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Research Paper

A DEA–based efficiency evaluation method for metro-led urban underground public space

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Abstract

Despite the thriving development of metro-led urban underground public space (UUPS) and its significant benefits and costs, there remains a critical research gap in understanding and evaluating its efficiency. This paper intends to improve the post-evaluation system of metro-led UUPS by proposing an efficiency evaluation framework based on data envelopment analysis. The public and the private sectors are taken as different coexisting decision-makers, and a pair of linear programming is built accordingly (with different assignments of discretionary and non-discretionary inputs) for each decision-making unit. The directional vector is calculated based on CRITIC weights to model the searching process of referential cases in terms of urban renewal. The empirical study of twenty metro-led UUPSs in central Shanghai reveals that (1) the proposed evaluation framework is feasible and discriminative, (2) the efficient form of metro-led UUPS in Shanghai is mainly limited to a compact pattern with a low proportion of pure public space, (3) the essential solution to promote efficiencies is closer cooperation between different parties, and (4) efficiency evaluation is crucial to avoiding the “the-more-the-better” type of development. The findings of this study are expected to shed light on the future planning and operation of metro-led UUPS.

Keywords: Data envelopment analysis; Directional distance function; Efficiency; Metro-led; Underground public space

1 Introduction

Public spaces are considered a main source of urban vitality and crucial for building a livable city (Lopes & Camanho, 2013). In many well-developed metropolises such as Shanghai, Tokyo, New York, etc., due to the shortage of urban space and the broadened utilization of metro, urban underground public spaces have been developed systematically in metro-led areas (hereafter abbreviated as metro-led UUPS) following the transit-oriented development (TOD). Metro-led UUPS usually refers to the underground public spaces within a metro station’s influence scope of 800 m (Li et al., 2019) that are physically and economically connected to the very metro station (Ma et al., 2022). Under the TOD strategy, the metro-led area possesses a noticeably large value.

Much research has been done to study the functionalities of metro-led UUPS. A well-functioning metro-led UUPS is demonstrated with the ability to comprehensively benefit society, economy and the transport system in the following ways: (1) enriches the pedestrian network and connects blocks (Yuan et al., 2020); (2) raises accessibility and encourages the use of metro (Ma et al., 2022); (3) provides stable and comfortable indoor climate for recreation (Qiao et al., 2024), which is also car-free and safe (Bélanger, 2007; Cui et al., 2013); (4) offers accessible and convenient one-stop public services and commerce (Ibraeva et al., 2020; Rahman et al., 2022); (5) generates considerable revenue with high sales rate per unit area (Zacharias & Xu, 2007); (6) offers more business opportunities and jobs (Bélanger, 2007; Cui, 2021). On this basis, but also driven by the development of multisource spatiotemporal urban data and cross-disciplinary knowledge (Peng et al., 2023), planning methods and post-evaluation methods for metro-led UUPS are continuously developed to ensure the realization of the functionalities

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(Bobylev, 2010; Dong et al., 2021; Hong et al., 2024; Jia et al., 2024; Li et al., 2024; Ma et al., 2022, 2023; Peng et al., 2020; Shahrabi, 2024; Zhuang & Zhang, 2016).

A comprehensive post-evaluation system is often made up of evaluations of both effectiveness and efficiency (Dyckhoff & Souren, 2020). The effectiveness refers to how well the functionalities are achieved, and the efficiency concerns how well resources are used in the process. The efficiency analysis has not been uncommon for specific underground infrastructures such as urban utility tunnels and underground logistics systems (Pan et al., 2023; Zhang et al., 2021). However, there is an obvious research gap in the efficiency study of metro-led UUPS. It is speculated that the gap here may be partly due to the relatively affordable construction costs of metro-led UUPS, behind which is the ignorance of its huge opportunity costs, and that the public service is easily mistaken for something "the more the better". The fundamental problem lies in the ambiguous nature of metro-led UUPS as both a public welfare and for-profit project (Qiao et al., 2022).

To fill the research gap and contribute to the sustainable development of metro-led UUPS, this paper innovatively proposes an efficiency evaluation method built on data envelopment analysis (DEA) technology, which is a quantitative and non-parametric method capable of dealing with a small sample. As discussed above, the research gap and practice failures can be the result of the ambiguity of publicness. Accordingly, we take the public sector and the private sector as different coexisting decision-makers and build a pair of linear programming for each decision-making unit. By this design, we hope to not only provide a useful tool for post-evaluation but also shed light on the operating failures of metro-led UUPS and provoke possible solutions for future development.

2 Literature review

As stated in the Introduction, many studies in recent years have evaluated the effectiveness of metro-led UUPS based on the clarified functionalities, but few have explored the efficiency of metro-led UUPS.

In research on effectiveness, efforts have been made mainly to increase the comprehensiveness of evaluation indicators and to balance objectivity and professionalism by trying out different methods of weighting (Dong et al., 2021; Hong et al., 2024; Jia et al., 2024; Liu et al., 2020; Ma et al., 2022). One problem is a common misuse of indicators about costs, such as total area, opening hours, etc. It should be noted that more efforts, in other words, larger consumption of resources, do not necessarily result in better functioning. On the contrary, efforts make part of the costs of operating metro-led UUPS that must be restrained to achieve more efficient and sustainable development (Zhang et al., 2024). There have already been numerous cases of underutilized metro-led UUPSs despite their large scale and high-quality interior design, which should be a wake-up call. Another problem is that the evaluation results are relative, and with the cases graded the highest taken as effective, all other cases are suggested to get improvements in certain "quantity" and/or "quality". This is now fostering a "the more the better" type of unsustainable development of metro-led UUPS. From an administrative point of view, the development of metro-led UUPS also requires upper limits.

An attempt has been made by introducing the interaction of supply and demand in evaluating metro-led UUPS (Ma et al., 2022). Two evaluation frameworks are proposed in the study, respectively, for the functionality effectiveness and the development demand of metro-led UUPS. However, both the supply and the demand are relative values measured under different frameworks, which makes them incommensurable. In other words, it is questionable to comprehend a metro-led UUPS with a medium level of demand and a medium level of functionality effectiveness as reaching the perfect supply–demand balance. A more scientific approach has yet to be developed.

Though the efficiency of metro-led UUPS remains unstudied, the efficiency issue has long been high-profile in the field of public services. The methods can be mainly divided into two types, i.e., monetary techniques and non-monetary ones. The former is often adopted to translate non-monetary benefits into monetary terms to counteract non-negligible monetary costs like high construction costs that often impede the implementation of projects. Non-monetary approaches are suitable for evaluating services that are mainly characterized by non-financial data and therefore difficult to aggregate all indexes under the same scale (Dyckhoff & Souren, 2020; Niewerth et al., 2022), which is the case of metro-led UUPS. The most used methods of this type are DEA and stochastic frontier analysis (SFA). The fundamental difference lies in the formation of the production frontier. An ex-ante parametric modelling of the production frontier is necessary for applying SFA, which is hard to acquire for metro-led UUPS because the production from multiple urban resources to the multiple functionalities of metro-led UUPS is rather complicated and intertwined. Besides, the parametric production function of SFA is characterized by one single output, while there are multiple outputs generated by metro-led UUPS. In particular, the study of metro-led UUPSs is usually based on a small sample. In this case, SFA can be impacted and provides a small chance of reliable results (Andor & Hesse, 2011). On the contrary, DEA is a quantitative and non-parametric method that is suitable for a small sample with multiple intertwined inputs and outputs.

