Spatial accessibility and functional layout impacts on urban underground space development: a case study of Shanghai

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Abstract. Over the past decade, China’s megacities such as Shanghai and Beijing have witnessed great progress in their metro networks. With the rapid development of metro system, urban underground space (UUS) in China has been widely utilized in a systematic manner, following the principles of transit-oriented development. A comprehensive understanding of the impacts of the built environment on UUS is doubtlessly conducive to the high-quality and sustainable urban development. However, there are fewer researches conducted to study the impacts on UUS compared with those studies focusing on ground level space. Moreover, quantitative researches using multi-source big data on underground space are limited, which makes it hard to reveal the development regulation with high-precision at a large scale. This paper aims to study the impacts of spatial accessibility and functional layout on UUS. Shanghai, as one of the most prosperous megacities in China with well-developed underground space, was selected as the case study. In this paper, open data from Open Street Map and Point of Interest (POI) in AMAP was adopted. Indices such as integration (index of space syntax) of metro line, road length, road density, POI density, and entropy of POI were chosen to reflect the spatial accessibility and functional layout. Underground POI (UPOI) density was set as a proxy of UUS development intensity. A quantitative analysis using multiple linear regression model was conducted. The results showed that both two kinds of indices strongly correlated to the underground space development, whereas the influences of selected indices on UUS were different. At last, the characteristics of UUS in Shanghai and further development strategies were discussed, which provided a perspective of smart growth for planners, designers and authorities.

1. Introduction

With the unprecedented urban sprawl, megacities in China are suffering serious urban problems such as traffic congestion, air contamination, noise pollution and the lack of land resources. In recent years, it is widely accepted by the scholars and governors that UUS development is a feasible measure to alleviate the above-mentioned issues [1-3]. Indeed, numerous international underground utilization cases in cities such as London, Paris and Tokyo have indicated that the underground urbanism is a worldwide trend orienting sustainable and resilient development [4]. UUS utilization in China began with the air defense underground space. Since 1980s, the development form has gradually transformed from single function for air defense to multiple functions. Over the past decade, 43 Chinese cities have
planned or constructed their rail transit systems. Accompanied by the great progress in metro networks, urban underground space (UUS) in China has been widely utilized in a systematic manner, following the principles of transit-oriented development [5,6]. A comprehensive understanding of the impacts of the built environment on UUS is doubtlessly conducive to the high-quality and sustainable urban development. However, there are fewer researches conducted to study the impacts on UUS compared with those studies focusing on ground level space.

Additionally, urban planning and design techniques based on big data have been widely studied. Scholars and designers begin to use multi-source data (point of interest (POI), mobile phone location data, location-based service data, social media data, space syntax, smart transportation card data, etc.) to reveal the complex regulation of urban development and support the decision-making at a fine scale with high accuracy [7-10]. Nevertheless, there are only limited researches using multi-source data to study the UUS development. Conventional researches based on limited data focus more on the qualitative methods for the planning and design of UUS, which cannot reflect the insight of the complex coupling effect between built environment and underground space.

This paper aims to systematically study the impacts of spatial accessibility and functional layout on UUS. Shanghai, as one of the most prosperous megacities in China with well-developed underground space, was selected as the case study. To study the impacts of built environment on UUS, an index system was established to evaluate the spatial accessibility and functional layout. Besides, a quantitative analysis using multiple linear regression model was conducted accompanied with the use of GIS. Based on the reported results, the characteristics of UUS in Shanghai and further development strategies were discussed, which provided a perspective of smart growth for planners, designers and authorities.

The paper was organized as follows. Section 1 presented a brief introduction about the related work. Section 2 introduced the case study area as well as the indices and the regression model adopted in this study. The results of the case study were reported in Section 3. Further discussion and analysis were conducted in Section 4.

