Evaluation of Spatial Performance of Urban Underground Public Space: A Case Study of Wujiaochang Sub-center in Shanghai

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Abstract. Urban underground public space (UUPS) creates extra open space for local citizens, increases neighborhood vibrancy and improves the walkability of local blocks. Recently, huge amounts of UUPS have been built in Shanghai with the rapid development of metro systems. Among them, construction of UUPS in Wujiaochang Sub-center has achieved a great success in spatial performance with a systematic planning and implementation for more than 15 years. This paper proposes a comprehensive evaluation method for UUPS with 7 quantitative indices to assess the spatial performance in the aspects of social development, spatial structure development and traffic development. Evaluation results indicate that the UUPS in Wujiaochang Sub-center provides efficient public space for diverse activities to improve local vitality, improves urban compactness and dramatically increases the local pedestrian network efficiency and metro service scope. The study hopes to provide insights of a better UUPS planning and constructive suggestions for the future.

Keywords. Urban underground public space, Spatial performance, Evaluation system

1. Introduction

Urban underground public space (UUPS) is accessible to the public for transportation, shopping, communication and resting, which can be divided into two parts in terms of space ownership. The first part is the activity space invested by public sectors such as sunken plazas, non-payment areas of metro stations, underground streets and other public service facilities below public land. The second part is owned by the private but open to citizens free of charge during service hours, such as the building
basements for commercial service, which can also be defined as the privately owned public space (POPS) [1].

Similar to the ground public space (e.g. parks and squares), UUPS is critical to social development and urban sustainability [2, 3]. Utilization of urban underground space (UUS) is vital to alleviate traffic congestions and land insufficiency [4]. The construction of UUPS supplements urban activity space for the public, especially in old downtown areas, and is a good way to improve urban vitality during the urban renewal. Additionally, inter-connected UUPS around metro stations, acting as pedestrian systems for walking and transportation, also contributes the local city compactness [5].

With the rapid development of UUS in Shanghai, a great amount of UUPS has been built and put into operation around metro stations in the central urban area such as UUPS around Lujiazui Station, Hongqiao Railway Station (Hongqiao CBD) and Wujiaochang Station & Jiangwan Stadium Station [6]. Among them, the UUPS of Wujiaochang Sub-center has been a successful example after a systematic planning and continuous planning implementation for more than 15 years. Due to different planning and construction periods, UUPS layout and space functions vary greatly, bringing different effects on neighborhood development. Spatial performance indicates the comprehensive effects of entire urban space layout on urban transportation, economy, social and environmental development. From the perspective of spatial performance of UUPS, traditional questionnaire surveys are limited to the sample size and subjectivity of interviewees, making the results hard to be compared between different cases. Previous studies usually focused on one aspect of the UUS spatial performance and a comprehensive evaluation system still lacks [7-9]. Therefore, there is a need to build a systematic evaluation method with quantitative indices to assess UUPS spatial performance and provide experience and guidance for future planning.

This paper takes the UUPS of Wujiaochang Sub-center as a case study to explore its spatial performance and research on its planning experience. Firstly, it establishes a spatial performance evaluation system for UUPS from the perspective of society, spatial structure and traffic improvement. Then quantitative indices are used to assess and analyze the comprehensive effects of Wujiaochang UUPS. Based on these findings, this paper finally summarizes the experience of the case study so as to guide the UUPS planning in the future.

2. Methodology

2.1. Study area

Wujiaochang Sub-center is located in the northeast of the city center, which is one of the most energetic and vibrant sub-centers in Shanghai. After the operation of Wujiaochang Station and Jiangwan Stadium Station in 2010, shopping malls and office buildings nearby are totally connected by sunken plazas and underground streets to form a large UUPS complex with diverse functions. The average daily passenger flow of the two metro stations is over 78,000 according to the data in April, 2015.

Development of UUPS and its overall layout is highly related to metro stations. To simplify the data acquisition and make it comparable with other similar cases, 800-meter buffer zones of the two metro stations with total area of 3.02 km² are adopted as the main study area. Figure 1 indicates the land use and the detailed layout of UUPS in the study area. The total area of UUPS is over 175,000 m², including sunken plazas, underground linking corridors, underground shopping space and non-payment areas of
metro stations. UUPS is inter-connected with each other on B1 floor and only the UUPS in Hopson One Complex is located both on B1 and B2 floors.