From the original models (Banker et al., 1984; Charnes et al., 1978) to numerous variants, different DEA models have been developed and applied widely to study the efficiency of public or quasi-public institutions, such as hospitals, schools, police offices, etc. (Ben Yahia et al., 2018; Kohl et al., 2019; Nepomuceno et al., 2022). Some efforts have also been made to employ DEA to evaluate public projects or services with intangible inputs and outputs of society. For example, Lopes & Camanho (2013) used indicators related to environment quality, city and building features, green space availability, etc. as inputs and issues regarding crime and health as outputs to assess the efficiency of public green space in 174 European cities. Guo et al. (2018) evaluated the efficiency of railway stations on the Tokyu Den-en Toshi Line in Japan using ridership as the output and nine indicators concerning the density, diversity, and design (3Ds) aspects of population, land-use and transportation design as the inputs.

In conclusion, the DEA technique has the potential for measuring the relative efficiency of metro-led UUPSs with functionality effectiveness taken as outputs and physical as well as intangible resources invested taken as inputs.

3 Methodology

3.1 DEA models in pairs for coexisting decision-makers

DEA is a linear programming-based technique for evaluating the relative efficiency of a homogeneous set of decision-making units (DMUs) that use multiple inputs to produce multiple outputs (Zhang et al., 2024). The dual programming is in envelopment form, of which DMUs that are Pareto efficient constitute the efficient frontier, and by projection onto the efficient frontier, the inefficiency of the evaluated DMU is measured (Dyckhoff & Souren, 2020).

In this study, the input orientation is adopted to measure the efficiency by the maximum possible optimization of inputs. Each metro-led UUPS is considered a DMU. However, as metro-led UUPS is made up of both pure public space and privately owned public space (POPS), the inputs are provided by the public and private sectors respectively, and the two sectors have separate discretionary power. To cope with the situation, two LPs are established respectively from the government's point of view (POV) and the private sector's POV. The same group of inputs and outputs is used, but the inputs are set as discretionary (under managerial control) or non-discretionary according to the managerial characteristics of POVs. Non-discretionary inputs are considered exogenously fixed, thereby no improvement is required in them (Banker & Morey, 1986).

In addition, to model the process of searching for and redeveloping towards referential cases in urban planning terms, directional distance function (DDF) (Färe & Grosskopf, 2000) is embedded in the LPs for directing the projection of inefficient DMUs onto the efficient frontier. Criteria importance through intercriteria correlation (CRITIC) method is selected to fetch the intrinsic information of the dataset so that inefficient cases can be matched with the efficient ones that share similar development conditions. Data of each discretionary input are first min–max normalized by Eq. (1) to be between 1 and 2 because DEA models are sensitive to 0 values. The standard deviation of each indicator (denoted by $\sigma_j,\ j = 1, 2, \cdots, n$) and linear correlation coefficient between each pair of indicators (denoted by $r_{jk},\ j, k = 1, 2, \cdots, n$) are then calculated. Through Eq. (2), all the information emitted by each indicator (denoted by c_j) is gathered, and the CRITIC weight (denoted by $w_j,\ j = 1, 2, \cdots, n$) is thereby allocated through Eq. (3).

$$x_{ij} = \frac{X_{ij} - X_j^{\min}}{X_j^{\max} - X_j^{\min}} + 1, \tag{1}$$

$$c_j = \sigma_j \sum_{k=1}^{n} \left(1 - r_{jk}\right), \tag{2}$$

$$w_j = c_j / \sum_{k=1}^{n} c_k, \tag{3}$$

where x_{ij} is the normalized value of X_{ij}, X_{ij} is the measure of the ith alternative with respect to input j, and $X_j^{\max}$ and $X_j^{\min}$ are the largest and smallest alternatives of input j, respectively.

The reciprocal values of CRITIC weights are used for building the directional vector $\boldsymbol{g}_x = (x_i * 1/w_i)_{i \in I_{\mathrm{D}}}$ of discretionary inputs in the model so that the similarity in the most decisive aspects is prioritized.

The two-phase LP with DDF projection is finally established through Eqs. (4) and (5) as follows:

Phase 1:

$$\begin{cases} \max\ \beta \\ \text{s.t. } \sum_{r \in U} \boldsymbol{x}_{ri}\ \lambda_r \le \boldsymbol{x}_{oi} -\ \beta \boldsymbol{g}_x, \text{ for } \ i \in I_{\mathrm{D}} \\ \sum_{r \in U} \boldsymbol{x}_{ri}\ \lambda_r \le\ \boldsymbol{x}_{oi}, \text{ for } i \in I_{\mathrm{ND}} \\ \sum_{r \in U} \boldsymbol{y}_{rj} \lambda_r\ \ge\ \boldsymbol{y}_{oj}, \text{ for }\ j \in O \\ \sum_{r \in U} \lambda_r = 1 \\ \lambda_r \ge 0,\ r \in U,\ i \in I,\ j \in O, \end{cases} \tag{4}$$

Phase 2:

$$\begin{cases} \max\ \sum_{i \in I_{\mathrm{D}}} s_i^- + \sum_{i \in I_{\mathrm{ND}}} s_i^- + \sum_{j \in O} s_j^+ \\ \text{s.t. } \sum_{r \in U} \boldsymbol{x}_{ri}\ \lambda_r + \boldsymbol{s}_i^- = \boldsymbol{x}_{oi} -\ \beta^* \boldsymbol{g}_x, \text{ for }\ i \in I_{\mathrm{D}} \\ \sum_{r \in U} \boldsymbol{x}_{ri}\ \lambda_r + \boldsymbol{s}_i^- = \boldsymbol{x}_{oi}, \text{ for }\ i \in I_{\mathrm{ND}} \\ \sum_{r \in U} \boldsymbol{y}_{rj} \lambda_r - \boldsymbol{s}_j^+ = \boldsymbol{y}_{oj}, \text{ for }\ j \in O \\ \sum_{r \in U} \lambda_r = 1 \\ \lambda_r \ge ,0,\ r \in U,\ i \in I,\ j \in O \end{cases}, \tag{5}$$

where the objective β is the largest possible contraction ratio of inputs of DMU_o ($o = 1, 2, \cdots, r$) in the direction of $\boldsymbol{g}_x$ that indicates the degree of inefficiency; U, I, and O refer to the sets of DMUs, inputs, and outputs separately and I is divided into two sets (I_{ND} for non-discretionary inputs and I_{D} for discretionary ones); $\boldsymbol{x}_{oi}$ and $\boldsymbol{y}_{oj}$ are the vectors of observed inputs and outputs of DMU_o; β^* is the corresponding solution of Phase 1; the decision variable λ_r is the composite weight of DMU_r in set U and $\sum_{r \in U} \boldsymbol{x}_{ri} \lambda_r$ makes total inputs of a virtual DMU that can be the optimization target of the evaluated DMU_o; $\boldsymbol{s}_i^-$ $(i \in I_{\mathrm{D}})$, $\boldsymbol{s}_i^-$ $(i \in I_{\mathrm{ND}})$, and $\boldsymbol{s}_j^+$ are the vectors of slacks of discretionary inputs, non-discretionary inputs and outputs separately; s_i^- $(i \in I_{\mathrm{D}})$, s_i^- $(i \in I_{\mathrm{ND}})$, and s_j^+ that constitute the objective function of Phase 2 are components of s_i^- $(i \in I_{\mathrm{D}})$, s_i^- $(i \in I_{\mathrm{ND}})$, and s_j^+.