2. Data and Methods

2.1. Study Area

Shanghai, as one of the most prosperous cities in China, is selected as the case study area. Being the center of economy, finance, trade, shipping and innovation, the city has experienced the unprecedented development in recent decades. Nowadays, it has become a world-famous megacity with more than 24 million residents. As of 2019, underground space in Shanghai is estimated to exceed 100 million, which is the most large-scale in China. Besides, Shanghai has the longest metro system in the world with more than 700 km operation line. The rapid growth of metro systems also boosts the comprehensive and integrated utilization of UUS. At present, various underground facilities have been successfully developed in Shanghai such as metro system, underground road, underground public space, utility tunnel, civil defense underground space, etc. The UUS development mode of Shanghai is fairly typical among those densely populated megacities in China. Hence, investigation on the influence of built environment on UUS is conducive to the sustainable and smart urban development of China’s cities.

In this case study, with a total area of more than 6340.5 square kilometers covering 16 districts (Figure 1). Since UUS surrounding metro station is of obvious social and economic benefits, the metro-led underground space is set as the unit of UUS. Generally, metro-led underground space refers to the necessary space for metro operating, parking, crowd evacuation, management and public security. Besides, inside building space of the station as well as the surrounding underground space connected to it should be included. To simplify the data acquisition and processing, UUS within 400-meter buffer zone of metro station is adopted as the metro-led underground space. The case study covers the majority of metro lines (from Line 1 to Line 17), with 334 metro stations to be investigated.
2.2. Data and Selected Metrics

2.2.1. Measurement of UUS development In China, data about UUS development is mainly kept by the department of civil defence, and it is not available to the public. Recently, several cities such as Shanghai and Shenzhen have published the statistical data of public underground space (civil defence data excluded), whereas the data is highly incomplete.

The emergence of big data, which is of high volume and high accuracy, provides a new tool to measure the UUS development. In this research, point of interest (POI) is selected as one of the data sources. POI data was collected from AMAP, one of the most famous map suppliers in China. There are 552,442 POIs in total in Shanghai, covering 12 kinds of facilities (catering, scenic site, transportation, public facility, education, finance and insurance, hotel, residential, medical care, automobile service, sports and recreation, life service). At present, the location information of POI contains longitude and latitude only. Therefore, the data was processed in Python to extract the underground POIs (UPOI) by key strings search. Finally, a total of 14,265 UPOIs were obtained, accounting for 2.58% of the POIs.

In densely populated cities, the aggregation of urban space will play a more significant role in developing a sustainable and resilient city, and the high-density and intensive UUS development has been confirmed to be conducive to this process [11]. Concerning urban intensity, various indicators including UUS volume, UUS use density, UUS volume per person, and floor area ratio, have been adopted to measure the development intensity of urban space and subspace [12,13]. Nevertheless, all-round data of UUS use with high precision is not available due to the confidentiality as well as tremendous time and labour cost, and it is hard to conduct the site investigation and data acquisition on urban scale.

Thereby, UPOI and POI- a kind of emerging big data with good timeliness and wide coverage- were selected as the indicators for urban intensity. With respect to UPOI, they nearly cover entire public underground space (civil defence UUS excluded), the density of UPOIs within a unit is hence set as the proxy of UUS development intensity. Indeed, UPOI density is positively correlated to the frequently used indicator such as UUS volume or area since the building footprint of UPOI can be treated uniform when considering a large quantity of points. Although there exist some errors caused by the simplification, the tolerance could be accepted to study the development regularity of UUS use. Figure 2 indicates the composition of UPOIs in Shanghai, of which catering type occupies nearly the half. In terms of the Transportation, it is at around one third of the total POIs, and the majority of

Figure 1. Study area of the research.
them are underground parking lots. As for Life Service and Leisure, the total of them take about 10% of UPOIs. It can be deduced that the functional mixed value of underground space stands at a low level.

![Composition of UPOI](image)

**Figure 2.** Composition of UPOI in Shanghai.

2.2.2. *Spatial Accessibility Metrics* Three indices were selected to evaluate the spatial accessibility within the unit region, namely road length density, number of roads and integration of metro station. Road length density means the total road length divided by the unit area. Number of roads refers to the roads within the unit region. Previous studies on ground space level indicate that these two indices are highly correlated to the spatial accessibility with a positive influence. With respect to the integration of metro station, it is an index in space syntax to measure the arrival-departure attraction of segment in the spatial network.

