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Unravelling the Formation Mechanism of Sustainable Underground Pedestrian Systems: Two Case Studies in Shanghai

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Abstract: The development of subterranean non-motorized traffic infrastructure, commonly referred to as the underground pedestrian system (UPS), has become increasingly necessary in densely populated megacities worldwide as a means of advancing the sustainable development goal 11, which aims to promote sustainable cities and communities. To improve the overall spatial performance, it is imperative to decipher the fundamental formation mechanism of sustainable underground pedestrian systems (SUPSs) that is simultaneously influenced by spatial morphology and pedestrian behaviors. Thereby, two representative case studies, namely the Wujiaochang UPS and the Loushanguanlu UPS located in Shanghai, were selected for an in-depth investigation. This study employed correlation and regression analysis to examine the impact of spatial configuration variables and spatial attribute factors on pedestrian flow distributions in distinct SUPSs. The findings indicate that the variables of betweenness, as measured by both Euclidean and Angular metrics, along with the presence of metro station locations and commercial space connected by the UPS, are the three most significant factors influencing pedestrian behaviors in both scenarios. The disclosure has been made that the Wujiaochang UPS is seamlessly integrated into a comprehensive three-dimensional pedestrian network both above and below ground. By contrast, it appears that the Loushanguanlu UPS exhibits a greater degree of self-sufficiency as an underground system. This study aims to elucidate the mechanism underlying the development of SUPSs, thus offering effective guidance for the implementation of three-dimensional walking systems in cities that prioritize sustainability.

Keywords: underground pedestrian system; sustainable development; spatial morphology; pedestrian behavior; formation mechanism

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1. Introduction

An underground pedestrian system (UPS), which connects urban transportation infrastructures, retail complexes, department stores, and office buildings via underground corridors or commercial streets, is a comprehensive and integrated way for urban underground space (UUS) utilization [1–5]. UPS development aligns well with the United Nations sustainable development goals (SDGs), particularly sustainable cities and community (SDG 11), which seeks to make cities and human settlements inclusive, safe, resilient, and sustainable. UPS contributes to the construction of a more compact, walkable, and sustainable megacity [6–11], improves urban resilience during catastrophic events [12,13], acts as a critical catalyst during urban regeneration [14–17], and reduces accidents caused by pedestrian–vehicle collision [18,19]. By creating a climate-controlled environment for all-weather urban activities, the UPS provides additional public space for walking and resting in densely and intensively developed urban centers, which is widely applied in metropolitans, such as Montreal [20], Singapore [21], Osaka [22], Hong Kong [23], and Shanghai [24,25]. In high-density cities, such as Hong Kong [23] and Seoul [26], UPS involving both public underpasses and its connected private building basements grows larger and more complicated as UUS utilization increases. It interacts simultaneously with underground rail transit systems and simultaneously interacts with the street network aboveground to create a multidimensional urban public transportation system and a city that is compact and walkable.

In addition to the previously mentioned external contribution of UPS development to urban sustainability, this study will probe into the internal sustainability of the UPS, i.e., the formation mechanism of a sustainable UPS (SUPS). As a crucial component of a three-dimensional pedestrian network in a compact urban environment, the foremost indicator of a SUPS should be its spatial performance as measured by pedestrian mobility [27,28]. Regarding the formation mechanism, urban planners and architects tend to determine the underlying relationship between spatial performance and spatial morphology of the UPS, which is the basis of the sustainable design of the UPS.

UPSs typically have an uneven distribution of pedestrian flow. Some underground pathways are overcrowded and popular for pedestrians, whereas others have fewer users [10]. Furthermore, some UPSs are well designed, whereas others have poor operations and few pedestrians. The spatial morphology is a crucial consideration for urban sustainability [29,30]. As elaborated by Schwander et al. (2012) [31], space is not homogenous. Socioeconomic activities and UUS development are likely to correlate to spatial morphology [32–36]. Previous research has demonstrated that a network configuration and attractor distributions can influence simultaneously pedestrian movement patterns on the street [37–39]. To explain observed pedestrian flow rates, space syntax theory, and the morphological measures, such as integration, and choice by a restricted radius are typically applied. It was discovered that pedestrians prefer to choose simple routes with the Euclidean shortest paths and angular shortest paths [38,40,41]. In addition, researchers confirmed that walking behaviors are jointly influenced by spatial attributes and conventional space configuration properties measured by space syntax. Chang and Penn (1988) employed movement attractors and generators to modify the conventional spatial configuration model [42]. Bhlla and Pant (1985) and Kang (2017, 2018) verified the positive relationship between pedestrian behaviors and urban land use characteristics, bus stop or metro station locations, and destination density for both the skywalk system and ordinary ground street network [43–45].

With development of compact city concepts and UUS utilization, numerous researchers have centered their attention on the pedestrian behaviors of UPSs within the entire three-dimensional network [46]. Similar to studies on street networks, spatial configurations are typically regarded as a significant factor in pedestrian distributions. Zacharias (2000) tested the relationship between UPS network integration and pedestrian density of the Montreal UPS by means of regression analysis [47]. The result indicated that walking patterns are only weakly related to variables of the single-level (the UPS level) configuration, and the Montreal UPS is not a self-contained walking system without ground networks. Moreover, observation of pedestrian flows in the Tsim Sha Tsui UPS (Hong Kong) and its ground street network revealed a relationship between underground and ground walking systems to the pedestrian distribution in Hong Kong [23,48]. Zhuang et al. (2014) proposed that conventional two-dimensional space syntax properties with factors, such as vertical transition, vertical types, and floor levels can produce more accurate regression results for pedestrian flows in a multilevel pedestrian network [49]. Recently, numerous underground or aboveground corridors of privately owned buildings have been integrated into a comprehensive public walking system as part of the construction of a three-dimensional walking network. Zhang and Alain (2019) conducted research on walking systems in central Hong Kong and found that the variable of betweenness (a typical indicator to measure the through-traffic potential) within a combination of an indoor and outdoor three-dimensional pedestrian network can better decode pedestrian activities and the spatial configuration [50]. Cui et al. (2015) examined pedestrians via questionnaires in three UPSs in Shanghai, revealing that metros and commerce districts are two vital factors influencing UPS usage [24]. Most of the user destinations are retail locations associated with or within UPSs.

In conclusion, studies on single-level pedestrian networks (typically street networks) demonstrate that spatial morphological factors, such as spatial configuration and spatial attributes, can significantly influence walking behaviors and route selections. Moreover, it is revealed that pedestrian flows may be affected simultaneously by underground and aboveground networks, making a complete three-dimensional system more appropriate for spatial configuration analysis. Existing studies of regression analysis for pedestrian behavior, however, have been limited to specific cases, such as the UPS in Montreal. There lacks quantitative analysis in a densely populated urban-built environment, such as Chinese megacities. Also, the definition and selection criteria for a SUPS remains unclear, exerting substantial difficulties to decipher the formation mechanism of a SUPS in distinct scenarios [24]. The subsequent question should be whether the analysis of the UPS in China can still achieve a similar conclusion as in western countries and, if so, how to select the most appropriate metrics and variables of network spatial configurations and attributes to quantitatively identify the formation mechanism of a SUPS. In addition, it is essential to understand the relationship between a complex UPS and an urban street network to determine whether the UPS truly interacts with the ground street network to form a sustainable three-dimensional walking network.

In conjunction with the rapid development of metro systems and urban revitalization projects in Chinese cities in recent years, UPSs have been extensively constructed. Among these cities, Shanghai is the most representative regarding SUPS development. In this study, the Wujiaochang UPS and Loushanguan Road UPS in Shanghai were selected as two typical cases of SUPSs in distinct scenarios. The first scenario is representative of integrated underground space planning. The latter is fully implemented under urban revitalization. In this study, the selection criteria of SUPSs, outlines of two selected cases, and data sources are presented in Section 2. Section 3 illustrates the fundamental analysis procedure and variables as the methodology, along with the results and discussion in Section 4. Conclusions are finally drawn in Section 5.

2. Data and Materials

2.1. Screening Selection Criteria of a SUPS

To probe into the formation mechanism of a SUPS, it is a prerequisite to define a SUPS accurately. As depicted in Section 1, the development of the UPS typically aligns with the primary goals of SDG 11 (sustainable cities and community), thus making cities and human settlements more inclusive, safe, resilient, and sustainable. To this end, we set out to propose an explicit selection criterion for a SUPS from the perspective of interior sustainability. SDG 11 is composed of 10 sub-goals, covering a wide range of fields, such as urban planning, public transport, and urban resilience. Based on a thorough and holistic inspection on SDG 11, we ultimately selected two sub-goals that are most relevant to the interior sustainability of UPS as follows.

- By 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport (SDG 11.2);
- By 2030, provide universal access to safe, inclusive, and accessible green and public spaces (SDG 11.7).