For ease of interpretation and comparison, the β of each DMU is later converted into a measure of efficiency θ_o through Eq. (6).

$$\theta_o = 1 - \frac{1}{m}\sum_{i=1}^{m}\beta_o\frac{1}{w_i}, \tag{6}$$

where m designates the number of discretionary inputs and $\frac{1}{m}\sum_{i=1}^{m}\beta_o\frac{1}{w_i}$ refers to the average improvement ratio of discretionary inputs of DMU_o.

The efficiency measure obtained by the model above is recognized as pure technical efficiency (PTE), i.e., the sole efficiency of management. The potential improvement of efficiency that can be brought by a general scale-up of the production is not counted. If getting rid of the constraint $\sum_{r\in U}\lambda_r = 1$, a different assumption of constant returns-to-scale (CRS) will form which postulates the radial expansion and reduction of all observed DMUs as possible (Cooper et al., 2007). This means that no distinction will be made as to whether the cause of inefficiency is managerial techniques or scale of production, so the resulting efficiency measure is a mix of PTE and scale efficiency (SE, indicating the gap to the optimal scale of production) and is commonly called technical efficiency (TE). Therefore, an SE has been proved reasonable to be measured by TE/PTE. When a DMU gotSE < 1 and $\sum_{r\in U}\lambda_r < 1$ at the same time, the DMU is in an increasing returns-to-scale (IRS) stage that a radial scale-up can raise the comprehensive TE. If a DMU got SE < 1 but $\sum_{r\in U}\lambda_r > 1$, it is indicated that the production unit is already beyond the most efficient scales. The latter is called the decreasing returns-to-scale (DRS).

Inputs and outputs, as well as the measures that form the indicator system, will be introduced in the following sections.

3.2 Inputs of metro-led UUPS

The number of DMUs and that of inputs and outputs are recommended to follow the relation below:

$$n \geq \max\{3(m+q),\ m \times q\}, \tag{7}$$

where n, m, and q designate the number of DMUs, inputs, and outputs separately so that an adequate degree of freedom and the efficiency discrimination of DMUs can be guaranteed (Cooper et al., 2007). A homogeneous set of metro-led UUPS is usually limited in number. For example, in this study, the number is 20. Therefore, a simplified but comprehensive indicator system that only consists of the most representative and recognized inputs and outputs is established, including four inputs and three outputs. The number slightly exceeds the limitation in Eq. (7), but the results in Section 5 prove the evaluation framework to be discriminative enough and the number to be acceptable.

Metro-led UUPSs provide places, facilities, and other necessities for potential users (mainly consisting of the downward movement of active population from ground level and the passengers of metro stations from underground) and enable public activities to take place. This process can be analogous to an industrial production process, where the potential users are the raw material, and the places, as well as operation, are the equipment and labor, which together produce the products that are the various public activities.

(1) Average floor area ratio (x_1)

The average floor area ratio of a metro-led area indicates the three-dimensional density of buildings constructed above ground and is positively associated with the active population on site. Thus, this index is used to indicate the potential users of metro-led UUPS coming from ground level:

$$x_1 = S_{\mathrm{b}}/S_{\mathrm{l}}, \tag{8}$$

where S_{b} represents the total floor area of the overground buildings and S_{l} is the total area of the metro-led area.

This input is considered discretionary in the government's POV and non-discretionary in the private sector's POV.

(2) Metro station accessibility (x_2)

Another major part of metro-led UUPS users comes from metro passengers. Generally, the passenger volume of a metro station is decided by the importance of the station and, when planned properly, an important metro station is usually of high accessibility. Consequently, the accessibility of the metro station in the entire metro network is adopted as the second input to indicate the volume of potential users of metro-led UUPS delivered by the metro. Betweenness is a commonly used measure of flow potential derived from the topological centrality based on space syntax theory (Chiaradia et al., 2014; Cooper, 2015). It is thereby taken as the measurement in the following form:

$$x_2 = \sum(\mathrm{BtC}_n)_i/m, \tag{9}$$

where m is the number of adjacent metro stations of the measured station and $(\mathrm{BtC}_n)_i$ is the betweenness of the ith adjacent station. The topological measurement of betweenness can be calculated by the encapsulated tool of spatial design network analysis (sDNA). See (Cooper, 2024) for a more detailed computation of BtC_n.

This input is considered discretionary in the government's POV and non-discretionary in the private sector's POV.

(3) Composite devotion by the public sector (x_3)

The contribution of the public sector mainly consists of resources and manpower. For brevity, the total area of pure public space (such as the public passages and plazas under roads and public green spaces) is chosen to represent resource input. The diameter of the circumscribed circle of pure public space is used for indicating the managerial effort (i.e., the manpower input) because the public sector plays the role of glue by connecting and uniting all POPSs in a metro-led UUPS with the scattered pure public spaces. The larger this diameter, the more far-reaching influence the public sector has, and in turn, the more effort it takes. Finally, the multiplicative aggregation of those two elements makes the composite input 3:

$$x_3 = S_{\text{pps}} \times d_{\text{pps}}, \tag{10}$$

where S_{pps} is the total area of pure public spaces in the metro-led UUPS, and d_{pps} is the diameter of the circumscribed circle of that set of pure public spaces.

This input is considered discretionary in the government's POV and non-discretionary in the private sector's POV.

(4) Composite devotion by the private sector (x_4)

Similarly, the composite measurement of the private sector's contribution is also made up of two parts, with the total area of POPS used to indicate resource input and the connectivity of the metro-led UUPS network (calculated in units) chosen to indicate the general managerial efforts. A unit here means a continuous space with certain integrity that is managed by a sole entity (such as the underground floor of one commercial complex or the underground pedestrian network run by the public sector). The well-known beta index is adopted as the connectivity measurement (Wang, 2009).

$$x_4 = S_{\text{pops}} \times \frac{2e}{n}. \tag{11}$$

In this formula, S_{pops} is the total area of POPS in the metro-led UUPS operated by the private sector; $\frac{2e}{n}$ is the beta index where e and n denote the number of lines and the number of vertices of the metro-led UUPS network built in a unit manner.

This input is considered discretionary in the private sector's POV and non-discretionary in the government's POV.

3.3 Outputs of metro-led UUPS

The outputs (correspond to the effectiveness) are systematically selected based on previous studies, covering the comprehensive effects metro-led UUPS places on the economy, the society, and the transport system, respectively.

(1) Economic vitality (y_1)

As has been discussed, metro-led UUPSs generate economic benefits by providing extra underground commerce with high sales rates and offering more business opportunities and jobs. Generally, the most straightforward indicators can be sales or revenue of the metro-led UUPS, but the data is almost impossible to acquire. Therefore, average retail rent is taken as the alternative, which is accessible through mainstream retail renting websites:

$$y_1 = \sum r_i \times \frac{\left(S_{\text{uups}}\right)_i}{S_{\text{UUPS}}}, \tag{12}$$

where r_i is the average retail rent of the ith UUPS unit in the metro-led UUPS, $\left(S_{\text{uups}}\right)_i$ refers to the area of this unit, and S_{UUPS} is the total area of the metro-led UUPS.

