Potential Evaluation for Compound Use of Urban Municipal Infrastructure Land in High-Density Cities: A Case Study in Shenzhen, China

Jing Dong, Bin Zhang, Fei Guo, Ruonan Guo, Jun Cai, and Hongchi Zhang

***Abstract*—As an important part of stock renewal in high-density cities, the compound use of urban municipal infrastructure land (UMICU) plays an important role in improving the efficiency of land-resource utilization and mitigating not in my backyard (NIMBY) effects. However, compared with the reuse of industrial land and other stock land, there have been few practical studies on UMICU. In this study, we proposed an approach to evaluate UMICU potential from a city-scale perspective. A complete and feasible workflow was also established to define potential land for UMICU, comprehensively analyze suitable compound use directions, construct an index system for UMICU combining demand and supply levels, quantitatively calculate indices based on remote sensing and geographic information system, and accurately evaluate UMICU potential using the technique for order preference by similarity to an ideal solution-Monte Carlo simulation model to derive the priority of each potential land for UMICU under different compound use modes and develop optimization strategies. A case study in Shenzhen, China, demonstrated the applicability and implications of the workflow. The results showed that UMICU can be subdivided into park renovation, commercial development, public-service compound, and municipal compound mode. The area of low-potential plots under the park renovation mode accounted for the lowest percentage (1.7%), while the area of low-potential plots under the commercial development mode accounted for the highest percentage (36.5%). Under all four compound use modes, the area of high-potential plots of Nanshan Street was the highest. The method is flexible and easy to adapt to different local contexts, allowing evaluators to introduce parameters considering the availability of local data, and will help decision-makers to scientifically implement the UMICU in the most effective land, which provides a strong reference for high-quality development in other high-density cities facing land scarcity and prominent NIMBY effects.**

***Index Terms*—Compound use, geographic information system (GIS), high-density cities, potential evaluation, remote sensing, urban municipal infrastructure.**

I. Introduction

Rapid urbanization has caused urban problems such as disorderly expansion of construction land, a low-quality living environment, and inefficient land use. Urban renewal for the compound use of stock land has become an important breakthrough to solve spatial development bottlenecks in high-density cities [1], [2], [3], [4], [5], [6], [7]. As cities move from a high-growth phase to a high-quality development phase and as awareness of environmental protection increases, the public is gradually paying attention to urban municipal infrastructure (UMI) and its compound use (UMICU) [8], [9], [10], [11], [12], [13]. UMICU focuses on the compound and 3-D construction of UMI with large areas, single functions, and not in my backyard (NIMBY) effects [14]. However, blind decisions in terms of UMICU are not only detrimental to the proper allocation of spatial resources but also cause large economic losses and risks [15], [16]. Therefore, it is imperative to explore how to effectively and reasonably reuse the land resources of UMI to eliminate NIMBY effects and achieve high-quality development in high-density cities [17], [18].

UMICU is an important aspect of the compound use of stock land [14], [19], [20], [21]. On one hand, various types of UMI form the basis in supporting urban development, such as water supply, power supply, gas supply, environmental sanitation and transportation, which are the main factors affecting the comprehensive service level of the city [22], [23], [24], [25]. However, low land cost and strong specialization lead to insufficient compound use of UMI, especially in megacities with important political and economic status and rich UMI. It is urgent to fully tap into the potential of UMI and realize the compound use of land resources [26], [27]. On the other hand, UMI such as sewage treatment plants and landfills produce odors, noises, and radiation due to the special requirements of equipment, functions, processes, etc., which has an NIMBY effect on the surrounding areas, affects the quality of the living environment, and becomes a negative space in the city. UMICU can resolve public resistance to NIMBY facilities, make urban land more flexible and resilient, and improve the quality of life of citizens [28], [29]. At the same time, with the increasing maturity of engineering technological conditions, underground UMI has great advantages in upgrading the safety, stability, and post stage maintenance of infrastructure. For example, in some large cities in Finland, Sweden, Norway, Japan, Netherlands, South Korea, England, Singapore, and Malaysia, a number of underground sewage treatment plants have been established [15], [30]. This is an effective lifecycle option in terms of reducing pollution and adverse effects of production activities on NIMBY UMI and the

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Jing Dong, Fei Guo, Ruonan Guo, Jun Cai, and Hongchi Zhang are with the School of Architecture and Fine Art, Dalian University of Technology, Dalian 116024, China (e-mail: jdong@dlut.edu.cn; guofei@dlut.edu.cn; 20180803@mail.dlut.edu.cn; caimans@dlut.edu.cn; zhanghc@dlut.edu.cn).

