63; Xili community business district has excess leisure facilities at night, with an average FSR as high as 1.82; The old factory buildings in Shekou are facing the problem of disjointed function and demand all day, and the average FSR is only 0.41, which indicates that these areas need targeted function adjustment and optimization to match the actual demand.

The simulation comparison of the optimization schemes in Table 2 shows that the three strategies have different effects in terms of transformation cost, STAI promotion and functional mixed entropy: the economic priority scheme has the lowest transformation cost (320 million yuan), the STAI promotion is 28%, and the functional mixed entropy is increased to 1.87; The cost of the balanced scheme is 450 million yuan, the STAI is increased to 41%, and the functional mixing entropy is 2.35; Although the vitality priority scheme has the highest cost (610 million yuan), the STAI is increased by 53%, and the functional mixed entropy is significantly increased to 3.02, indicating that it has the most remarkable effect in enhancing spatial vitality and diversity.

Table 1. Spatial mismatch diagnosis.

Region type	Period of time	FSR mean	Principal contradiction
Science park office area	12:00-14:00 on weekdays	0.63	Catering service gap
Xili community business	19:00-21:00 on weekdays	1.82	Excess leisure facilities
Shekou old factory building	whole day	0.41	Function is out of touch with demand.

Table 2. Comparison of multi-objective optimization results.

Plan	Reconstruction cost (100 million yuan)	STAI promotion rate	Functional mixed entropy
Status	-	0%	1.02
Scheme a (economic priority)	3.2	+28%	1.87
Scheme b (balanced type)	4.5	+41%	2.35
Scheme c (vitality first)	6.1	+53%	3.02

4. Conclusion

It is found that the traditional static planning model is difficult to adapt to the dynamic demand of modern urban space, while the high spatial-temporal resolution and semantic richness of POI data combined with the spatial analysis algorithm of GIS can effectively capture the dynamic evolution law of building functions. By introducing STAI, the activity degree of different functional types in time dimension is quantified, and the characteristics such as the difference of day and night use of office buildings and the seasonal operation mode of shared space are identified. At the same time, based on the spatial mismatch diagnosis technology of FSR, the problems such as the catering service gap in the office area of the Science Park, the excess leisure facilities in the Xili community business district and the disconnection between the function and demand of the old factory building in Shekou were clarified. Multi-objective optimization simulation further puts forward three strategies: economic priority, balanced and vitality priority, which show differentiated effects in terms of transformation cost, STAI promotion and functional mixed entropy respectively. The empirical study shows that although the vitality priority scheme has the highest cost, it significantly improves the spatial vitality and diversity (STAI increases by 53%, and the functional mixed entropy reaches 3.02), which provides a scientific basis for the efficient, economic and diversified development of urban space. This study not only enriches the theoretical system of urban spatial optimization, but also provides a new paradigm for meticulous planning and management in the construction of smart cities.

This research frame provides a new start for further exploration of "urban". Future studies may employ long-term POI time-series data to dynamically model how spatial functions change across different parts of a city, thereby improving our understanding of the evolutionary path and driving force of urban phenomena such as commercial gentrification and functional decline. With the integration of real-time streaming data such as social media check-ins and shared mobility data, we can improve the temporal resolution of STAI model, contributing to near real-time monitoring and adaptive management of urban space. Another interesting approach is the design of predictive tools able to predict future spatial mismatches provided the FSR in combination with other socio-economic data. Such an approach would allow urban planners to move beyond reactive optimisation towards a more proactive intervention, playing an anticipatory role in shaping the future of the city.

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