(2) Social vitality (y_2)

Social vitality is best measured by the total amount and the spatiotemporal diversity of spontaneous activities (such as sitting, strolling, and chatting). However, it would be very manpower- and time-consuming to carry out field research to acquire the data (Zhang et al., 2024). Thus, an alternative indicator is adopted here, which is the density of recreation-related POI in the metro-led UUPS. The POI data have been long and widely used for indicating space vitality (Dong et al., 2021; Ma et al., 2022) and can be acquired through open web maps. After data cleansing and reclassification, the social output can be measured as follows:

$$y_2 = n_{\text{RPOI}}/S_{\text{UUPS}}, \tag{13}$$

where n_{RPOI} is the total number of recreation-related POI in the metro-led UUPS, mainly including retail, catering, leisure, and daily services.

(3) Improvement in public transport services (y_3)

The most representative effect of metro-led UUPS on transportation is the promotion of the metro as a public transport. Although it is better to be quantified by measurements of passenger flow, the amount that should be owing to the utilization of metro-led UUPS is difficult to extract. Given that accessibility is the most essential characteristic of urban rail transit, and that the metro is widely welcomed if accessible would be embraced by most of the public, the promotion of accessibility to the metro station brought by metro-led UUPS can be used to indicate the increased use of metro transport. Previous studies have shown that in daily urban life, the preferred travel distance on foot is approximately a 10-min walk (Ma et al., 2022), so the indicator is calculated by the difference between the 10-min accessible area of the metro station with and without metro-led UUPS:

$$y_3 = (S_{\text{m2}} - S_{\text{m1}})/S_{\text{m1}}, \tag{14}$$

where S_{m2} and S_{m1} refer to the 10-min-walking accessible area of the metro station with and without metro-led UUPS, respectively. The 10-min accessible area can be calculated by the Network Analyst in ArcGIS with the default walking pace of 5 km per hour, which is commonly known as the preferred walking speed (Mohler et al., 2007).

4 Study area

Shanghai is the most thriving economic center and the leading city of modernization in China. It is also one of the earliest Chinese cities to develop a metro and an urban underground public space. Now, Shanghai has the most mileage of rail transit in the world (Dong et al., 2021) and the highest share ratio of rail transport in urban public transportation in China (Chinese Academy of Engineering et al., 2021). Consequently, it has been frequently chosen as the studied case and reference for developing metro-led UUPS (Dong et al., 2021; Li et al., 2024; Ma et al., 2022; Peng et al., 2020). As discussed above, the neglect of efficiency also exists in the metro-led UUPS development of Shanghai. These are parts of the reason why it was chosen to be the study area in this paper. In addition, comparisons are intended to be made between the efficiency evaluation results and the results drawn from a previous study on effectiveness by Ma et al. (2022). Therefore, 20 metro-led UUPSs shown in Fig. 1 in the central urban area of Shanghai have been chosen as the studied cases, which are consistent with the choice of the previous effectiveness study.

The multisource urban data (such as spatial layouts of metro-led UUPS, the structure of the metro network, POI, etc.) used for calculating inputs and outputs were all collected in 2021 to be consistent with those used by Ma et al. (2022) on the effectiveness evaluation. The spatial layout of the metro-led UUPSs and the road network in metro-led areas was mainly collected by field research, based on which secondary indexes such as the total area of the metro-led area, the total area of pure public spaces in the metro-led UUPS, etc., were calculated. Retail rent data were obtained from mainstream retail renting websites, including winshang.com, shanghai.baixing.com, sh.58.com, and shanghai.anjuke.com. POI data were collected by searching in bounds through the application programming interface of AMAP, one of the most frequently used open web map applications in China.

5 Results and discussion

5.1 Quadruply efficient and inefficient metro-led UUPSs

The evaluation results in Table 1 below show that 8 metro-led UUPSs, which are 40% of all UUPSs analyzed, are quadruply efficient (E^{++++}), i.e., relatively efficient in both scale and pure managerial aspects in both POVs. The observed inputs and outputs (after min–max standardization) of these quadruply efficient cases are illustrated using colored curves in Fig. 2. Those cases have distributed values of x_1, x_2, x_4 and y_1, y_3, but are visibly narrow on the value ranges of x_3 and y_2. A further Mann–Whitney test shows that the median difference of y_2 between the quadruply efficient cases and the others is statistically significant (Table 2), while that of x_3 is not. This is possibly because x_3 of all those 20 metro-led UUPSs is skewedly distributed

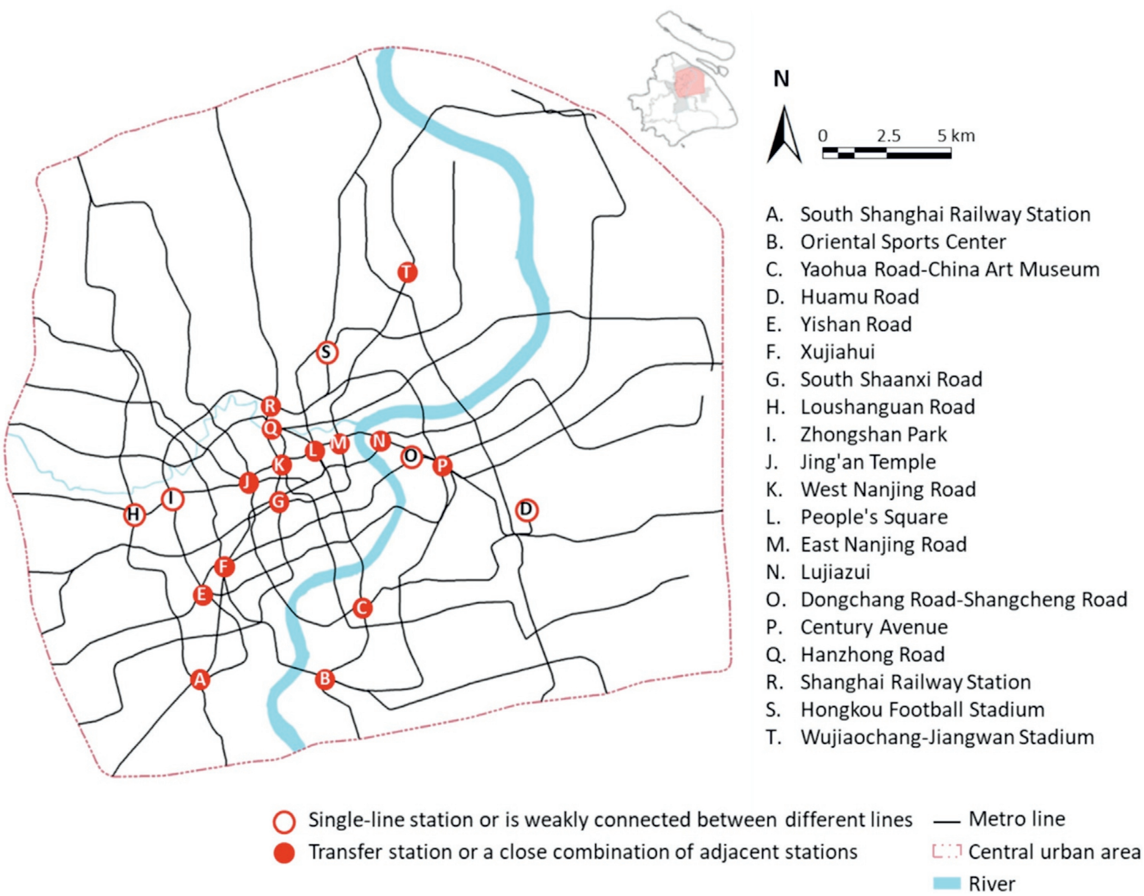

Fig. 1. Location of the 20 metro-led UUPSs in the central area of Shanghai.