We further interpreted these two SDG sub-goals into the screening selection criteria of a SUPS. Firstly, a SUPS should be closely integrated with the surrounding public transports, such as bus stops and metro stations. Secondly, a SUPS should act as a critical component of public activity spaces. Thirdly, a SUPS demands a necessary spatial scale to form a three-dimensional walking system, and the corresponding spatial performance of a SUPS measured by pedestrian flow should be superior to increase the overall beneficiaries of sustainable development.

Following the selection criteria of a SUPS, we preliminarily determined 96 SUPSs in Shanghai, with all chosen cases interconnected to the surrounding metro-led underground space. To enhance the representativeness of the selected cases, we further strengthened the selection criteria regarding spatial scale and public activity spaces. According to Shanghai

Master Plan 2017–2035, which is the latest and most important master planning in Shanghai, there is a hierarchical public activities center system, comprising of a city center, a city sub-center, a local center, and a community center. To jointly consider the spatial scale and the hierarchy of a public activities center system, we reserved those SUPSs located in a city center or a city sub-center with a metro-led underground space over 70,000 m^2. As shown in Table 1, there were 10 satisfactory SUPSs after two rounds of selection, and almost all of them received a good reputation from various media with regard to their spatial design and spatial experience.

Table 1. Selected SUPSs in Shanghai.

SUPS (Name by the Interconnected Metro Station)	Development Area of Interconnected Metro-Led Underground Space (10^4 m^2)
Hongqiao Railway Station	43.06
Wujiaochang	17.60
Yaohua Road-	13.58
Lujiazui	11.76
Shanghai South Railway Station	9.94
Loushanguan Road	9.57
Jinshajiang Road	9.42
People’s Square	8.05
Linping Road	7.80
Century Avenue	7.22

Due to the tremendous labor cost of recording pedestrian flow in SUPSs, we had to reduce the size of selected cases again. For the third round of selection, we invited eight scholars, six planners, and five architects to form an expert team. All experts have at least five years of professional experience in UPS development, and they were asked to select only two cases from the aforementioned ten SUPSs. Based on the relevant materials of SUPSs provided by us, the experts needed to make cautious decisions to determine the most representative SUPSs, with a holistic consideration of various factors concerning planning mode, service effects, and design quality. The detailed selection criteria as well as the corresponding reference materials are listed below.

- The selected case should have the highest quality regarding spatial design, with excellent performance in terms of light, spatial scale, color, and geometric scale, in order to give full play to the spatial attractiveness of the SUPS (experts can compare this factor based on the large number of on-site photographs of various nodes of the SUPS of the cases provided by the research team);
- The selected case should have the most representative location conditions, and among cases with similar location conditions, the case with the best performance in other indicators should be selected (experts can judge this factor based on the location map and text description of the current status of regional development provided by the research team);
- The selected case should have the most reasonable spatial configuration, avoiding extremely monotonous spatial patterns and extremely circuitous spatial patterns (experts can judge this factor based on the SUPS plan projection map provided by the research team);
- The selected case should have the best space-use efficiency (experts can judge this indicator based on the authoritative media reports provided by the research team and the experts’ experience).

Ultimately, the Wujiaochang UPS and Loushanguan Road UPS, which are the top two frequently chosen cases, were selected as the final representative SUPSs in Shanghai for subsequent case studies.

2.2. Outlines of Study Cases

As shown in Table 2, the Wujiaochang UPS is located in the core area of Jiangwan-Wujiaochang sub-center in Shanghai with a total walking area of over 72,000 m^2. As depicted in Figure 1, it connects two metro stations (Wujiaochang Station and Jiangwan Stadium Station), two sunken plazas (Wujiaochang Plaza and KIC Plaza I and II), one underground commercial street (Pacific Fresh City), and seven urban complexes or shopping malls on the B1 floor. The Implementation of the Wujiaochang UPS constituted the majority of the sub-center's comprehensive planning for the UUS from 2005 to 2017 [51]. The primary objective of the UPS planning is to make the sub-center more walkable and connect urban blocks separated by five wide arteries on the ground.

Table 2. Space information of the Wujiaochang UPS and Loushanguan Road UPS.

		Wujiaochang UPS	**Loushanguan Road UPS** [1]
Floor area of UPS [2] (m^2)		72,000	31,000
Floor area of UPS-connected UUS [3] (m^2)		399,000	357,000
Floor area of UPS-connected building space (m^2)		1,141,000	1,115,900
Length of underground walking route (km)		5.1	2.7
Privately owned public space (POPS) proportion of UPS [4]		58%	84%
Vertical transition [5]	Indoor	14	13
	Outdoor	32	7

[1] Friendship Mall and its connected underpass are excluded. [2] Only includes pedestrian walking space. [3] Includes walking space, commercial areas, and parking lot areas. [4] POPS refers to the space built and owned by private sectors but open to the public for walking and resting to act as public space [52]. In both UPSs, some of the key underground public routes are composed by the privately owned building basements to act as POPS. [5] Only includes staircases and escalators.

Figure 1. Overall layout of the Wujiaochang UPS.

As depicted in Figure 2, the Loushanguan Road UPS is located in Hongqiao Commercial Area and is a newly planned and built UPS based on the local urban regeneration project from 2015 to 2019. The area to the south of the Loushanguan Road Metro Station is dotted with shopping centers and complexes. The UPS plan aims to integrate them and create a walkable and accessible urban complex in order to improve the shopping experience for pedestrians and customers. Five newly constructed underpasses connect the metro station to nine shopping malls or complexes along the Loushanguan Road UPS. Importantly, 84% of the approximately 31,000 m^2 of total public walking space is the indoor walking space of the connected building basements owned by the private sector but accessible to the public. The UPS connects different levels of existing buildings, including the B1 and B2 floors, due to the varying basement elevations of existing structures.

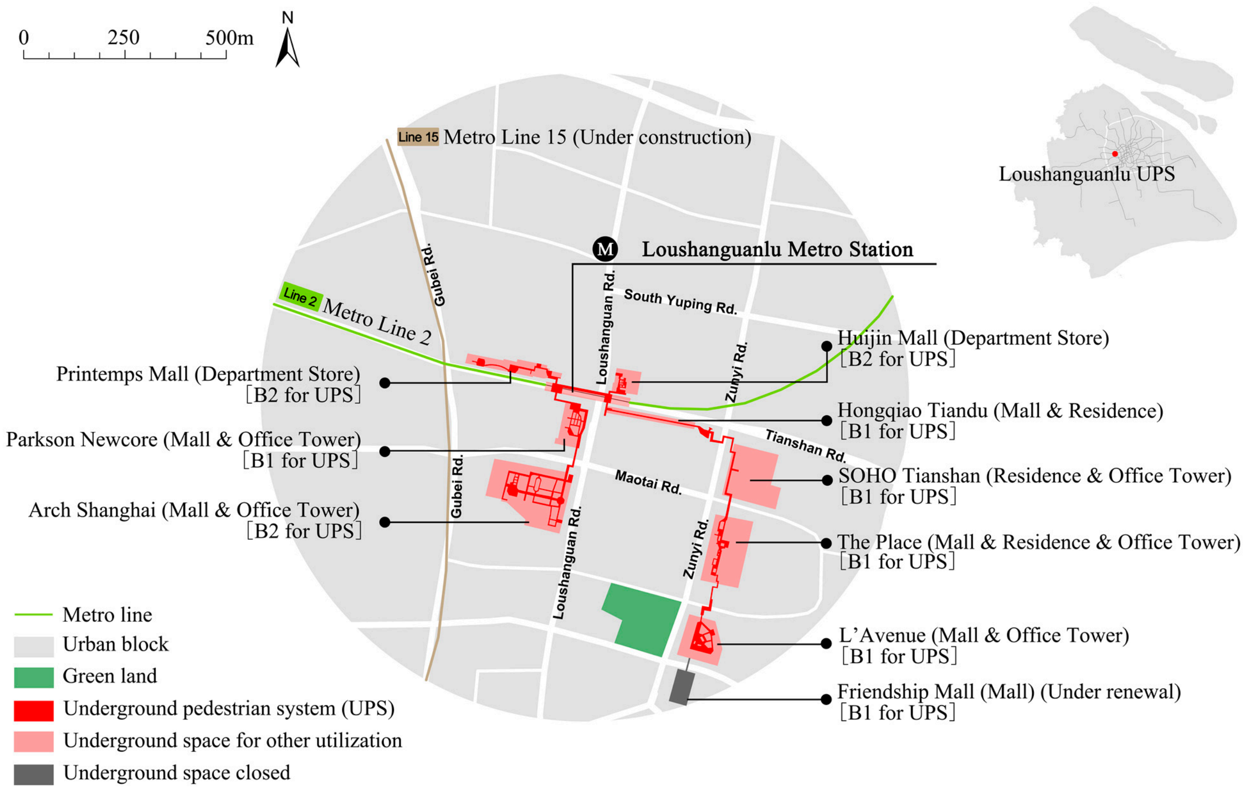


Figure 2. Overall layout of the Loushanguan Road UPS.