Bin Zhang is with the Shenzhen Municpial Engineering Consulting Center Company, Ltd., Shenzhen 518049, China (e-mail: zhangbin@ibrcn.com).

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added value of compound use incorporating regional potentials and needs [16].

At present, research on the compound use of stock land mainly focuses on the reuse of industrial land and construction land [1], [16], [31], [32], [33], [34], [35], [36]. Few studies have been conducted on UMICU, and the limited studies have mainly been characterized by underground space utilization [21], [37] and case studies on the compound use of individual UMI plots (mainly WWTPs) [38], [39]. In terms of underground space utilization of UMI, Ye and Zhu [21] clarified that UMI underground development is one of the most important contents of urban underground space planning, they studied the main factors affecting UMI underground development in urban planning, and they initially established a feasibility evaluation system for UMI underground development. Li et al. [17] analyzed the importance of urban underground infrastructure for highly concentrated megacities and proposed an urban development strategy focusing on underground development of UMI such as waste-to-energy plants, wastewater treatment plants, and waste compacting/transfer stations to save surface land resources and improve livability. In terms of case studies, Shao et al. [40] investigated the Pantai underground wastewater treatment plant in Malaysia that provided nearly 140 000 m^2 of leisure parks on the basis of meeting production and living demands and bringing spiritual satisfaction and enjoyment to the surrounding residents. Sun et al. [15] reviewed the modes, designs, and cases of low-cost underground wastewater treatment plants and concluded that they become environmentally friendly, resource-intensive, and sustainable wastewater treatment plants by constructing comprehensive office buildings, parking lots, sports fields, and other functional buildings or green spaces in the aboveground space, alleviating the problems of urban land occupation and environmental pollution. Koda et al. [18] analyzed the functional and infrastructural incorporation of the Radiowo landfill in the surrounding landscape and proposed reclamation and social applications to reintroduce it into social life. The "Guangzhou guidelines for compound land use of municipal infrastructure" issued by the Guangzhou Municipal Planning and Natural Resources Bureau [10] proposed 48 combination modes for UMICU by considering relevant excellent cases at home and abroad, such as sewage treatment plant + ground park, substation + commercial facilities, waste transfer stations + park, etc. Although UMICU can offer immense development potentials, including economic, social, and environmental benefits, the inherent complexity of these plots requires considerable efforts to successfully complete their renewal, and their compound use potential needs to be evaluated to assist the allocation of limited resources to those UMI plots that are most critical, practical, or profitable [31]. However, studies that have systematically evaluated the potential for UMICU at the urban scale and have provided a general analytical framework for selecting different compound use modes have not been found.

The above discussion shows that the current compound use of stock land lacks targeted and practical research on urban-scale UMI. The potential evaluation of UMICU is a prerequisite for optimal decisions regarding UMI. However, the literature has not introduced an appropriate perspective to the field of UMICU and has not further established an effective evaluation method accordingly. Appreciation of the literature limitation invites the research question of this study: How can the potential of UMICU be effectively evaluated at the urban scale from a comprehensive perspective that considers different compound use modes? Therefore, this article aims to develop an effective UMICU potential evaluation method and provide a general analytical framework for the selection of UMICU modes. In line with this overarching research aim, four specific research objectives are as follows:

1) to clarify the classification of UMICU modes;
2) to develop a UMICU potential evaluation model;
3) to demonstrate the effectiveness of the established UMICU potential evaluation model by conducting a Chinese context-based case study;
4) to propose targeted optimization strategies by synthesizing the research findings.

This study provides a scientific decision basis for the determination of UMICU objectives, timing and strategies and the formulation of related policies, and the application in Shenzhen can provide a strong reference for compound land use in other high-density cities facing the problems of land scarcity and prominent NIMBY effects of UMI under high-quality development.