Table 1
Efficiencies of 20 metro-led UUPSs.[a]

DMU	No.	Status of efficiency[b]	Private sector's POV			Government's POV		
			PTE	SE	RTS	PTE	SE	RTS
South Shanghai Railway Station	A	E^{--}_{pri}	0.966	0.633	IRS	1.000	0.832	IRS
Oriental Sports Center	B	E^{--}_{gov}	1.000	0.724	IRS	0.922	0.840	IRS
Yaohua Road-China Art Museum	C	E^{--}_{pri}	0.725	0.669	IRS	1.000	0.863	IRS
Huamu Road	D	E^{++}	1.000	0.735	IRS	1.000	0.967	IRS
Yishan Road	E	E^{++++}	1.000	1.000	CRS	1.000	1.000	CRS
Xujiahui	F	E^{----}	0.936	0.876	IRS	0.831	0.939	IRS
South Shaanxi Road	G	E^{++++}	1.000	1.000	CRS	1.000	1.000	CRS
Loushanguan Road	H	E^{----}	0.672	0.808	IRS	0.928	0.804	IRS
Zhongshan Park	I	E^{++++}	1.000	1.000	CRS	1.000	1.000	CRS
Jing'an Temple	J	E^{++++}	1.000	1.000	CRS	1.000	1.000	CRS
West Nanjing Road	K	E^{--}_{gov}	1.000	0.948	IRS	0.883	0.893	IRS
People's Square	L	E^{++}	1.000	1.000	CRS	1.000	0.992	DRS
East Nanjing Road	M	E^{++++}	1.000	1.000	CRS	1.000	1.000	CRS
Lujiazui	N	E^{----}	0.701	0.893	IRS	0.930	0.854	IRS
Dongchang Road-Shangcheng Road	O	E^{----}	0.961	0.857	IRS	0.969	0.786	IRS
Century Avenue	P	E^{++++}	1.000	1.000	CRS	1.000	1.000	CRS
Hanzhong Road	Q	E^{--}_{gov}	1.000	0.764	IRS	0.964	0.740	IRS
Shanghai Railway Station	R	E^{--}_{gov}	1.000	0.721	IRS	0.803	0.762	IRS
Hongkou Football Stadium	S	E^{++++}	1.000	1.000	CRS	1.000	1.000	CRS
Wujiaochang-Jiangwan Stadium	T	E^{++++}	1.000	1.000	CRS	1.000	1.000	CRS

[a] DMU for decision-making units, PTE for pure technical efficiency, SE for scale efficiency, RTS for return-to-scale, CRS for constant RTS, IRS for increasing RTS, and DRS for decreasing RTS.
[b] E^{++++} for quadruply efficient, E^{----} for quadruply inefficient, E^{--}_{pri} for doubly inefficient from private sector's POV, E^{--}_{gov} for doubly inefficient from government's POV, and E^{++} for doubly efficient in terms of PTE.

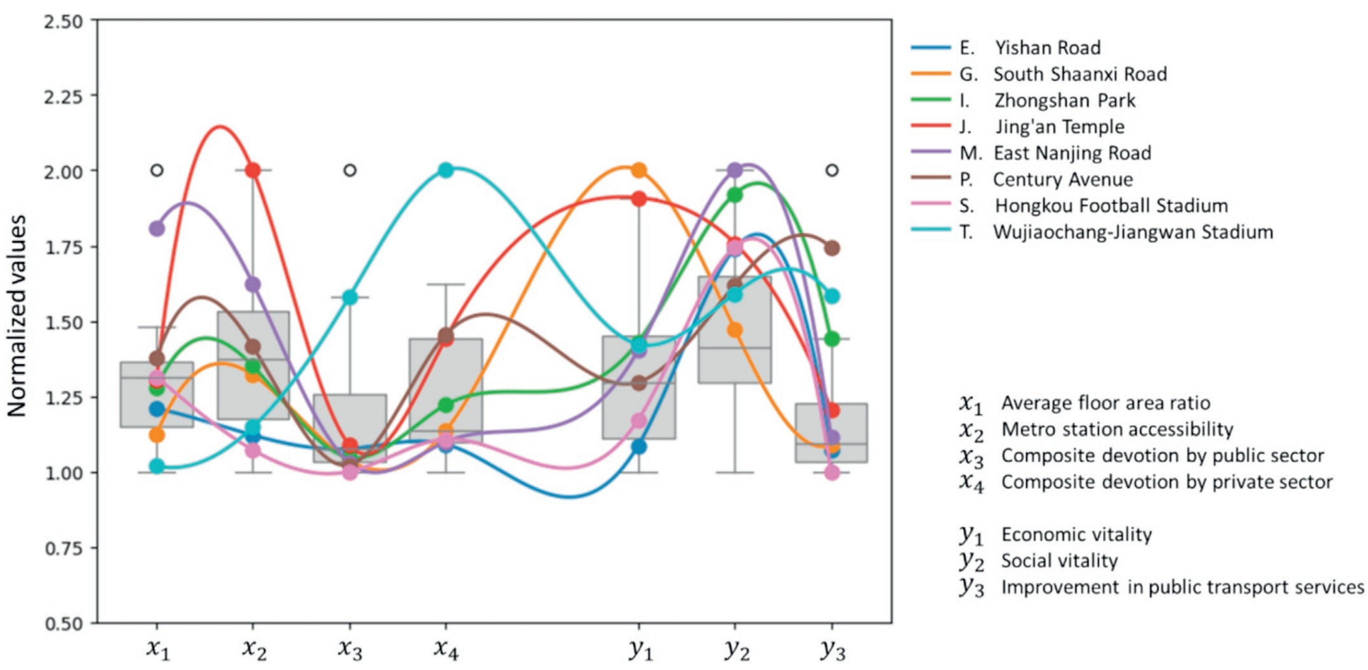

Fig. 2. Boxplots of inputs and outputs of metro-led UUPSs with the data of quadruply efficient ones illustrated by curves.

with only a few outliers. It can be inferred from the significant difference in the density of underground RPOI (y_2) that so far, the successful form of underground commercial is generally limited to a type characterized by small units and high density.

Four metro-led UUPS are quadruply inefficient (E^{----}), namely Xujiahui (F), Loushanguan Road (H), Lujiazui (N), and Dongchang Road-Shangcheng Road (O). As illustrated by Fig. 3, the development intensity aboveground (x_1) and the accessibility of the metro station

Table 2
Results of Mann–Whitney test of output 2 between quadruply efficient metro-led UUPSs and the rest.