![Integration of Shanghai metro network (R=n)](image)

**Figure 3.** Integration of Shanghai metro network (R=n).

In this study, the integration was calculated in Depthmap using radius n in axial map, which reflects the accessibility of metro network (figure 3). Since the integration is the attribute of line, the mean value of surrounding lines’ integration was adopted as the ultimate integration of metro station, as shown as in equation (2). Where $INM$ denotes the integration of a metro station; $i$ denotes the serial
number of the metro line within 100-meter buffer zone; \( Int_i \) denotes the integration of \( i^{th} \) line. To conclude, these metrics measure the spatial accessibility of both underground and ground level.

\[
INM = \sum_{i=1}^{n} Int_i / n
\]  

(1)

2.2.3. Functional Layout Metrics
Both land use and spatial functions (services) have been verified to be strongly related to the UUS development [11,13]. With regards to functional layout, POI density and entropy of POI were selected as the metrics. The definition of POI density is the same as the UPOI density, which includes all of the POIs (both underground and above ground) in the region. POI density is a useful metric to reflect the development intensity the region. Generally, the higher the POI density, the better the locational condition is.

POI entropy is a kind of indices to measure the mixed degree according to Shannon’s theory. As mentioned above, POI collected from AMAP are divided into 12 categories. The entropy of POI was calculated based on category as shown in equation (2). Where \( EP \) denotes the entropy of POI; \( p_i \) denotes the proportion of the \( i^{th} \) POI.

\[
EP = - \sum_{i=1}^{n} p_i \cdot \ln p_i
\]  

(2)

Since metro-led underground space is of high benefits among all kinds of UUS, its functional layout was crucial. Based on the theory of transit-oriented development, urban space around public transportation should follow the principles of ‘3D’, namely diversity, density and design. POI density and entropy of POI are two indices to measure the functional density and diversity. With respect to design, it is excluded in this part because the study focuses more on the UUS planning rather than design.

2.3. Methodology
As is illustrated in figure 4, there are three major steps to conduct the entire analysis, namely data acquisition, data processing and regression analysis. Firstly, necessary multi-source data needs to be collected from online open platform. Road network and metro station information were downloaded from Open Street Map. POI data was acquired by API provided by AMAP.

![Figure 4. Technical framework of the research.](image)

Secondly, the data needs to be further processed to meet the requirements of the final analysis. Axial map of metro network was drawn in Autocad using the point information of metro station. In.
this part, the metro network of Open Street Map was discarded since the polyline among stations should be transformed to straight line segments according to the basic theory of Space Syntax. Then, the integration (R=n) was calculated using Depthmap. Besides, UPOIs were extracted from POIs using key string matching in Python.

Finally, the regression analysis was conducted. Using QGIS for the geo-processing, all of the data were manufactured to acquire the variables for regression. After the indices were calculated within the buffer zone of metro stations, the regression analysis was implemented in SPSS. Here, multiple linear regression model was adopted. The form of regression function is shown in equation (3), where UPD, RC, RL, ITM, PD, EP represent UPOI density, road count, road length, integration of metro station, POI density and entropy of POI respectively.

\[ \text{UPD} = \beta_0 + \beta_1 \cdot RC + \beta_2 \cdot RL + \beta_3 \cdot ITM + \beta_4 \cdot PD + \beta_5 \cdot EP + \varepsilon \] (3)

Stepwise method was adopted during the regression to extract those insignificant variables. After the regression was completed, collinearity among variables was tested.