![Image](image_url)

(a) Land use of Wujiaochang Sub-center  
(b) UUPS layout in Wujiaochang Sub-center

Figure 1. Land use of the study area and UUPS layout.

2.2. Establishment of evaluation system

A comprehensive but simple evaluation system is the key to the spatial performance analysis. Evaluation indices should be quantitative rather than qualitative so that the results can be compared to other cases. According to the aforementioned introduction, individual users and the neighborhood as an entity can both be viewed as the direct beneficiaries of the construction of UUPS. The evaluation aspects or factors that are most focused by these two objects are discussed to summarize the possible indices. With regards to individual users, well-planned UUPS means a high accessibility, amenity-filled inner space and diverse activity space. What’s more, they are also concerned whether it is convenient to reach the metro stations. In terms of the entire neighborhood, how the UUPS creates diverse urban space, improves traffic convenience and urban compactness and how it promotes TOD (Transit-oriented development) modes should be considered. Thus, the basic evaluation system of UUPS spatial performance can be classified into 3 aspects with 7 indices as indicated in Figure 2.
2.3. Calculation of evaluation indices

2.3.1 Social development (1) UUPS supply intensity measures the development scale of UUPS in the study area. Adequate material space for the public is the guarantee of diverse and vibrant activity space. As POPS do not provide 24-hour public service, a reduction factor should be considered during the calculation. The index can be computed as equation (1).

\[ \text{SI} = (S_1 + \alpha S_2)/S_I \]  

where \( S_1 \) is the area of 24-hour UUPS and non-payment zones in metro stations [m²]; \( S_2 \) is POPS area [m²]; \( \alpha \) is the reduction factor, which is 0.8; \( S_I \) is the total area of the study area [km²].

(2) Shannon Entropy is used to compute the diversity of UUPS functions as shown in equation (2). Pedestrian walking is the basic but not the only function of UUPS. Recently, development of UUPS also emphasizes on its public activity character with more sunken plazas, underground atriums and squares for multiple uses, including transfer, public gathering, resting and exhibitions. A higher function entropy indicates a higher probability to encourage users to stay and enhance the community vibrancy.

\[ \text{FE} = -\sum_i \frac{S_i}{S_{UUPS}} \cdot \ln \frac{S_i}{S_{UUPS}} \]  

where \( S_i \) is the area of the \( i \)th function of UUPS [m²]; \( S_{UUPS} \) is the total area of UUPS [m²].

(3) UUPS quality is a comprehensive index to reflect the satisfaction of UUPS environment, facilities and service. Higher space quality appeals people to use, stay and enjoy the space, thus enabling vibrancy to thrive. To simplify the data gathering process, this paper directly adopts the commenting values from dianping.com, which is one of the biggest and most popular online review websites for shopping malls, restaurants, scenic spots and public space in China. The quality index of UUPS is calculated by the average score of every single UUPS unit weighted by its space area.

2.3.2 Spatial structure development (1) UUPS accessibility indicates the topological spatial relationship between the underground network and entire urban space in the research area. The sDNA software is used to analyze the accessibility of 3D urban space network [10, 11]. Multi-floor walkways and their
vertical links (e.g. escalators and stairs) are simplified as nodes and links. The mean depth of each single link in the whole network is computed and indicated by Mean Euclidean Distance (MED) within a specific analysis radius, where a smaller MED represents a higher accessibility for the material space [10].

(2) Urban compactness represents the block connecting effect of UUPS in the study area. Urban blocks divided by ground traffic routes can be stapled by interconnected underground corridors and sunken plazas of UUPS, thus constructing the protected and shorter links between each blocks to enhance the sense of city compactness for local citizens. The index can be calculated as equation (3). The higher the ratio is, the higher compactness the neighborhood is.

\[
UC = \frac{S_b}{S_b'}
\]

where \( S_b' \) is the total area of the blocks connected by UUPS \([\text{m}^2]\); \( S_b \) is the total area of all blocks in the study area \([\text{m}^2]\).

2.3.3 Traffic development (1) Pedestrian route directness (PRD) is the ratio of real pathway distance and the straight line distance. It can be used to explain the walking route efficiency. The closer PRD is to 1, the more efficient the pedestrian network is. By means of the PRD measurement method provided by Paul (1997) [12], points that are 400 m and 800 m from the center of the study area are selected and then employed to measure the most direct pedestrian route between the points and the center to compare with the straight line distance. How and how much the index changes with and without the UUPS and be used to explain the traffic development performance.