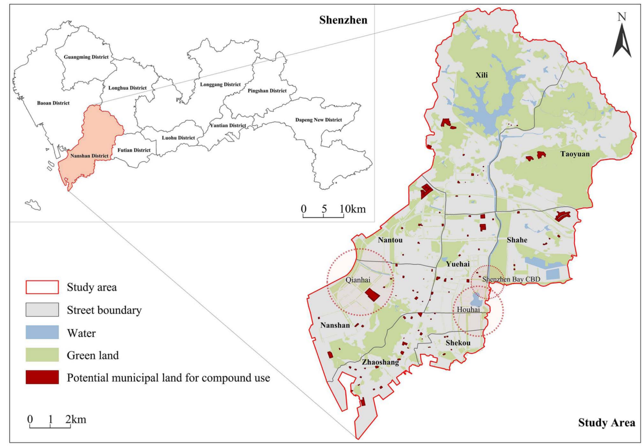

Fig. 1. Location of the study area.

II. Study Area and Data Sources

A. Study Area

Situated in southern China within the Pearl River Delta Region, Shenzhen is one of the fastest land-development cities in China (see Fig. 1). As a pioneer for all kinds of economic and institutional reforms, Shenzhen has attracted many scholars to uncover major problems of urbanization in China [32]. Compared with other mega first-tier cities in China, the constructible land area in Shenzhen is only 1004 km^2, which is approximately 1/8 of the land area of Beijing, 1/4 of that of Guangzhou and 1/3 of the area of Shanghai, and land resources are scarce [41]. According to the results of the Third National Land Survey published in 2022, Shenzhen's land-area development intensity has reached 50%, far exceeding the international practice alert line of 30% [42], making it a typical, high-density area with a small area, high density, and rapid economic development. The contradiction between high economic and population growth and land scarcity is the main problem facing the sustainable and coordinated economic and social development of Shenzhen. Urban renewal has become an important means to alleviate the conflict between people and land in Shenzhen, and the compound use of stock land is imperative [32].

Nanshan District, the study area of this article, is the center of scientific research, education and sports in Shenzhen, and Qianhai and Houhai are the twin poles of regional development in Nanshan District. The Qianhai Free Trade Zone is centered on high-tech industries and the headquarters economy, and the Qianhai Shenzhen–Hong Kong Modern Service Industry Cooperation Zone Comprehensive Planning noted that Qianhai is encouraged to adopt mixed functions and compound 3-D use of land space and is committed to creating an interconnected, balanced and diversified 3-D urban space. Houhai is the center of recreation, commerce and culture, and its 3-D use has taken shape. Qianhai–Houhai will be one of the core areas of Shenzhen's 3-D land development in the future. In addition, Shenzhen was approved to be the first national pilot for high-quality infrastructure development in 2022, which requires exploring replicable experiences for infrastructure construction. A pilot project of high-quality infrastructure development has proposed new requirements for the innovative development of UMI in Shenzhen. In this context, it is of great theoretical and practical significance to explore and promote UMICU in Nanshan District, Shenzhen.

B. Data Sources

This study used five datasets to measure all necessary indices, including four survey datasets: a geospatial dataset, a building and land-plot dataset, a socioeconomic dataset, a remote sensing image dataset, and a POI dataset. The geospatial dataset was downloaded from the Resource and Environment Science and Data Center.[1] It included the digital elevation model (DEM), soil type, administrative centers and boundaries, and transportation networks. The building and land-plot dataset came from the Shenzhen Municipal Natural Resources and Planning Bureau, and included land-plot data (shape and land use type) and building data. The socioeconomic dataset was obtained from the Nanshan District Statistical Bulletin 2021,[2] and included street population data and GDP data. The house price data were crawled from the real estate information website[3] using Python web crawler technology. Landsat 8 remote sensing data downloaded from the geospatial data cloud was L1T, the image was acquired on October 2, 2021, and the quality of the selected image data was good. The POI dataset came from the POI database of Gaode Map, and included medical facilities, educational facilities, recreational facilities, restaurants, shopping facilities, bus/subway facilities, etc.

[1] [Online]. Available: https://www.resdc.cn/
[2] [Online]. Available: http://www.szns.gov.cn/
[3] [Online]. Available: https://www.anjuke.com/