2.3. Data Sources

2.3.1. Three-Dimensional Walking Network

Two types of three-dimensional walking networks were established. The first only consists of the UPS and its associated UUS network, which is the underground network (UN). The second is the entire network (EN), which consists of the UN and surficial indoor and outdoor walking routes within an 800 m buffer zone. The authors have rectified the raw walking networks from Open Street Map data (www.openstreetmap.org accessed on 26 June 2023) to formulate a subtle model. The original topological errors were eliminated, and the three-dimensional roads were supplemented into the initial two-dimensional model to enhance the overall model performance. Pedestrian routes and vertical transitions, such as escalators and stairwells were mapped as center lines and intersections using a technique proposed by Cooper et al. (2018) [39].

2.3.2. Location Data

There are two types of location data, namely the transportation location and points of interest (POI) location. The former one includes locations of bus stops and metro stations.

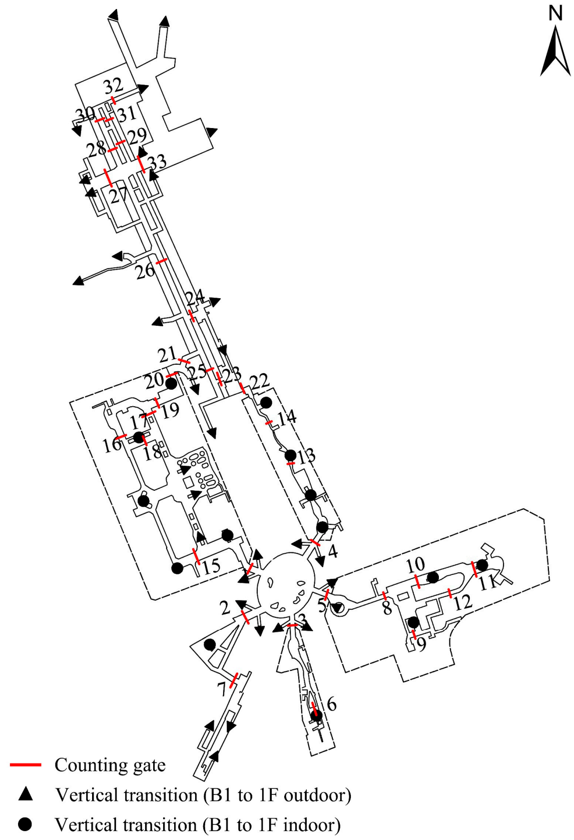
POI locations involve the data of local retail, catering, sports and recreation, and life service information within the analyzing buffer specified in Section 2.3.1. All location data were retrieved from AMAP (www.amap.com accessed on 15 April 2019), which is one of the leading online map service suppliers in China.

2.3.3. Floor Area of Commercial Space

Internet inquiries were conducted to determine the floor area of commercial space that is connected to or in the UPS.

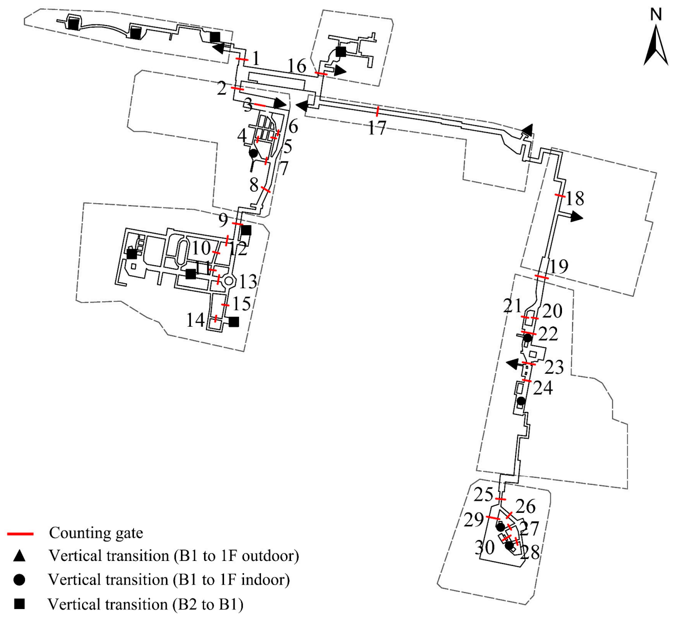
2.3.4. Pedestrian Volume

In both SUPSs, pedestrian information was collected using the gate method. The number of pedestrians crossing a notional gate in both directions within a given time interval is counted as the movement data [42,48]. A total of 33 and 30 counting gates at underground corridors were selected in the Wujiaochang UPS and Loushanguan Road UPS, respectively, as shown in Figure 3. According to Zacharias's study [47], rainy weather has a significant positive effect on pedestrian patronage of UPSs in Montreal so that the selected counting dates should avoid rainy days. Therefore, pedestrian counts were undertaken at 10:00 a.m. and 15:00 p.m. within 1.5 min on 30 June (Sunday) and 10 July (Wednesday) for the Wujiaochang UPS in 2019 and 6 October (Sunday) and 12 November (Tuesday) for the Loushanguan Road UPS in 2019. Despite the variation of data collection dates, the seasonal impacts on pedestrian behaviors concerning the local climate were weak, and the dates with important events or holidays were not selected. Moreover, the movement data collection also avoided the interference from the social distancing policies during COVID-19. Overall, the impact of different data collection times on our study findings would be limited. Two SUPSs ultimately tallied 4968 and 1647 pedestrians, respectively. The average volume of pedestrian traffic at each counting gate is listed in Table 3.



(**a**) Wujiaochang UPS.

Figure 3. *Cont.*



(**b**) Loushanguan Road UPS

Figure 3. Layout of vertical transitions and pedestrian counting gates.

Table 3. Mean weekday or weekend pedestrian movement volume per 1.5 min at counting points.

Wujiaochang UPS				Loushanguan Road UPS			
Counting Gate Number	**Weekdays**	**Weekends**	**Total Average**	**Counting Gate Number**	**Weekdays**	**Weekends**	**Total Average**
1	75	57.5	66.25	1	38	28	33
2	56	46	51	2	35.5	45.5	40.5
3	42	28	35	3	24	52	38
4	78	91	84.5	4	1	8	4.5
5	89	120.5	104.75	5	10.5	13	11.75
6	9.5	20.5	15	6	1.5	0.5	1
7	57	62	59.5	7	5	19	12
8	45	77	61	8	12	32	22
9	17.5	28.5	23	9	20.5	22.5	21.5
10	39	44.5	41.75	10	3.5	8	5.75
11	18	41	29.5	11	6	14.5	10.25
12	6	21.5	13.75	12	19	19	19
13	43	43.5	43.25	13	6	10.5	8.25
14	32	38.5	35.25	14	0.5	1	0.75
15	41	60.5	50.75	15	4	2.5	3.25
16	19.5	35	27.25	16	46	28.5	37.25
17	29	37.5	33.25	17	30.5	8.5	19.5
18	11	23.5	17.25	18	11.5	4	7.75
19	17	41	29	19	13	22	17.5
20	29.5	29	29.25	20	13	17.5	15.25
21	33	31.5	32.25	21	2	4	3
22	33.5	52.5	43	22	11	28.5	19.75
23	27.5	43	35.25	23	18.5	24.5	21.5
24	41.5	22.5	32	24	11	2	6.5
25	45.5	57	51.25	25	2.5	3	2.75
26	66	75	70.5	26	3	4.5	3.75
27	24.5	28.5	26.5	27	3.5	6	4.75
28	33.5	30.5	32	28	3.5	7.5	5.5
29	10	10	10	29	3.5	3	3.25
30	17.5	21.5	19.5	30	1	1.5	1.25
31	6	5	5.5				
32	10.5	17	13.75				
33	23.5	17	20.25				
Total	2253	2715	4968	Total	721	926	1647

3. Methodology

3.1. Analytical Framework

3.1.1. Correlation Analysis

The first step is to analyze the correlation between variables of spatial configuration and attribute and pedestrian volume of each SUPS in order to determine whether there exists a linear relationship within a statistical significance of 5%. Variables with no significant correlation should be eliminated prior to the subsequent regression analysis at the next step. By contrast, correlations between pedestrian behaviors and configurational variables of the UN and EN models must be tested independently to determine whether the SUPSs in Shanghai are more self-contained systems or interconnected ones.