	Quadruply efficient DMUs ($n_1 = 8$)	The rest ($n_2 = 12$)	U statistic	Z statistic	p-value
y_2	1.742(1.6,1.9)	1.335(1.1,1.4)	0	−3.703	0**

** $p < 0.01$.

(x_2) of these 4 cases are notably above average but have not resulted in higher outputs. The 4 most inefficient cases have different characteristics, which can represent 4 different types of failure in metro-led UUPSs. DMU F is mediocre in most aspects, with a relatively bigger effort put into the operation of pure public spaces, but turns out to have a low PTE in the government's POV and a low SE in the private sector's POV. This might indicate an inappropriate proportion of space function. On the other hand, DMU H has evidently put in bigger efforts into the operation of POPS than most of the others, but turns out to perform badly in all aspects and the PTE in the private sector's POV is very low. The operation of the private sector in this case seems to be rather flawed. By comparing the failures of DMU F and H, it can also be inferred that the mismatch of investments between the public and private sectors can be devastating. DMU N has notably large x_1 and x_2, and a relatively insufficient follow-through involvement of the public sector (i.e., x_3), resulting in a waste of the rest inputs and a poor PTE from the private sector's POV. Whereas, the private sector has not suffered much inefficiency at DMU O, although public inputs in this case are even more insufficient. This can be partly due to the conserved involvement of the private sector. The comparison between DMU N and O indicates a possible inclination of the private sector to be more and more conservative in developing metro-led UUPS, if the public sector does not get deeper involved.

5.2 Insights from the private sector's POV

The top 80% benchmarks and the slack movements of the technically inefficient DMUs from the private sector's POV are listed in Table 3. Except for the quadruply inefficient DMUs discussed above, the UUPSs of South Shanghai Railway Station (A) and Yaohua Road-China Art Museum (C) are also doubly inefficient (E_{pri}^{--}). The PTE of DMU A is close to 1, and there are few slacks of inputs, but the SE is the lowest of all. The proportion of POPS in DMU A is one of the smallest, so are the average retail rent (y_1) and RPOI density (y_2). It can be concluded that DMU A basically plays the role of a pure transport hub but provides few other public services, which is not so appropriate for a hub in central urban area. DMU C is very inefficient in both scale and pure technical aspects, with some excessive nondiscretionary inputs provided by the public sector but insufficient output of recreation vitality (y_2). Besides that, the operation of the private sector in this case is undoubtedly flawed; there may be other negative factors

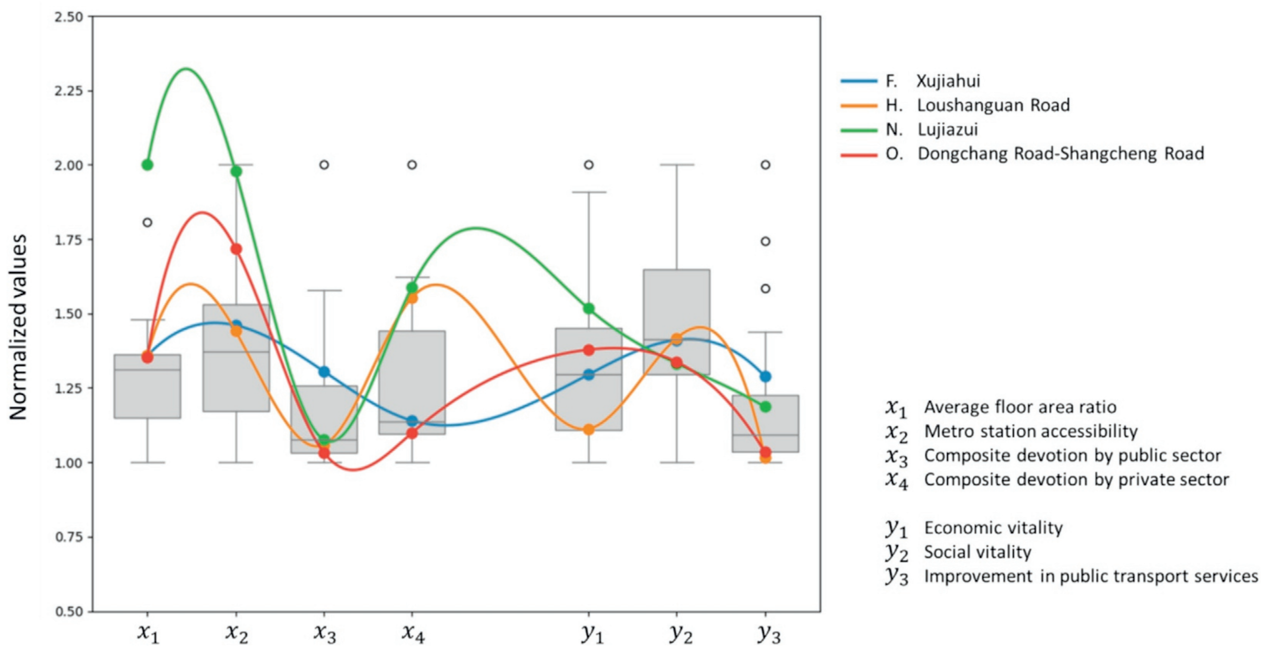

Fig. 3. Boxplots of the normalized input and output data of metro-led UUPSs with the data of quadruply inefficient ones illustrated by curves.

Table 3
Benchmarks and slacks of the technically inefficient (PTE < 1) metro-led UUPSs from the private sector's POV.

DMU		PTE	SE	Benchmarks	Input slacks	Nondiscretionary input slacks			Output slacks		
					x_4	x_1	x_2	x_3	y_1	y_2	y_3
South Shanghai Railway Station	A	0.966	0.633	D: 0.821	0	0	0	0	0	0	0
Yaohua Road-China Art Museum	C	0.725	0.669	D: 0.884	0	0	0.081	0.241	0	0.226	0.020
Xujiahui	F	0.936	0.876	Q: 0.387, L: 0.265, E: 0.216	0	0.123	0.188	0	0	0	0.054
Loushanguan Road	H	0.672	0.808	Q: 0.592, E: 0.254	0	0	0.122	0	0.057	0	0.044
Lujiazui	N	0.701	0.893	Q: 0.354, G: 0.352, I: 0.253	0	0.856	0.665	0	0.341	0.229	0
Dongchang Road-Shangcheng Road	O	0.961	0.857	Q: 0.623, G: 0.263	0	0	0.289	0	0	0.240	0.585

outside the evaluation framework that are responsible for the result, as deduced from experience. A further pedestrian route directness measurement (see Fig. 4) of the external road network is supplemented. Results show that DMU C and other UUPSs with low PTE of the private sector (such as DMU H and N) share the commonality of low external accessibility in pedestrian terms, which existed before the private sector started to operate, and can only be improved by a renewal led by the public sector.

The most used benchmarks from the private sector's POV, as shown in Table 3, are the UUPSs of Hanzhong Road (four times), Huamu Road (two times), Yishan Road (two times), and South Shaanxi Road (two times). The total floor area ranges from 15 154.581 to 175 952.970 m^2 for all the metro-led UUPSs, while in those benchmark cases, the total floor area only ranges from 15 154.581 to 43 897.758 m^2. A similar compact pattern of spatial layout is detected where a wider service range of a metro station does not have to bind with a significant scale-up of the total area.