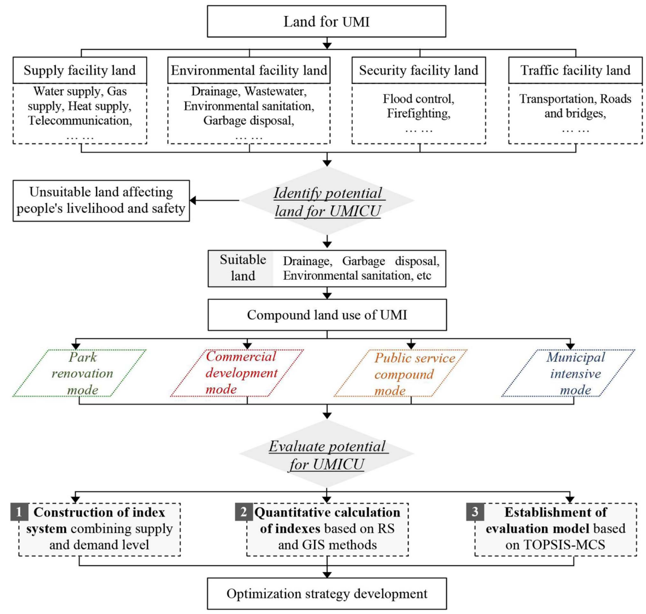

Fig. 2. Technique flowchart of the methodology.

III. Methodology

Fig. 2 shows a flowchart of the methodology used in this study. First, the potential land for UMICU was defined. Second, the UMICU modes were classified. Third, the UMICU potential evaluation index system was constructed by combining the supply (feasibility) and demand level (necessity), and indices were calculated based on RS and geographic information system (GIS) methods. Last, the technique for order preference by similarity to an ideal solution (TOPSIS) method [43], [44], [45] was used to obtain potential scores under different compound use modes. Monte Carlo simulation (MCS) was used to simulate different weights [46], and the TOPSIS method was repeated many times to obtain stable evaluation results. Based on the results, targeted optimization strategies were developed.

A. Definition and Identification of Potential Land for UMICU

In the context of high-quality development of UMI and engineering technological innovation, potential land for UMICU is defined as the existing NIMBY UMI land that is suitable for compound use in terms of livelihood safety, public health, and technical feasibility [27]. Previous studies have examined various types of UMI from different perspectives. Table I lists several typical studies with their identified results on the types of UMI. Combined with the definition, the potential land for UMICU in this article was finally determined to include six categories: water supply, power supply, telecommunication, drainage, environmental sanitation, and transportation.

B. Classification of Compound Use Modes

UMICU needs to balance the relationships between economic development and social harmony, public interest and personal

TABLE I
TYPICAL STUDIES IDENTIFIED RESULTS ON THE TYPES OF URBAN MUNICIPAL INFRASTRUCTURE

Literatures	Types of urban municipal infrastructure
[47]	Water supply; Transportation; Environmental sanitation; Gas supply; Drainage
[48]	Road; Wastewater; Water supply
[49]	Roads; Lighting; Drainage; Telecommunication; Bridge; Water supply; Power supply
[50]	Water supply; Drainage; Natural gas; Roads and bridges; Environmental sanitation
[51]	Water supply; Gas supply; Electricity supply; Heat supply; Transportation; Telecommunication; Drainage; Sewerage; Garbage disposal
[27]	Watter supply; Gas supply; Power supply; Telecommunication; Drainage; Sewage; Garbage disposal; Transportation
[10]	Water supply; Electricity supply; Gas supply; Heat supply; Telecommunication; Transportation; Environmental sanitation; Drainage; Firefighting; Flood control

interest; make up for the historical debt of infrastructure accumulated in the process of general expansion; consider solving the practical problems of residents around the plots; and bring positive benefits to the surrounding residents by establishing spaces or facilities with significant positive externalities, highlighting the spatial justice of UMICU. Therefore, on the basis of satisfying safety, fire-protection and sanitation conditions; eliminating NIMBY effects; promoting the high-quality development of UMI; and improving the quality of urban space, UMICU can be divided into four main directions: the park renovation mode, the commercial development mode, the public-service compound mode, and the municipal compound mode.

The park renovation mode (mode I) focuses on ecological environmental factors, turning the ground cover of UMI into a comprehensive open park, providing people with green leisure space, while alleviating the heat-island effect, improving surface runoff, perfecting the green-space network system, reducing negative impacts on the surrounding land value, and generating better environmental and social benefits. The commercial development mode (mode II) considers the location value, plot conditions and other factors, and through the composite development of commercial facilities and UMI, the overall value of the plot is increased by commercial revenue, thus compensating for the property loss of surrounding residents due to negative externalities and the high costs arising from composite development. The public-service compound mode (mode III) considers the demands for citizen' living services and plot conditions and improves the living quality of surrounding residents with public-service benefits by introducing public-service facilities such as cultural activity centers and gymnasiums. On the basis of the comprehensive consideration of integration mode, plot conditions and other factors, the municipal compound mode (mode IV) forms UMI clusters according to the usage status of the original UMI and the layout needs of the surrounding UMI to improve the efficiency of land use.