(2) Metro station service area represents the 10-minute walking area from the metro station, which can be calculated by the network analysis module of ArcGIS. It is assumed that the pedestrian walking speed is 1.0 m/s, speed at vertical stairs is 0.5 m/s, and average waiting time at traffic light intersections is 20 s based on the observation data. The change of the service area before and after the construction of UUPS demonstrates the performance of promoting the metro-based TOD modes.

3. Results & Discussion

3.1. Social development performance

| Table 1. Social development performance of UUPS. |
|-----------------------------------------------|
| UUPS supply intensity (m²/km²) | UUPS function entropy | UUPS quality* |
|--------------------------------|----------------------|-------------|
| 48,994                         | 1.020                | 8.89        |

* Scale of 1-10, where high values represent a high satisfaction of individual users.

According to Table 1, UUPS supply intensity is 48,994 m²/km² with a total development amount of approximately 175,900 m². Main functions of UUPS can be classified into commerce, pedestrian walking, metro transfer and integrated activity zones with an average entropy of 1.020. Figure 3 indicates the function entropy of every single unit in the UUPS system. The entire entropy is higher than single UUPS unit, demonstrating that an integrated and inter-connected underground complex plays a more vital role in promoting the urban vitality than single and unsystematic UUPS. Except for shopping service space, the integrated activity zones, namely Wujiachang Sunken Plaza, KIC Sunken Plaza and the atrium of Hopson One Complex on B1 Floor, take 12.4% of the entire space and are the most
energetic nodes in Wujiaochang UUPS according to the field investigation. Landscape sketches, benches and multi-media displays comfortable resting and communicating space. Public gatherings and free culture exhibitions are also held there to bring the space vibrancy. On the other hand, POPS in the study area accounts for 82.2% of the entire UUPS, which is all connected together by underground passages. The publicity and openness rise after the private building basements are integrated into the UUPS system, which brings a large number of potential space users to achieve a win-win situation all around and raises the POPS efficiency. Furthermore, integrating POPS into UUPS system decreases the strained municipal resources and enhances the UUS development efficiency in contrast to the situation that only UUPS below public land is built by the government.

Based on the scores commented by more than 22,000 people in dianping.com, Wujiaochang UUPS obtains a high space satisfaction with 8.89. Figure 3 displays the quality index of every single part of the UUPS. Variation coefficient of the quality scores is only 0.037, indicating a good consistency of the space quality. Furthermore, the commenting scores of Wujiachoang Sunken Plaza, Hopson One Complex, Pacific Fresh City and KIC Sunken Plaza are over 9.0, as shown in Figure 4. Open space and a high floor height avoid the sense of depression in UUS. Aesthetically pleasing designs and warm lighting create unforgettable space images, thus eliminating negative impressions of UUS.

![Figure 3](image1.png)

*No commenting scores in dianping.com.

**All 11 single UUPS units are viewed as an entire UUPS complex to be evaluated by the methods in Section 2.3.1.

**Figure 3.** Function entropy and quality scores for every single unit of Wujiaochang UUPS.
3.2. Spatial structure development performance

Table 2. Spatial structure development performance of UUPS.

|                  | Entire UUPS | Jiangwan Stadium Station | Wujiachang Station | Urban compactness |
|------------------|------------|--------------------------|---------------------|------------------|
| Accessibility    | High       | High                     | Low                 | 32.4%            |
| (MED'= 719.8)    | (MED'=638.5)| (MED'= 814.3)            |                     |                  |

* Scale of 603.3 - 1859.9, where low MED represents high space accessibility.

The accessibility and urban compactness indices are shown in Table 2. As indicated in Figure 5, UUPS is located in the core area of the study zone with a high accessibility for local citizens. Densely-distributed vertical links between the ground network and the underground system also contribute its high accessibility. Besides, there exist two local activity cores in UUPS, namely Jiangwan Stadium Station Core and Wujiachang Sunken Plaza Core. However, Wujiachang Station is located on the periphery of the whole system with a much lower accessibility than the other station and the whole underground system based on the data in Table 2. Generally, metro stations should be built as the local core node. According to the land use data in Figure 1, urban land on the south of the station is not fully developed with a quite low road network density and no underground public space. From the current situation, the site location of Wujiachang Station is poor as people should take more time to reach the station from any other space of the system. On the other hand, the analysis result points out that it is necessary to change the urban land use around Wujiachang Station to redevelop the local area in the future as it exists high development potential.
Figure 6 reveals the layout of the urban blocks directly connected by UUPS. The urban compactness index is 32.4%, which is a high one. UUPS is located on both sides of the metro Line 10. The total building area, connected by UUPS, is up to 1.16 million m² with an average FAR of 3.39, which is more than 2 times of that of the entire sub-center. It demonstrates that the land development is closely related to the metro line under the guide of the compact city theory. Moreover, the UUPS, connecting Wujiaochang Station and Jiangwan Stadium Station, forms a 1km-length south-north underground activity axis and establishes an integrated station group development mode. It plays the role of strengthening and integrating the functional network of each unit of the station group [13].