3.1.2. Linear Regression Analysis

The second step is to conduct linear regression analysis as expressed in Equation (1). Spatial configuration and attribute variables set aside in the first step are used as independent variables to test whether they influence pedestrian flows and to measure their effects on pedestrian flows based on partial correlation coefficients. Variance inflation factors (VIF) and the stepwise method are employed to identify multicollinearity and eliminate its side effect.

$$P_i = \beta_0 + \beta_1 IV_1 + \beta_2 IV_2 + \cdots + \beta_n IV_n + \mu_i \quad (1)$$

where P_i is pedestrian volume at counting gate i, β_0 is the intercept (constant item), β_1 to β_n are the estimated slope coefficients of each independent variable, IV_1 to IV_n are independent variables selected from step one, and μ_i is the error term of the regression model.

3.2. Spatial Morphological Measures

3.2.1. Spatial Configurations

Spatial design network analysis (sDNA) simplifies urban streets and underground corridors into nodes and links with three-dimensional spatial information. It can be utilized to quantify the centrality, accessibility, and navigability of each space in three-dimensional network models [44,53–55]. In this study, spatial configuration variables, including betweenness and closeness with defined radii and specific metrics of both the UN and EN models were selected by means of sDNA [56].

Betweenness reflects the through traffic potential of each underground corridor for pedestrians [57]. It measures the number of times the selected link lies on the shortest path via the selected metrics between other pairs of links within a scope of radii as expressed in Equation (2) [53]. The greater the betweenness is, the greater the underground corridor's potential to attract through traffic. Closeness reveals the centrality or accessibility of each underground corridor in the whole walking network. In this study, network quantity penalized by distance (NQPD) within a specific radius and selected metrics is employed as the variable of closeness, as shown in Equation (3) [53]. It is calculated as the proportion of links divided by the distance between one link to any other links within the radius based on the selected metrics [44]. A greater NQPD indicates greater link accessibility.

$$Bt_{MR} = \sum_{x \in N} \sum_{y \in R_x} P(y) OD(x, y, z) \quad (2)$$

where Bt_{MR} means the betweenness with metrics M and radius R; N represents the set of links in three-dimensional walking networks; R_x represents the set of links in the network radius R from link x; $P(y)$ means the proportion of any link y within radius R, which is from 0 to 1 in continuous space; and $OD(x,y,z)$ means the shortest paths from link x to link z via link y based on metrics M.

$$NQPD_{MR} = \sum\nolimits_{y \in R_x} \frac{P(y)}{d_M(x, y)}. \quad (3)$$

where $NQPD_{MR}$ means the variable of closeness with metrics M and radius R; $d_M(x,y)$ represents the shortest paths from link x to link y within radius R based on metrics M.

In general, angular metrics and Euclidean metrics are applied to the metrics of betweenness and closeness variables. The angular metric computes cumulative angular changes in pedestrians at corners and intersections based on the premise that pedestrians prefer simple and direct routes over winding paths [31]. It reflects the cognitive difficulty inherent to navigation for individuals [40,41]. By contrast, Euclidean metric measures meter-based length for pedestrian walking since people typically prefer the shortest route to their destinations [44]. Underground spaces lack landmarks, and indoor mobile navigation systems are insensitive. In a large and complicated underground space, individuals with a poor sense of direction may become lost more easily. Additionally, previous research has demonstrated that people prefer shorter walking paths on the ground. This study employed both angular and Euclidean metrics to test whether pedestrians can modify their walking patterns to enhance walking efficiency in a SUPS and to determine which metric more accurately reflects pedestrian behavior.

Furthermore, influence scopes ranging from 400 m to 800 m were typically selected as analysis radii based on transit-oriented development (TOD) theory in previous studies [23,47,50,56]. Similarly, radii of 400 m, 600 m, and 800 m were applied, respectively, to test their effects in this study. All the selected variables of spatial configurations are listed in Table 4.

Table 4. Spatial configuration variables of three-dimensional networks.

Types	Metrics	Radii (m)	Variables
Betweenness	Euclidean	400	Bt_{E400}
		600	Bt_{E600}
		800	Bt_{E800}
	Angular	400	Bt_{A400}
		600	Bt_{A600}
		800	Bt_{A800}
Closeness	Euclidean	400	$NQPD_{E400}$
		600	$NQPD_{E600}$
		800	$NQPD_{E800}$
	Angular	400	$NQPD_{A400}$
		600	$NQPD_{A600}$
		800	$NQPD_{A800}$

3.2.2. Spatial Attributes

(1) Mean distance to metro stations (*MDM*)

Typically, metro station construction is the impetus for UPS development. According to the previous research on UPS users in Shanghai, 68.2% of the people arrive at the UPS by metro, and 70.7% of the users walk through UPSs in order to reach metro stations [24]. Metro stations are both significant pedestrian attractors and generators, so they should be factored into the evaluation. The variable describing metro station locations is computed as follows.

$$MDM = \sum_i^I w_i \times d_i \tag{4}$$

where I represents the amount of metro stations within the UPS, and it is two for the Wujiaochang UPS and one for the Loushanguan Road UPS; w_i means the weight of metro station i, which is computed by its average passengers of the station; d_i means the distance to metro station i from the gate counting point.

(2) Mean distance to bus stops radius R (MDBR)

Despite the fact that only about 11.5% of the interviewees in Shanghai UPSs arrive by bus [24], buses remain a significant component of urban public transportation systems.

The likelihood that SUPSs will serve as a quick and convenient connection bridge between metro stations and bus stops influences the pedestrian distribution in SUPSs. There exists a service scope for each individual bus stop, and the number of passengers at each stop varies according to the number of bus lines. Therefore, the average distance between the gate counting point and bus stops within a service area of radius R and the number of bus lines is computed in Equation (5).

$$MDB_R = \sum_j^J w_j \times d_j \quad (5)$$

where R is the influence radius of the bus stop, which is set as 400 m, 600 m, and 800 m corresponding to the radius of Bt_{MR} and $NQPD_{MR}$; J represents the amount of bus stops within the scope of radius R; w_j means the weight of bus stop j, which is computed by the bus lines of the stop; d_j means the walking distance to bus stop j from the gate counting point.

(3) POI density within radius R (PDR)

Land use has impacts on pedestrian distribution for urban street networks and skywalk systems [43,44,47]. According to the aforementioned variables, retail, catering, sports and recreation, and life service-related points of interest were chosen to represent the land use influence within a specific service scope of 400 m, 600 m, and 800 m. The variable can then be represented as follows.

$$PD_R = \frac{n_{POI}}{S_R} \quad (6)$$

where n_{POI} is the total amount of POI within the service scope of radius R (400 m, 600 m, and 800 m) from the counting point; S_R is the space area of the real service scope of radius R.

(4) Mean distance to UPS-connected commercial areas (*MDCL*)

According to previous research, commercial space adjacent to the UPS is highly correlated with pedestrian destinations and reflects the character of local land use patterns [24,48]. Subsequently, mean distance to UPS-connected commercial areas is calculated in Equation (7).

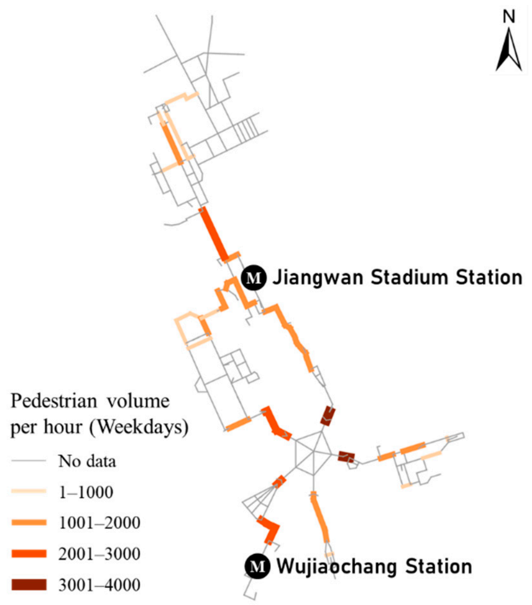
$$MDCL = \sum_l^L w_l \times d_l \quad (7)$$

where L represents the amount of commercial space connected to the UPS; w_l means the weight of commercial space l, which is computed by floor area of the commerce; d_l means the walking distance from the gate counting point to the center of the commercial space within the UPS.