C. Potential Evaluation for UMICU

1) Index System Construction and Calculation:

a) Index system construction: The compound land use indicates the interactive effect between the supply level representing land attributes and the demand level representing urban sustainable development. At the land-attribute (supply) level, plot shape, size, and other land conditions directly affect the feasibility of UMICU. Therefore, it is important to consider whether the plot's own attribute characteristics meet the conditions for compound use. At the urban sustainable development (demand) level, considering three dimensions of sustainability (social, economic, and environmental) [33], environmental, economic, and social benefits of UMICU can help mitigate the negative impacts of NIMBY UMI and meet the multiple demands of urban high-quality development, which in turn affects the necessity of UMICU. Therefore, it is necessary to construct a UMICU potential index system combining the supply and demand levels based on the literature and the compound use concept.

The literature has identified many factors that affect the reuse potential of urban construction land [1], [52]. A review of these studies can provide valuable references for constructing the UMICU potential index system, although there have been no targeted studies on UMI. Table II provides a list of relevant literature presenting various indices for the reuse potential of different types of construction land. As seen from Table II, previous studies have primarily focused on land attributes, location conditions, surrounding facilities, and other factors when constructing the reuse potential index system. However, they have overlooked environmental indices, such as the heat island effect. Therefore, it is necessary to increase the measurement of environmental indices. In addition, few studies have systematically constructed and quantified the UMICU potential index system by combining demand and supply levels.

Following the principles of systematicity, representativeness, independence, accessibility, and quantifiability [53], we retained indices that constrain the degree of difficulty in construction (such as elevation, slope, etc.) and affect the differences in the demand for compound use (such as land value, population density, greening ratio, etc.). Duplicated and redundant indices were eliminated, such as industrial agglomeration and commercial agglomeration. Additionally, based on the environmental issues in the study area, relevant environmental indices were included, such as urban heat island, surface runoff, and landscape connectivity. Finally, 16 indices were selected from the environmental, social, and economic benefits at the demand level, as well as

TABLE II
TYPICAL LITERATURES FOR INVESTIGATING THE REUSE POTENTIAL INDICES OF URBAN CONSTRUCTION LAND

Literatures	**Land type**	**Indices**
[54]	Brownfield	Proximity to public transportation facilities; Proximity to recreation facilities; Proximity to community facilities; Population density; Residential density; Distance from flood zones; Distance from agricultural fields, soil and geology properties
[21]	Municipal infrastructure	Per capita GDP; Locational value; Land use property; Greening ratio; Population density; Land development intensity; Construction density
[52]	Construction land	GDP; Population density; Land development intensity; Compound utilization degree; Location conditions; Infrastructure accessibility; Investment in fixed assets; Shannon diversity index; Vegetation coverage; Slope
[55]	Brownfield	Distance to doctors; Distance to pharmacies; Distance to employment; Distance to schools; Distance to green spaces; Distance to meeting places; Distance to shops
[56]	Brownfield	Elevation; Slope; Property value; Building stories; Architectural structure; Building age; Land value; Former land use type; Size of land parcel; Plot ratio; Landscape fragmentation; Medical facility density; Educational facility density; Recreational facility density; Restaurant density; Shopping facility density; Government agency density; Financial services density; Enterprise density; Road accessibility; Distance to district center; Distance to park/open space; Distance to water area/ coastline; Population density
[25]	Construction land	Elevation; Slope; Building density; Plot ratio; Land ownership; Land value; Plot shape; Population density; Residential agglomeration; Industrial agglomeration; Commercial agglomeration; Road network density; Transportation convenience; Public service facilities aggregation; Municipal infrastructure
[1]	Industrial land	Building density; Plot ratio; Average output of land; Average tax on land; Average employees on land; Distance to highway entrance; Distance to railway station; Construction land type

the land conditions and geological conditions at the supply level, to construct the UMICU potential index system (see Table III).

b) Quantitative calculation of indices: Indices C_1–C_6, C_9–C_{10}, and C_{12}–C_{16} were measured with survey datasets. Using Landsat 8 remote sensing image data, the average surface temperature of the evaluation unit was calculated by RS and GIS (C_1). Using the DEM, soil type and land-use-type data, surface runoff under the 2-year return period rainfall event simulated by GIS and the SCS-CN hydrological model (C_2), the landscape connectivity (C_3) was calculated based on the connectivity index and the graph theory method, and the greening ratio (C_{10}) was calculated by considering the service area of different levels of green space. The road network density (C_5) was calculated based on the transportation network data intersected with the established 3 m fishing net, and land value (C_6) was calculated using spatial interpolation with the socioeconomic dataset. Land-attribute indices, C_{12}, C_{13}, and C_{14}, were calculated using the building and land-plot dataset, and C_{15} and C_{16} were calculated using the DEM.