3. Results

3.1. Distribution of UUS development

Explicit spatial distribution of UUS development in Shanghai was processed in QGIS using UPOIs from AMAP. Figure 5 illustrates the entire UUS development distribution as well as the metro-led UUS development distribution respectively. An aggregated pattern of the spatial distribution of UUS development could be observed in both figures. Additionally, monocentric pattern of UUS is more significant than polycentric pattern at present. In terms of the metro-led underground space, its spatial layout is highly consistent to that of the entire UUS. In other words, those high intensity UUS development in Shanghai is likely to be integrated with the development of metro-led space.

Figure 5. (a) Entire distribution of UUS development; (b) Distribution of metro-led UUS development.

3.2. Results of Regression analysis

Descriptive characteristics of five selected indicators and the proxy of UUS development are listed in Table 1, with a total of 334 samples. The results show that road count, POI density and UPOI density are three variables of high discreteness. Road length has a less significant discrete tendency. While entropy of POI and integration of metro station show a central tendency. It can be observed that both spatial accessibility and functional layout indicators are of obvious otherness, and a large heterogeneity exists in the built environment and UUS development.
Table 1. Summary of statistical characteristics of variables

| Indicator | Explanation                          | Minimum | Maximum | Mean   | Standard Deviation | Unit |
|-----------|-------------------------------------|---------|---------|--------|--------------------|------|
| RL        | Road length                         | 0.323   | 31.871  | 8.094  | 4.496              | [km] |
| RC        | Road count                          | 1.000   | 317.000 | 38.800  | 39.208             | -    |
| PD        | POI density                         | 0.000   | 2153.000| 376.130 | 406.622            | -    |
| EP        | Entropy of POI                      | 0.000   | 7.421   | 4.965  | 1.443              | -    |
| ITM       | Integration of metro station        | 0.224   | 0.742   | 0.477  | 0.141              | -    |
| UPD       | UPOI density                        | 0.000   | 392.000 | 21.810 | 50.974             | -    |

Multiple linear regression was conducted using stepwise method, in which the criteria was set as F value <= 0.050 to enter and F value >=0.100 to remove. RC was thus excluded. The coefficients of the regression model with highest $R^2$ are listed in Table 2. Because obtained VIF values of four variables are between 1 to 10, it can be judged that there are no multicollinearity symptoms. Except for road count, the other four variables are all significant at 0.05 level. The adjusted $R^2$ of the model is 0.648, which indicates that the model is of high interpretation. In terms of the standardized coefficients, POI density has the strongest positive impact on UPD. Road length is also positively correlated to UPD, with slighter influence compared with PD. Both ITM and PD have negative influence on UPD, which is contrary to the expectation. In addition, the negative influence of EP is significantly higher than that of ITM.

Table 2. Coefficients and collinearity statistics of multiple linear regression

| Indicator | Explanation                                | Coefficients       | Standardized Coefficients | t       | VIF |
|-----------|-------------------------------------------|---------------------|---------------------------|---------|-----|
| Intercept | -                                         | 42.240* (8.752)     | -                         | 4.826   | -   |
| PD        | POI density                               | 0.135* (0.007)      | 1.073*                    | 18.853  | 3.065 |
| EP        | Entropy of POI                            | -9.568* (2.029)     | -0.271*                   | -4.716  | 3.120 |
| ITM       | Integration of metro station              | -64.643* (18.157)   | -0.179*                   | -3.560  | 2.396 |
| RL        | Road length                               | 0.001* (0.000)      | 0.079*                    | 2.140   | 1.295 |

Standard errors are shown in parentheses and values with * are significant at 0.05 level.

4. Discussion

4.1. Impacts of Built Environment on UUS Development

The results of regression model show that the POI density is the most important indicator of built environment. We could deduce that regional development intensity should be the key factor to be considered when developing UUS. The more aggregated the region is, the more benefits there are to utilize UUS. Nevertheless, functional mixed value (EP) shows a negative impact on UUS development, which is not consistent to the regulation of ground space. The relationship between subspace and
ground space may be the reason for the abnormal phenomenon. At present, UUS is treated as a kind of auxiliary space. When urban space is multi-functional, the demand for underground space is limited.