5.3 Insights from the government's POV

The most used benchmarks from the government's POV as shown in Table 4 are the UUPSs of South Shaanxi Road (five times), Hongkou Football Stadium (five times), and Huamu Road (four times). Similar to the private sector's POV, a compact pattern of metro-led UUPS and underground pedestrian system development is detected for the public sector. However, there is also a sign of a radically different development pattern existing alongside, which is typified by the case of Wujiaochang. The UUPS of Wujiaochang (T) is one of the most famous cases of metro-led UUPS in Shanghai. A lot of research has been done to explore its success (Ma et al., 2023; Zhou et al., 2022). The case is characterized by an overwhelmingly centered sunken plaza, which generates high accessibility and intervisibility and thereby an integral sense of place for recreation. Such a design can be rarely witnessed in other metro-led UUPSs. This is possibly the reason why DMU T is not only quadruply efficient but also very well-performing in all functionalities, yet has hardly been chosen as a benchmark. In other words, the managerial technology of DMU T is distinguished so that it constructs part of the Pareto frontier in a different direction. Taking another look at Fig. 2, the proportions of inputs in DMU T are distinctly different from the others. It is indicated that the public sector either builds the minimum number of passages to simply connect underground space units or gets deeply committed to developing a highly unified recreation system in the mero-led UUPS. So far in China, there are some successful practices of the first type, while the second type is very rare.

Compared with conclusions from the previous study on effectiveness evaluation of these 20 cases (Ma et al., 2022), some large cases that have been considered well-performing (such as DMU H) now turn out to have low efficiency,

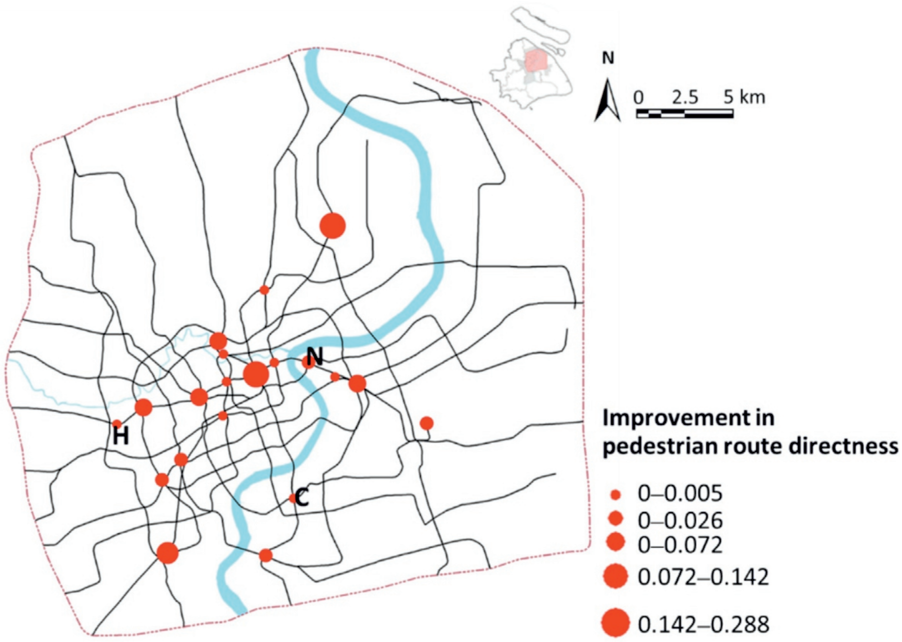

Fig. 4. Improvement in pedestrian route directness of metro-led area brought by metro-led UUPS.

while some small cases (such as DMU E and S) have now been proven to be practical and economical. It is verified that large inputs do not necessarily result in the successful functioning of metro-led UUPS. On the contrary, both the public sector and the private sector seem ill-equipped to handle large cases at present. Additionally, the efficiency measurements also show differences from the supply–demand relationships calculated by the previous study. For example, the case of East Nanjing Road was regarded in short supply, while in this study, it is not only efficient but also in a CRS stage. On the other hand, the metro-led UUPS of Wujiaochang, which is also efficient and in CRS stage, was claimed to be in surplus. In a word, the effectiveness should not be the only value to pursue. For smart governance and sustainable development, efficiency control is crucial.

From the government's POV, except for the quadruply inefficient DMUs listed in Fig. 3, the UUPSs of Oriental Sports Center (B), West Nanjing Road (K), Hanzhong Road (Q), and Shanghai Railway Station (R) are also doubly inefficient (E_{gov}^{--}) as shown in Table 4. The SE of DMU Q and R are the smallest. Besides, DMU R also has a low PTE as well as obvious redundant x_3. Since it is in an IRS stage and its role as a large public transportation hub is prior, it is recommended that the managerial technology of the public sector be improved in the first place, followed by an increment in other inputs. The proportions of pure public space (see Fig. 5) in the abovementioned UUPSs are all over 0.4, while the average value of all 20 metro-led UUPSs is 0.303, and the average value of the mostly used benchmarks from the government's POV is only 0.076. It seems that the public sector generally does a bad job in those cases where it plays the leading role. Given that none of the doubly inefficient cases from the government's POV is doubly efficient from the private sector's POV and that all these cases are in the IRS stage, it would be very beneficial to carry out the regeneration of these cases to improve the efficiency of both parties simultaneously. It also shows that a comprehensively successful development of metro-led UUPS depends on the effective collaboration of the public and private sectors.

5.4 Inspiration for cooperation between public and private sectors

Conservatively speaking, the government should try to economically provide only the most crucial passages within the pedestrian system of metro-led UUPS, so that more underground spaces can be arranged by the market to generate vitality as much as possible. At the same time, cooperation between different developers can be supervised by the government with those crucial passages playing the role of glue. To take a step forward, incentive policies (such as land price remission or floor area ratio bonus) as well as regulations can be introduced to encourage and guide the private sector to develop commerce along the underground pedestrian system.

The private sector and the commercial spaces are virtually the ones that turn a metro-led pedestrian system into a public activity space system. Besides managerial skill, another key factor in its successful operation is the good service of the metro, including passenger accessibility through metro network and pedestrian accessibility within metro-led areas, neither of which can be easily controlled

Table 4
Benchmarks and slacks of the technically inefficient (PTE < 1) metro-led UUPSs from the government's POV.

DMU		PTE	SE	Benchmarks	Input slacks			Nondiscretionary input slacks	Output slacks		
					x_1	x_2	x_3	x_4	y_1	y_2	y_3
Oriental Sports Center	B	0.922	0.840	D: 0.763, G: 0.088	0	0.008	0	0	0	0.067	0
Xujiahui	F	0.831	0.939	D: 0.515, T: 0.182, G: 0.151	0	0.062	0	0	0	0	0
Loushanguan Road	H	0.928	0.804	S: 0.774, D: 0.226	0	0.279	0	0.429	0.028	0.237	0.005
West Nanjing Road	K	0.883	0.893	G: 0.730, S: 0.267	0.001	0.129	0	0	0	0.022	0.030
Lujiazui	N	0.930	0.854	S: 0.410, G: 0.386, P: 0.204	0.577	0.596	0	0.400	0	0.283	0
Dongchang Road-Shangcheng Road	O	0.969	0.786	S: 0.736, G: 0.247	0	0.462	0	0	0	0.295	0
Hanzhong Road	Q	0.964	0.740	S: 0.896	0	0.015	0	0	0	0.054	0
Shanghai Railway Station	R	0.803	0.762	D: 1.000	0	0.099	0.260	0	0.007	0.057	0

by the private sector. This contradiction can impede the initiative of the private sector. Put it all together, and it is easy to tell an urgent need for building up joint development committees to unite the two sectors and take charge of each unified metro-led UUPS.