Indices C_4 and C_9 were sourced from local government websites in China. C_7–C_8 and C_{11} were measured with the POI dataset. To obtain the evaluation unit index values, the official statistics and POI data (in point-data format) needed to be rasterized, and then a statistical analysis needed to be conducted by overlaying with evaluation units. Due to the spatial spillover and neighborhood effects of facility aggregation and population density, we introduced the kernel density method to quantify these indices [56].

2) Evaluation of Compound Use Potential:

a) TOPSIS-based potential evaluation: TOPSIS is a classical and widely used multicriteria, multiattribute decision evaluation method. This method evaluates the relative merits of each evaluation object by calculating the distance between the evaluation object and the positive and negative ideal solutions [43], [44], [45]. The TOPSIS method mainly includes the following steps.

1) Creating the original matrix and its normalization
Index matrix X is created with m rows (m indicates evaluation objects) and n columns (n indicates the number of indices), where each element of the matrix X is $x_{ij}, i = 1, 2, \ldots, m, j = 1, 2, \ldots, n$. The index matrix is as follows:

$$X = (x_{ij})_{m\times n} = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \ldots & x_{mn} \end{bmatrix}. \quad (1)$$

To eliminate errors caused by different dimensions, the index matrix is normalized and noted as the normalization matrix $B = (b_{ij})_{m\times n}$. The normalization formula is as follows:
For positive indices (larger is better)

$$b_{ij} = r_{ij} - \min(r_{ij}) / \max(r_{ij}) - \min(r_{ij}). \quad (2)$$

TABLE III
POTENTIAL EVALUATION INDEX SYSTEM FOR UMICU

Guideline layer	Element layer	Index layer	Index meaning	Calculation method
Demand level – urban sustainable development (A_1)	Environmental benefits (B_1)	Urban heat island (C_1)	Characterize the heat island distribution of the evaluation unit	The QIN_SC algorithm was used for surface temperature inversion, as detailed in [57].
		Surface runoff (C_2)	Characterize the surface runoff distribution of the evaluation unit	The SCS-CN (Soil Conservation Service Curve Number model) hydrological model was used to simulate surface runoff, as detailed in [58].
		Landscape connectivity (C_3)	Characterize the landscape connectivity of the evaluation unit	A connectivity quantification method based on connectivity index and graph theory was used to calculate landscape connectivity, as described in [59].
	Economic benefits (B_2)	GDP per land (C_4)	Characterize the economic status of the evaluation unit	$I = G/S$; G is the GDP value and S is the area of the evaluation unit.
		Road network density (C_5)	Describe the traffic convenience of the evaluation unit	$I = L/S$; L is the total length of roads and S is the area of the evaluation unit.
		Land value (C_6)	Characterize the potential value of land development in the evaluation unit	$I = \sum_{i=1}^{k} K_i P_i / n$; K_i is the house price of sample point i, P_i is the number of sample point i, and n is the total number of sample points.
		Public transportation convenience (C_7)	Characterize the public transportation service level of the evaluation unit	$I = \sum_{i=1}^{k} T_i / S$; T is the number of bus stops and S is the area of the evaluation unit.
		Commercial facilities aggregation (C_8)	Characterize the prosperity degree of the evaluation unit	$I = \sum_{i=1}^{k} Q_i / S$; Q is the number of commercial facility points and S is the area of the evaluation unit.
	Social benefits (B_3)	Population density (C_9)	Characterize the population concentration of the evaluation unit	$I = P/S$; P is the total population and S is the area of the evaluation unit.
		Greening ratio (C_{10})	Characterize the greening level of the evaluation unit	$I = S_g/S$; S_g is the green space area and S is the area of the evaluation unit.
		Public-service facilities aggregation (C_{11})	Characterize the life convenience of the evaluation unit	$I = \sum_{i=1}^{k} N_i / S$; N is the number of public-service facility points and S is the land area.
Supply level – land-attribute (A_2)	Land conditions (B_4)	Plot shape (C_{12})	Characterize the regularity degree of the evaluation unit	$I = A/S$; A is the plot perimeter and S is the area of the evaluation unit.
		Plot size (C_{13})	Characterize the size of the evaluation unit	$I = S$; S is the land area.
		Land development intensity (C_{14})	Characterize the land development status of the evaluation unit	$I = \sum_{i=1}^{N} F_i / S$; F_i is the building area, N is the total number of buildings, S is the area of the evaluation unit.
	Geological conditions (B_5)	Elevation (C_{15})	Characterize the height of the evaluation unit relative to the reference plane	$I = h$; h is the elevation.
		Slope (C_{16})	Characterize the topographic relief of the evaluation unit	$I = h'/l \times 100\%$; h' is the elevation difference and l is the horizontal distance.