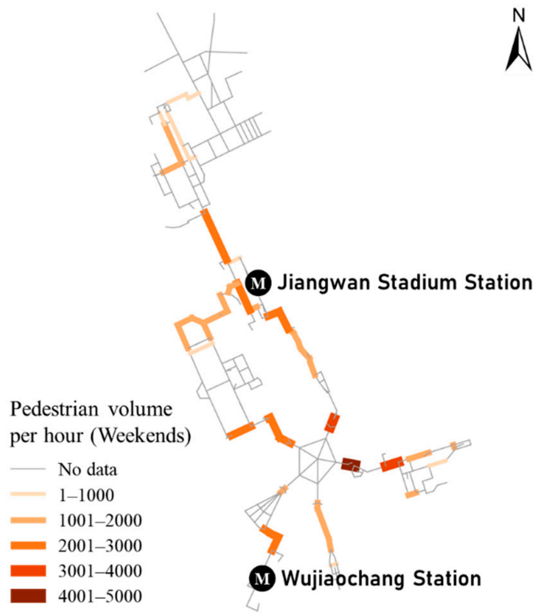
4. Results

4.1. Pedestrian Distribution Analysis

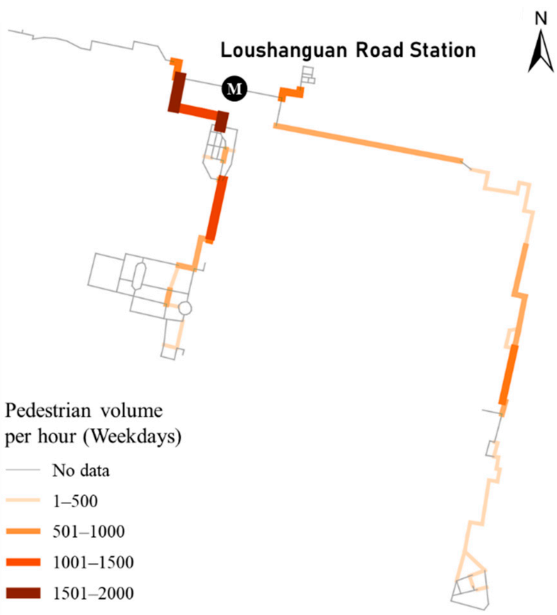
As the selected counting time avoids morning and evening peak hours, counting data were more likely to reflect pedestrian behaviors for shopping, strolling, and traffic transferring rather than working. According to Table 3, SUPS pedestrian volume at weekends is greater than that on weekdays in both SUPSs. The differences between weekdays and weekends can be explained by the fact that both UPSs are in traditional commercial areas of Shanghai, and it is evident that more shopping occurs on weekends, which can explain the differences between weekdays and weekends. As depicted in Figure 4, pedestrian flows of weekdays and weekends appear to follow similar patterns in both SUPSs. The correlation coefficients for pedestrian volumes on weekdays and weekends within the Wujiaochang UPS and Loushanguan Road UPS reached 0.85 and 0.77, respectively, which were both significant at the 0.01 level (double-tailed). Pedestrian distributions are relatively stable in both SUPSs, corroborating Zacharias's findings on walking behaviors in the Montreal UPS [47].



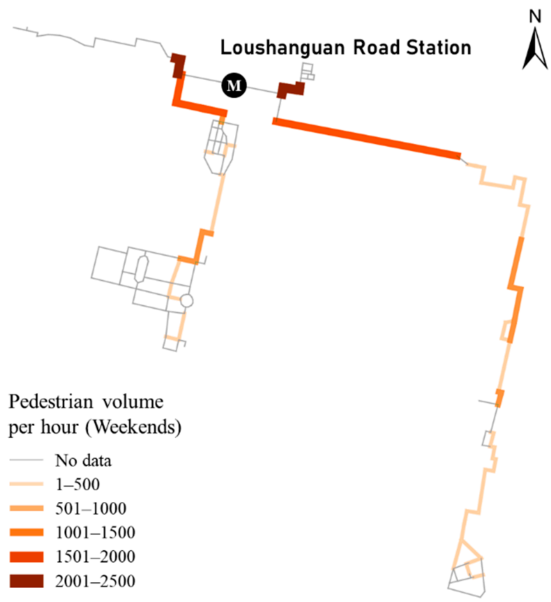
(**a**) Wujiaochang UPS—Weekdays



(**b**) Wujiaochang UPS—Weekends



(**c**) Loushanguan Road UPS—Weekdays



(**d**) Loushanguan Road UPS—Weekends

Figure 4. Mean weekday or weekend pedestrian volume per hour in the Wujiaochang UPS and Loushanguan Road UPS. (Pedestrian data are adjusted to the volume per hour for better display effects).

4.2. Spatial Configuration Analysis

Tables 5 and 6 present the correlation analysis results of the Wujiaochang UPS and Loushanguan Road UPS, respectively. It should be noted that an integrated variable of 0.5 (Bt_E + Bt_A) was also applied to test the correlations of pedestrian volume since Euclidean metrics or angular metrics have their own shortages to reflect walking behaviors. As suggested by prior research [39,57], the combination of the two metrics is likely to be more superior.

Table 5. Pearson correlation coefficient between weekday or weekend pedestrian volume and spatial configuration variables of the Wujiaochang UPS (EN model and UN model).

Model [1]	Radius	Bt_E		Bt_A		$NQPD_E$		$NQPD_A$		0.5 (Bt_E + Bt_A)	
		WD [2]	WE [3]	WD	WE	WD	WE	WD	WE	WD	WE
EN	400	0.741 **	0.740 **	0.799 **	0.711 **	0.554 **	0.321	0.679 **	0.462 **	0.790 **	0.742 **
	600	0.768 **	0.795 **	0.790 **	0.729 **	0.514 **	0.284	0.622 **	0.408 *	0.814 **	0.795 **
	800	0.733 **	0.750 **	0.749 **	0.680 **	0.401 *	0.156	0.431 *	0.187	0.799 **	0.773 **
UN	400	0.746 **	0.659 **	0.732 **	0.629 **	0.192	0.110	0.683 **	0.481 **	0.744 **	0.649 **
	600	0.737 **	0.653 **	0.756 **	0.647 **	0.151	0.120	0.642 **	0.560 **	0.751 **	0.654 **
	800	0.626 **	0.558 **	0.599 **	0.511 **	0.112	0.088	0.475 **	0.425 *	0.617 **	0.539 **

[1] EN refers to the entire network model for both underground and surficial street networks; UN refers to the underground walking system that is the UPS only. [2] WD represents the correlation between pedestrian volume on weekdays and variables. [3] WE represents the correlation between pedestrian volume at weekends and variables. * $p < 0.05$ ** $p < 0.01$.

Table 6. Pearson correlation coefficient between weekday or weekend pedestrian volume and spatial configuration variables of the Loushanguan Road UPS (EN model and UN model).

Model [1]	Radius	Bt_E		Bt_A		$NQPD_E$		$NQPD_A$		0.5 (Bt_E + Bt_A)	
		WD [2]	WE [3]	WD	WE	WD	WE	WD	WE	WD	WE
EN	400	0.395 *	0.483 **	−0.019	−0.058	0.211	0.321	−0.045	0.036	0.228	0.259
	600	0.379 *	0.388 *	0.116	0.078	0.367 *	0.332	−0.004	0.047	0.327	0.313
	800	0.340	0.286	0.051	0.053	0.314	0.281	−0.029	0.035	0.250	0.216
UN	400	0.536 **	0.635 **	0.561 **	0.665 **	−0.191	−0.092	−0.098	0.038	0.555 **	0.657 **
	600	0.540 **	0.657 **	0.583 **	0.706 **	−0.153	−0.053	0.041	0.176	0.571 **	0.694 **
	800	0.562 **	0.692 **	0.616 **	0.754 **	−0.142	−0.055	0.122	0.199	0.603 **	0.740 **

[1] EN refers to the entire network model for both underground and surficial street networks; UN refers to the underground walking system that is the UPS only. [2] WD represents the correlation between pedestrian volume on weekdays and variables. [3] WE represents the correlation between pedestrian volume at weekends and variables. * $p < 0.05$ ** $p < 0.01$.

Comparable to street networks on the ground, spatial configurations do have impacts on pedestrian flows in SUPSs based on the results of two analyses. In both SUPSs based on the EN and UN models, variables of betweenness (Bt_{MR}) had more significantly and highly positive correlations with pedestrian behaviors than the closeness ($NQPD_{MR}$). Betweenness of three-dimensional networks in the Wujiaochang UPS had higher impacts than that in the Loushanguan Road UPS. For instance, it could be observed that most of the Pearson correlation coefficients for $\boldsymbol{Bt_E}$ in both the EN and UN models of the Wujiaochang UPS are over 0.6, while the majority of the figures of the Loushanguan Road UPS are less than 0.6.

Regarding the Wujiaochang UPS, it was discovered that variables of betweenness from both models had high correlations, and the EN model seemed to have superior performance compared to the UN model. Only the variables of the UN model in the Loushanguan Road UPS exhibited a consistent and significant correlation with pedestrian behaviors. The outcome is diametrically opposed to that of the Wujiaochang UPS and the UPS in Montreal [47]. According to Figure 1, Wujiaochang sub-center is separated by five radial arteries without ground crossings. The fact that the UPS is the only pedestrian route with 32 outdoor entrances strengthens the connection between the SUPS and the ground street network. Clearly, the Wujiaochang UPS is more integrated with the entire three-dimensional network of the neighborhood's surface. In contrast, the Loushanguan Road UPS appears to be a more constrained pedestrian network. A local street network that is more walkable reduces the reliance of pedestrians on the UPS. In addition, the UPS consists of several basements of existing shopping malls with only seven exterior entrances. Fewer outdoor portals and more indoor vertical links concealed within buildings make it difficult for pedestrians to access the UPS from the street. Thus, it increases the UPS's autonomy, and most pedestrians are metro passengers and customers of UPS-connected buildings and shopping malls.