As for the spatial accessibility conditions, the rail transit network shows a much more significant impact compared with ground road network. The explanation may be that the majority of citizens go to UUS through metro networks rather than road network. However, multiple linear regression analysis indicate that the integration is negatively correlated to the UUS development, and the result of single linear regression show that the integration has a positive impact. Ruling out the possibility of collinearity, suppressor effect perhaps exists in the model. For metro-led UUS, there are more than one influential path among different variables, and the secondary impact is against the direct impact. Abnormal results could be observed that when POI density and integration index of some metro-led UUS reach are both at a high level, the development of UUS may decrease to some extent. For one thing, some regions with dense POIs are old town area, in which the UUS was not scientifically and massively developed at previous stage. For another, the transit-oriented development was not implemented well, and some regions where UUS is densely utilized are away from the metro stations.

4.2. Implications on Planning and Design Strategies
Although UUS development in Shanghai is a paradigm for China’s megacities, there exist some drawbacks and limitations in terms of the regression analysis results. Therefore, several feasible strategies for UUS planning and design in China’s megacities are listed as follows:

Principles of TOD should be implemented throughout the development of metro-led underground space. In line with the ground space, diversity and density are prerequisites of good-quality UUS. Besides, the design of metro-led underground space should be attached equal importance of ground space, especially those UUS in shallow layers [6].

Unlike the master planning of UUS which considers the synergy of subspace and surrounding urban space [14], the development of metro-led UUS in China is on a project-by-project basis. Indeed, UUS planning needs to be coordinated with the metro network planning, thus maximizing the benefits of large passenger flow of metro system [15,16]. Since UUS development is irreversible, the spatial accessibility of long-term network should be considered when compiling UUS planning. In addition, tools such as space syntax could be adopted to measure the accessibility of metro.

Public transports at ground level should be connected with the underground space through underground pedestrian links and sunken plaza. Hence, the benefits of the spatial accessibility on ground level could be utilized through the coordination of subspace and ground space.

In old town area, UUS development should be conducted during urban renewal to promote the urban vitality and liveability, thus maximizing the potential of UUS as multifunctional resources [13]. Hence, the lack of UUS development density in old town could be alleviated to some extent, and the regional vitality would increase as well.

The relationship between the functional layout of subspace and ground space is neither complementary nor mutually exclusive. There is a symbiotic relationship of the functions in different layers, and the integrated functional layout should be considered through subspace planning, thus enhancing the spatial diversity and balancing the regional land use [14].

Planning technology for underground space needs to be integrated with multi-source big data to achieve the goal of smart growth. Transportation card data and location-based service data should be further studied to find out the precise development regulation of UUS.

5. Conclusions
This paper focused on the impacts of built environment on UUS development. Choosing Shanghai as the case study, a multiple regression model was established using multi-source data related to spatial accessibility and functional layout. The results showed that the both two kinds of indices had significant influence on UUS utilization. Among all of the indices, POI density and total road length are positively related to the UUS development, whereas the POI entropy and integration of metro line show a negative correlation.
The analysis conducted in this work indicates the difference between the impacts of built environment on underground space and that on ground level space, which means that some inappropriate development pattern still exists in the field of UUS in Shanghai. To utilize the underground space from a smart growth perspective, transit-oriented development needs to be integrated to the master and detailed planning to optimize the of underground space. Meanwhile, the coordination of the subspace and ground space should be paid more attention during the design of underground space.

Nonetheless, there are still some limitations in this work. Firstly, UPOI density as a proxy of underground space intensity is unable to reflect the real development status, more precise data of UUS development needs to be collected and adopted in further study. Secondly, more detailed indices such as the coordination between subspace and ground space, topology and spatial pattern of underground space are not included, which would reveal the development regulation at a fine scale. Thirdly, this study focuses on the physical connectivity metro network only when considering accessibility. However, the inner connectivity of underground complex, which is also a crucial part of underground connectivity, was not cooperated into this work due to the limited research scale [17]. Lastly, the analysis model should be integrated with other evaluation models to better support the decision-making of underground space utilization.

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