3.3. Traffic development performance
Table 3 demonstrates the evaluation result of traffic development performance. The change of PRD reaches 24.1% and the metro station service area increases by 25.1%, which represent excellent UUPS performance.

| Pedestrian route directness (PRD) | Metro station service area (hm²) |
|----------------------------------|---------------------------------|
| Without UUPS                     | 1.66                            |
| With UUPS                        | 1.26                            |
| Change                           | -24.1%                          |
|                                  | 81.9                            |
|                                  | 102.5                           |

* Scale of 1 to infinity, where low PRD represents good walking efficiency.

As shown in Figure 6, the study area is not quite walkable as the area is divided into 5 parts by a 100m-diameter roundabout and five 30 to 50 m-width arterial roads (that is Songhu Road, Handan Road, Siping Road, Huangxing Road and Xiangyin Road). There exist only 10 ground pedestrian crossing intersections on 5 arteries with an average distance of 480 m. After the completion of UUPS, the average distance reduces to about 220 m. It highly strengthens the walking connection on north and south sides of Handan Road and Xiangyin Road. Furthermore, UUPS creates a new 5.1km-length pedestrian route underground, which only raises the local walkway density by 10.8% but dramatically improves the
neighborhood walking efficiency by 24.1%. Therefore, building a systematic UUPS system is an effective way to construct a more walkable neighborhood and sew up the isolated urban blocks.

Figure 7 demonstrates the expansion of metro service areas after the completion of UUPS. The service scope of Wujiaochang Station raises by 69.2%, which is higher than that of Jiangwan Stadium Station. UUPS provides more effective, multiple and safer routes to cross the complicated intersection of 5 arteries, considerably minimizing the problem of a poor site location for Wujiaochang Station. On the other hand, the intersected service area of two metro stations are dramatically raised by 413.9%, indicating that the UUPS-linked station group development mode is a better way to serve the urban core area to provide better metro service. Additionally, appealing walking pathways and a good connection to adjacent building basements also encourage people to employ the metro-based TOD travel mode.

4. Conclusion
The paper proposes a simple and practical evaluation system with 3 aspects and 7 quantitative indices to analyze the spatial performance of UUPS in Wujiaochang Sub-center. The analysis results show that the development of UUPS has achieved a great success in increasing high quality public space with diverse space functions. The entire system is of high accessibility for local citizens, improves the city compactness and also promotes the neighborhood walkability and metro-based TOD mode. However, from the current situation, the location of the Wujiaochang Station is not optimal. It is necessary to adjust the land use of adjacent urban blocks of the station. On the other hand, the case study of Wujiaochang Sub-center also results in the following suggestions for the UUPS development.

- POPS is an essential part of the UUPS system, which provides relief to the strained municipal resources and should be encouraged and totally integrated during planning.
- UUPS is the public space underground other than pedestrian passages underground. Amenity-filled inner space design, high-accessibility overall layout and a mix of space functions should be emphasized to make people stay, use and enjoy the space.
- UUPS can be applied to improve the urban walkability and inter-connect urban blocks separated by wide traffic arteries. It also integrates the metro stations and overcomes the problem of the poor location of the metro station.
- UUPS connects the urban blocks and ground buildings, which improves the city compactness. It provides convenient and comfortable underground pedestrian routes to metro stations and local commercial or office buildings so that people may be encouraged to travel by metros rather than private cars to reduce severe congestion problems and make city center more sustainable.
- Metro station group development mode refers to the UUS development method that two or more metro stations are inter-connected by UUPS to build a large underground complex. It helps to expand the service area of every single metro station and improves the walkability of the locality, which is suitable to be applied during the UUS development in city centers or sub-centers.

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