In terms of metric selections, betweenness with both angular metrics and Euclidean metrics had similar correlations at a significance of the 0.01 level (double-tailed) for the EN and UN models of the Wujiaochang UPS and the UN models of the Loushanguan Road UPS. Variables with a combined metric of 0.5 ($Bt_E + Bt_A$) even revealed higher correlations than single metrics in the case of the Wujiaochang UPS. The results of the analysis indicate that UPS users have similar walking patterns to pedestrians on the ground. They prefer shorter distances with less walking to save time and fewer cumulative angular changes to avoid getting lost, so a combination of both angular and Euclidean metrics can reveal pedestrian behaviors in SUPSs more accurately.

However, proposing a unified influence radius for the spatial configuration analysis remains vague. A radius of 600 m for both the EN and UN models produced the strongest correlations of betweenness and pedestrian volume for the Wujiaochang UPS. It is quite consistent with the study conclusions reached by Cui et al. (2015) and Zhang et al. (2015) based on the case study of the Montreal UPS and questionnaires in Shanghai [24,56]. However, only Bt_{E400} was significantly correlated to pedestrian flows for the EN model, and a radius of 800 m yielded the highest correlation considering the UN model for the Loushanguan Road UPS. Despite the absence of a unified answer regarding the selection of optimal analysis radii for spatial configurations, differences among correlations with three radii of two cases were relatively minor. It is believed that the suitable radius should range from 400 m to 800 m.

It has been demonstrated that the spatial configuration has significant effects on pedestrian distributions of SUPSs. In both cases in Shanghai, the integration of betweenness with Euclidean and angular metrics improves correlations. The relationship between underground systems and ground walking networks differs in the two SUPSs. The Wujiaochang UPS substantially affects walking behaviors for local pedestrians in the entire neighborhood. However, the Loushanguan Road UPS is more self-contained. Furthermore, spatial configurations can only partially explain pedestrian behaviors with different correlations in the two SUPSs. Other factors, except the spatial layout elements, need to be evaluated in the following sections.

4.3. Spatial Attribute Analysis

Table 7 reveals correlation coefficients between pedestrian volume and four types of spatial attribute variables on weekdays and weekends. Analysis results of two SUPSs were quite consistent. *MDM* and *MDCL* both had a negative impact on pedestrian volume within radii from 400 m to 800 m, with the correlation coefficients ranging from −0.536 to −0.622. The proximity to pedestrian attractors, such as metro stations and shopping districts increases pedestrian flow, with the correlation coefficients being positive. The phenomenon completely corresponds to the questionnaires for UPS pedestrian behaviors of three UPSs in Shanghai [24]. It also confirms a strong attraction effect on both metro stations and commercial areas to UPS users. In both instances, correlation coefficients of *MDM* on weekdays were greater than that on weekends. It may be related to travel habits of pedestrians, as metro passenger volume is typically higher on weekdays, according to the data released by Shanghai Metro Company (www.shmetro.com accessed on 1 April 2019).

By contrast, variables of *MDB* had an inconsistent relationship with weekday and weekend pedestrian volume in two SUPSs. An analysis on MDB_{400} of the Wujiaochang UPS showed a positive correlation coefficient at the 0.05 level (double-tailed), which is contrary to conventional belief that bus stops are also generators for UPS users. One possible reason is that other factors affect the distribution of pedestrian flows and interfere with the correlation results of *MDB*, which should be further tested by partial correlation analysis. Furthermore, *PD* had a negligible effect on SUPS pedestrian behaviors, which should be eliminated before regression analysis. In comparison to the UPS-linked underground commercial space, the results demonstrate that aboveground commerce appears to have little influence on SUPS pedestrian distributions in both SUPSs. It is because that the distributions of vertical links for UPSs may not coincide with the distribution of commercial agglomeration areas on the ground. In addition, the analysis result demonstrates the significance of connecting commercial space to the entire underground system in order to attract UPS pedestrians and achieve underground space vitality.

Table 7. Pearson correlation coefficient between weekday or weekend pedestrian volume and spatial attribute variables of the Wujiaochang UPS and Loushanguan Road UPS.

UPS	Radius	*MDM*		*MDB*		*PD*		*MDCL*	
		WD [1]	WE [2]	WD	WE	WD	WE	WD	WE
Wujiaochang UPS	400	−0.606 **	−0.563 **	0.467 **	0.359 *	0.330	0.414 *	−0.536 **	−0.583 **
	600			−0.532 **	−0.309	0.190	0.297		
	800			−0.555 **	−0.421 *	0.048	0.159		
Loushanguan Road UPS	400	−0.570 **	−0.564 **	−0.512 **	−0.572 **	0.223	0.335	−0.626 **	−0.622 **
	600			−0.335	−0.339	0.169	0.201		
	800			−0.346	−0.304	0.114	0.215		

[1] WD represents the correlation between pedestrian volume on weekdays and variables. [2] WE represents the correlation between pedestrian volume at weekends and variables. * $p < 0.05$ ** $p < 0.01$.

4.4. Linear Regression Analysis

To quantitatively distinguish the extent of influence on SUPS pedestrian behaviors for distinct variables, partial correlation coefficients were computed during the regression analysis. Variables of 0.5 ($Bt_E + Bt_A$), *MDM*, *MDB*, and *MDCL* of three radii are tested, as shown in Tables 8 and 9. The UN model was chosen for the Loushanguan Road UPS, and the EN model was selected in the case of Wujiaochang to reveal real impacts of spatial configurations. As stated in Section 4.1, the pedestrian distribution was relatively stable on weekdays and weekends; the average pedestrian volume was applied here to simplify the analysis.

Table 8. Partial correlation coefficients between average pedestrian volume and spatial configuration and attribute variables of the Wujiaochang UPS (EN model).

Metric Radius (m)	Variable	Standardized Coefficient	Pearson Correlation Coefficient	Partial Correlation Coefficient	VIF
400	0.5 (Bt_{E400} + Bt_{A400})	0.665	0.794 **	0.686 **	2.270
	MDM	−0.394	−0.606 **	−0.297	7.333
	MDB_{400}	0.108	0.426 *	0.194	1.356
	MDB_{600}	−0.018	−0.430 *	−0.027	1.946
	MDB_{800}	0.037	−0.503 **	0.056	2.016
	MDCL	0.037	−0.583 **	0.028	7.610
600	0.5 (Bt_{E600} + Bt_{A600})	0.706	0.835 **	0.767 **	2.042
	MDM	−0.460	−0.606 **	−0.378 *	7.419
	MDB_{400}	0.050	0.426 *	0.103	1.380
	MDB_{600}	0.039	−0.430 *	0.067	2.013
	MDB_{800}	−0.032	−0.503 **	−0.059	1.742
	MDCL	0.101	−0.583 **	0.088	7.661
800	0.5 (Bt_{E800} + Bt_{A800})	0.671	0.815 **	0.783 **	1.770
	MDM	−0.448	−0.606 *	−0.381 *	7.364
	MDB_{400}	0.031	0.426 *	0.065	1.393
	MDB_{600}	0.083	−0.430 *	0.142	2.103
	MDB_{800}	−0.132	−0.503 **	−0.254	1.570
	MDCL	0.038	−0.583 **	0.035	7.390

* $p < 0.05$ ** $p < 0.01$.

Table 9. Partial correlation coefficients between average pedestrian volume and spatial configuration and attribute variables of the Loushanguan Road UPS (UN Model).

Metric Radius (m)	Variable	Standardized Coefficient	Pearson Correlation Coefficient	Partial Correlation Coefficient	VIF
400	$0.5\ (Bt_{E400} + Bt_{A400})$	0.446	0.652 **	0.622 **	1.489
	MDM	0.373	−0.605 **	0.325	5.579
	MDB_{400}	−0.161	−0.581 **	−0.157	4.859
	MDB_{600}	0.262	−0.360	0.354	2.277
	MDB_{800}	−0.427	−0.345	−0.448 *	3.444
	$MDCL$	−0.868	−0.666 **	−0.696 **	3.790
600	$0.5\ (Bt_{E600} + Bt_{A600})$	0.451	0.681 **	0.616 **	1.553
	MDM	0.374	−0.605 **	0.324	5.585
	MDB_{400}	−0.182	−0.581 **	−0.175	4.916
	MDB_{600}	0.256	−0.360	0.345	2.272
	MDB_{800}	−0.413	−0.345	−0.431 *	3.495
	$MDCL$	−0.826	−0.666 **	−0.673 **	3.859
800	$0.5\ (Bt_{E800} + Bt_{A800})$	0.483	0.723 **	0.645 **	1.625
	MDM	0.376	−0.605 **	0.334	5.571
	MDB_{400}	−0.182	−0.581 **	−0.180	4.894
	MDB_{600}	0.257	−0.360	0.355	2.271
	MDB_{800}	−0.405	−0.345	−0.435 *	3.489
	$MDCL$	−0.787	−0.666 **	−0.663 **	3.927

* $p < 0.05$ ** $p < 0.01$.