First of all, from an urban planning perspective, a joint development committee is better at ensuring the implementation of urban plan, post-evaluation, and responding to the feedback. The utilization of underground space is not as flexible as that of space above ground. This makes closer links between functionalities of the pure public space and POPS in metro-led UUPS and makes them better planned and operated as a whole. Additionally, as suggested by the study results, divided decision-makers and discretionary power can inhibit the improvement reactions to post-evaluation results. Furthermore, the form of a joint development committee with a leading role allows the externalities of metro-led UUPS to be dealt with through lower cost yet more flexible and timely negotiations, and the public interest can be more secured with the public sector dominating the committee based on its operation of the metro and the pedestrian system of metro-led UUPS (Quélin et al., 2017). The inclusion of the private sector as a decision-maker not only facilitates negotiation but also makes the decision-making process and operation more flexible and rational, subject to the market.

5.5 Limitations and future prospects

Although the set of inputs and outputs in this paper is built as representative as possible under the number limitation, it is still a bit too simplified and cannot cover all related aspects, such as the supplementary indicators discussed in Sections 5.2 and 5.3. Besides, two measurements (x_3 and x_4) are built as composites of space resources and manpower that are better separated to provide clearer meanings and instructions for decision-makers. For future studies, with more homogeneous metro-led UUPSs being studied, a more detailed and explicit indicator set is expected based on the above instructions.

Another limitation of this study also concerns the indicators. Because of some data limitations, not all measurements are made up of direct materials that go in or come out of metro-led UUPS. For example, the economic output (y_1) is measured by the average retail rent of metro-led UUPS. More accurately, it should be calculated by the corresponding store sales or revenue. Considering that the nature of DEA is production activity modelling, concrete and direct inputs and outputs (such as the volume of space and the number of visitors) are preferred to make evaluation results more interpretable and instructive. To overcome the limitation, the currently inadequate condition of urban data collecting and sharing asks for stronger promotion and leadership by governments, or perhaps the form of a joint development committee of metro-led UUPS itself will facilitate the construction of the required database and give rise to more scientific tools for decision support.

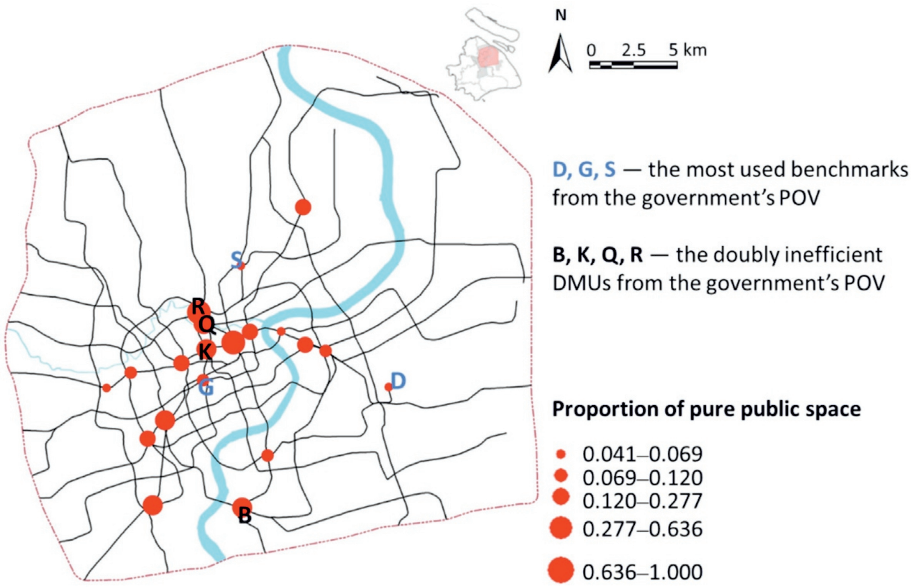

Fig. 5. Proportion of pure public space in metro-led UUPSs.

6 Conclusions

After decades of flourishing development of metro-led UUPS, the post-evaluation has come to researchers' concern, but efforts are mainly devoted to the functionality effectiveness while overlooking the efficiency. This paper contributes to the growing literature on the assessment of metro-led UUPS by proposing a DEA-based evaluation framework for measuring its efficiency and offering valuable information to decision-makers. The problem of multiple decision-makers is dealt with by building linear programming in pairs and assigning discretionary and non-discretionary inputs, respectively. The directional vector based on CRITIC weights is adopted to model the searching process of referential cases in terms of urban renewal. The proposed methodology has been applied to 20 metro-led UUPSs in central Shanghai as the empirical study, and the following conclusions can be drawn:

(1) The evaluation framework proposed is verified feasible and discriminative with eight metro-led UUPSs (40% of the selected cases) in the empirical study evaluated quadruply efficient and four evaluated quadruply inefficient. The quadruply efficient cases share a successful form of underground commercial of small units and high density, while the quadruply inefficient cases have different redundancy problems in inputs, but can be concluded as the mismatch of involvement of the public sector and the private sector. It is worth noting that the UUPS of Wujiaochang sets up a unique part of the Pareto efficient frontier that few inefficient cases can refer to. The planning and managerial techniques of the famous metro-led UUPS of Wujiaochang still call for further study.

(2) Comparative analysis across different POVs reveals that the improvement of the private sector primarily necessitates spatial structural improvements in the underground pedestrian network through public sector intervention. On the other hand, the public sector demonstrates suboptimal operation, especially in the cases it dominates (i.e., pure public space takes up most of the area). Therefore, to develop metro-led UUPS efficiently, an underground pedestrian network of high accessibility is recommended with a limited area of pure public space, so that the public sector can supervise and promote cooperation with all developers while leaving more room for recreation activities. A joint development committee is a better choice that can promote the coordination of two sectors and facilitate decision-making and execution.

(3) The most used benchmarks from both POVs follow a compact pattern in the corresponding discretionary inputs. Comparing the efficiency of evaluated cases with their effectiveness evaluated by previous studies, it is easy to notice that some large cases that used to be considered well-performing are now identified with low efficiencies, and some small cases scored low in the past evaluations of effectiveness are now proved to be practical and economical. It is verified that the "the-more-the-better" type of development of metro-led UUPS is neither sustainable nor efficient, and it is of great significance to incorporate efficiency measures into the comprehensive evaluation system of metro-led UUPS.

(4) For further optimization of the evaluation framework, efforts are expected to be made on data collection and enlarging the sample size of metro-led UUPS to allow a more detailed and explicit indicator set.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Zi-Yun Zhang: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fang-Le Peng:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Chen-Xiao Ma:** Writing – review & editing, Visualization, Investigation, Data curation. **Yong-Kang Qiao:** Writing – review & editing, Visualization, Funding acquisition.

Declaration of competing interest

Dr. Fang-Le Peng is an editorial board member for *Underground Space* and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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