Partial correlation analysis results demonstrated that the relationship between spatial configurations and pedestrian behaviors is remarkably positive in both SUPSs. Whereas different results were obtained in terms of the spatial attributes. For the Wujiaochang UPS, *MDM* was weakly correlated with the pedestrian volume. However, variables of MDB_{800} and *MDCL* were more highly relative to the pedestrian distribution in the Loushanguan Road UPS. Then, we examined the VIF values of two cases. Indices of *MDM* or *MDCL* were greater than 5.0 in both instances, which indicates a multicollinearity problem interfering with the regression results. By means of the correlation analysis, the coefficient of *MDM* and *MDCL* was 0.897 and 0.780 at the 0.01 level (double-tailed) for the Wujiaochang UPS and Loushanguan Road UPS, respectively, demonstrating a strong positive relationship between each other. Meanwhile, it also reveals that the layout of commercial space connected by the UPS is closely distributed around the metro stations in both cases. The overall layout of UPSs has emphasized the pivotal role of metro stations, which is a common element when constructing a UPS in Shanghai.

Stepwise regression was used to eliminate the multicollinearity issue and preserve the most significant variables influencing pedestrian behavior. Tables 10 and 11 display the regression results. Regression models for the Wujiaochang UPS were able to explain from 75.7% to 81.4% (Adjusted R^2) of the model uncertainty, and the ones of the Loushanguan Road UPS could explain from 69.3% to 70.6%, indicating satisfactory effects of the regression for both cases. Regression results with different metric radii were similar to each other, demonstrating stable and consistent impacts of spatial configurations at the micro levels with radii from 400 m to 800 m. In terms of the influence levels, spatial configuration factors of $0.5\ (Bt_E + Bt_A)$ ranked first according to standardized coefficients for the Wujiaochang UPS. The impact of spatial configurations on pedestrian behaviors was nearly 1.69 to 1.89 greater than the metro station location (*MDM*). Nevertheless, variables of *MDB* were eliminated as they could not pass the significance test during the regression. By comparison, the influence of commercial space locations (*MDCL*) was 1.24 to 1.52 times of that of the spatial configurations for the Loushanguan Road UPS. A bus stop location was also considered as one of the pedestrian generators despite a relatively low correlation around the SUPS. It should be noted that although *MDM* was eliminated owing to the multicollinearity with *MDCL*, it still had a much stronger impact on walking behaviors in the Loushanguan Road UPS than the locations of bus stops. A metro station remains one of the most crucial elements for SUPSs.

Table 10. Linear regression analysis results of the Wujiaochang UPS (EN Model).

Radius	Variables	Unstandardized Coefficient (β)	Standardized Coefficient	Partial Correlation Coefficient	VIF	Adjusted R^2
400	Constant	55.204				0.757
	0.5 (*BtE* + *BtA*)	0.007	0.670	0.800 **	1.109	
	MDM	−0.063	−0.396	−0.618 **	1.109	
600	Constant	52.910				0.814
	0.5 (*BtE* + *BtA*)	0.003	0.714	0.851 **	1.113	
	MDM	−0.061	−0.378	−0.651 **	1.113	
800	Constant	55.121				0.813
	0.5 (*BtE* + *BtA*)	0.002	0.703	0.850 **	1.080	
	MDM	−0.067	−0.415	−0.690 **	1.080	

** $p < 0.01$.

Table 11. Linear regression analysis results of the Loushanguan Road UPS (UN model).

	Variables	Unstandardized Coefficient (β)	Standardized Coefficient	Partial Correlation Coefficient	VIF	Adjusted R^2
400	Constant	88.098				0.693
	0.5 (*BtE* + *BtA*)	0.005	0.384	0.527 **	1.397	
	MDCL	−0.079	−0.585	−0.719 **	1.163	
	MDB_{800}	−0.058	−0.247	−0.381 *	1.303	
600	Constant	86.512				0.693
	0.5 (*BtE* + *BtA*)	0.003	0.390	0.526 **	1.448	
	MDCL	−0.075	−0.560	−0.693 **	1.230	
	MDB_{800}	−0.059	−0.249	−0.384 *	1.296	
800	Constant	82.375				0.706
	0.5 (*BtE* + *BtA*)	0.002	0.423	0.555 **	1.524	
	MDCL	−0.071	−0.523	−0.665 **	1.314	
	MDB_{800}	−0.057	−0.239	−0.378 *	1.297	

* $p < 0.05$ ** $p < 0.01$.

Subsequently, we compared the influence of *MDM* and *MDCL*. By means of a stepwise regression method, the factor of *MDM* was reserved for the Wujiaochang UPS while *MDCL* was retained in the models of the Loushanguan Road UPS to avoid the multicollinearity of the regression results. The significantly different outcomes appear to be attributable to the planning purposes of two SUPSs. The Wujiaochang UPS originates from the integrated UUS planning of Jiangwan-Wujiaochang sub-center. It emphasizes the integration of metro stations and other underground space to form a more walkable network, which is applied to sew up the disconnected surficial urban blocks. The greater impacts of spatial configurations and *MDM* may indicate the achievement of its planning objective and proves its integrating function for the entire walking systems on the ground and under the ground. By contrast, the UPS surrounding Loushanguan Road Station is intended to connect regionally dispersed commercial districts. A greater impact of *MDCL* on pedestrian volume verifies that pedestrian behaviors are indeed strongly related to the locations of commercial space connected by the UPS, and the planning purpose has been partially attained.

5. Discussion

5.1. Formation Mechanism of SUPS

As depicted in Figure 5, we proposed the formulation mechanism and corresponding analytical techniques for a SUPS based on the quantitative analysis. Most importantly, spatial configuration and spatial attributes were demonstrated to have a joint influence on the spatial performance (measured by the pedestrian flow) of a SUPS. In general, there are five fundamental principles concerning SUPS development as follows.

- The pedestrian distribution of a SUPS on weekdays and weekends tend to be similar, with the overall pedestrian volume on weekends being higher than that of weekdays;
- Metro stations and commercial spaces appear to be the most important spatial attractors for pedestrians in a SUPS, and planners should maintain the metro stations as the core and persuade adjacent private sectors of commercial space to connect with the SUPS.
- The walking behavior in a SUPS resembles that of a ground pedestrian system, i.e., pedestrians prefer more direct (fewest angle changes) and shorter routes (minimum walking length);
- Privately owned public space contributes to the establishment of the primary spatial configuration of a SUPS;
- The appropriate analyzing radii for pedestrian behavior within a SUPS typically range from 400 m to 800 m.

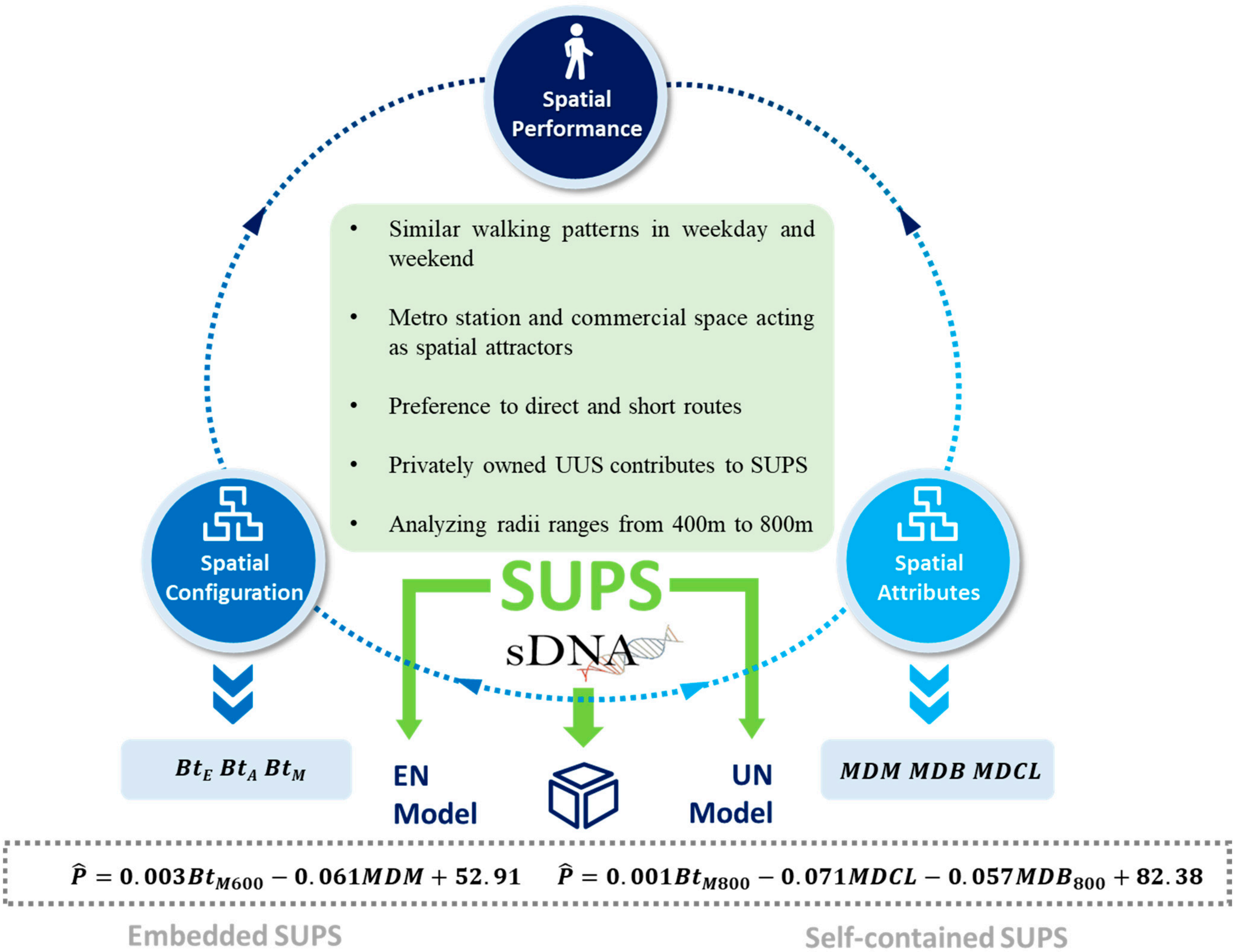


Figure 5. Formulation mechanism of a SUPS.

The formation mechanism can be further integrated into the data-driven design and analysis of SUPSs. The outcomes indicate that sDNA is applicable to the study of three-dimensional street networks underground and aboveground. Spatial configurations have significant positive impacts on the pedestrian distribution in a SUPS. Variables of betweenness and closeness can reflect the centrality of walking routes, and betweenness can better reveal underground walking behaviors for pedestrians in SUPSs. Among spatial attributes of urban transportations, the influence of metro station locations (*MDM*) on pedestrian flows is significantly greater than that of bus station distributions (*MDB*). Metro stations are one of the most important generators and destinations of SUPS pedestrians. Additionally, compared with the entire commercial space density (PD) around the counting points, the commercial space (*MDCL*) directly connected by the SUPS has a significant positive correlation with the distribution of pedestrian flows. It quantitatively proves that commerce is indeed a pivotal factor for SUPS utilization.

Another important contribution should be the diverse formation mechanism of distinct SUPSs. The Wujiaochang UPS is perfectly integrated into the entire walking system underground and aboveground. The two metro stations, namely Jiangwan Stadium Station and Wujiaochang Station, are important attractors, which reveals that the SUPS is a TOD walking system. By contrast, the Loushanguan Road UPS seems to be a more self-contained underground system. SUPS users are closely associated to commercial space connected to the SUPS, indicating that it is an UUS system geared toward the connectivity of local commercial areas. Thereby, we formulated distinct models to simulate the pedestrian distribution in two representative SUPSs, namely embedded SUPS (such as the Wujiaochang UPS) and self-contained SUPS (the Loushanguan Road UPS). It can be observed that the mixed measure of betweenness is adaptive to both SUPSs, whereas the spatial attributes factors differ in distinct models. For embedded SUPS, *MDM*, which measures the interconnection between SUPS and metro stations, plays a more important role. For self-contained SUPS, *MDB* and *MDCL*, which quantifies the connection of SUPS with commercial spaces and bus stops, appear to be more critical. Once the planners and decision-makers determine the development mode of SUPS, they can adopt the identified formulation mechanism to generate plausible design schemes of SUPS. Moreover, the quantitate model proposed in this study can also act as an efficient tool for the optimization and comparison of multiple schemes.

5.2. Challenges for SUPS Development

Although the formation mechanism and design techniques of individual SUPS have been preliminarily revealed in this study, the extensive development of SUPSs face a series of pressuring challenges that need to be addressed. It is crucial to exercise caution when considering the driving forces and barriers to SUPS development. Based on the selection criteria proposed in the previous section, a SUPS can be characterized as a large-scale three-dimensional pedestrian network with superior spatial performance, encompassing public activity centers and public transport stations. Undoubtedly, this definition aligns with the development practices of UPSs in densely populated megacities, like Shanghai. However, the development goal of a SUPS should not be limited to solely maximizing specific interior social benefits for sustainability.

Indeed, the economic factor has long been identified as the primary driving force behind underground space development [12]. Compared to their counterparts on the surface, UPSs require a significantly greater engineering investment. As a critical component of sustainable cities and communities, a SUPS cannot be analyzed in isolation, necessitating careful attention to the overall integration of UPSs with local urban development. Hence, we have identified two primary challenges in SUPS development from the perspective of integrated sustainable development.

The first challenge pertains to the integration of physical spaces. Most large-scale UPSs are completed in stages, meaning that the expansion of UPSs and their connections with adjacent basements and transport stations must be meticulously considered.

For newly developed UPSs, the planning techniques proposed in this study would contribute to the systematic integration across different temporal stages. However, for UPSs requiring redevelopment in old towns, integration should be carefully implemented using trenchless technology to minimize construction risks and reduce interference with the surrounding environment.

The second challenge relates to the integration of virtual functional spaces. Despite the emphasis on morphological design for the success of a SUPS, the functional synergy between UPS and surrounding spaces plays a crucial role in stimulating spatial vitality and economic growth [9,10]. In addition to transportation functions, UPS also encompasses public services and retail functions. The spatial distribution and quantity of various functional facilities within a SUPS should be determined by the functional configuration of adjacent urban functional spaces and local socio-economic conditions.

This study primarily investigates the interior sustainability of a UPS, raising the formation mechanism and corresponding planning and design methods of a SUPS. However, in future research, incorporating the external development environment into the model is expected to enhance the applicability of SUPS development.

6. Conclusions

The UPS has become an imperative to achieve SDGs in a densely populated built environment; however, the formation mechanism of a SUPS in high-density megacities remains unexplored, hindering the efficient and plausible design of the UPS toward urban sustainability. To bridge the research gap, we grounded the selection criteria of SUPSs to responsd to SDG 11 and revealed the underlying relationship between spatial performance and spatial morphology of a SUPS using statistical methods. The Wujiaochang UPS and Loushanguan Road UPS in Shanghai were employed as two representative cases to examine the formation mechanism of SUPSs. Specifically, the influence of spatial configurations and spatial attributes on SUPS pedestrian behaviors was quantitatively identified. The outcomes indicated that the spatial configurations and spatial attributes do have impacts on SUPS pedestrian behaviors, jointly constituting a diverse development mechanism for SUPSs. Underground walking behaviors resemble that of street networks on the ground. Commerce and metro transportation are two vital attractors or generators of SUPS pedestrians. Ultimately, we summarized the formation mechanism and corresponding design strategies for both self-contained and embedded SUPSs.

Nonetheless, this study has some limitations to be solved. First, the selected SUPSs had not been quantitatively evaluated regarding the gain of urban sustainability, resulting in an oversimplified formation mechanism of SUPSs. Despite the spatial performance measured by pedestrian volume, which is one of the most significant indicators concerning SUPS, a holistic assessment index system as well as the quantitative evaluation method need to be proposed. Second, a moderately insufficient sample size due to the limit of labor expense might partially diminish the validity of the study's conclusions. Only part of the underground corridors was counted and only two days with two off-peak times in the morning and in the afternoon were selected as the sampling times. The influence of variables on office-worker behaviors in a SUPS has not been researched. This research would contribute to sustainable planning and design of UPSs from an overall perspective; however, the refined regularities in distinct scenarios need to be further studied in upcoming research. For one part, the coupling effects of the impacts on SUPS development derived from different combinations of exterior built environment features in relation to land use, development intensity, and ground traffic conditions, should be figured out explicitly based on more sufficient case studies. For another, the operational performance data, such as building energy efficiency, should be incorporated into the quantitative assessment on interior sustainability of UPSs based on a superior monitoring system, which will help obtain a more profound understanding of SUPS development.

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