For negative indices (smaller is better)

$$b_{ij} = \max(r_{ij}) - r_{ij} / \max(r_{ij}) - \min(r_{ij}). \quad (3)$$

2) Weighting the normalized matrix
Due to the weight difference of indices under different compound use modes, the normalization matrix should be weighted, and the weights of n indices are w_1, w_2, …, w_n, respectively, and the weighted matrix is as follows:

$$Z = (z_{ij})_{m\times n} = (w_j * z_{ij})_{m\times n} = \begin{bmatrix} w_1 b_{11} & w_2 b_{12} & \dots & w_n b_{1n} \\ w_1 b_{21} & w_2 b_{22} & \dots & w_n b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_1 b_{m1} & w_2 b_{m2} & \dots & w_n b_{mn} \end{bmatrix}. \quad (4)$$

3) Calculating the potential value
The positive ideal solution Z^+ and the negative ideal solution Z^- of the weighted normalization matrix Z are denoted as follows:

$$\left.\begin{array}{l} Z^+ = [\max(z_{ij})] = \{c_1^+, \ c_1^+, \dots, \ c_n^+\} \\ Z^- = [\min(z_{ij})] = \{c_1^-, \ c_1^-, \dots, \ c_n^-\} \end{array}\right\}. \quad (5)$$

For each $z_i \in Z$, the Euclidean distance is calculated to the positive ideal solution D_i^+ and the negative ideal solution D_i^-

$$D_i^+ = \sqrt{\sum\nolimits_{j=1}^{n} \left(z_{i,j} - z_j^+\right)^2} \quad (6)$$

$$D_i^- = \sqrt{\sum\nolimits_{j=1}^{n} \left(z_{i,j} - z_j^-\right)^2}. \quad (7)$$

Finally, the potential value E_i of each evaluation object is calculated

$$E_i = D_i^- / \left(D_i^+ + D_i^-\right) \quad 0 \le E_i \le 1 \quad (8)$$

b) Uncertainty analysis based on MCS: The index weights are the only subjective input in the TOPSIS method. Considering the uncertainty of index weights, random sampling was conducted within the possible value range of the weight variables, and MCS was used to carry out the TOPSIS method multiple times to obtain multiple evaluation values and finally to obtain the stable ranking results of UMICU potential. The MCS method is as follows.

1) Assume that the functional relationship between UMICU potential Y and index weight variables $x_1, x_2 \dots, x_n$ is $Y = f(x_1, x_2, \dots, x_n)$
where $x_1, x_2 \dots, x_n$ are n mutually independent random variables, $0 < x_1, x_2 \dots, x_n < 1$, $x_1 + x_2 + \dots + x_n = 1$, and indices have different importance for different compound use modes (see Table IV). For example, in mode I, x_1–x_3 and x_9–x_{10} are greater than the remaining index weights; then, a set of random number sequences $\{x_1, x_2, \dots, x_n\}$ conforming to this distribution can be generated by using Python.
2) An evaluation result Y is generated by entering random number sequences $\{x_1, x_2, \dots, x_n\}$ obtained by sampling into the function $Y = f(x_1, x_2, \dots, x_n)$.

TABLE IV
DIFFERENCES IN THE REQUIREMENTS OF INDICES FOR DIFFERENT COMPOUND USE MODES

Compound use modes	Environmental benefits			Economic benefits					Social benefits			Land conditions			Geological conditions	
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
Mode I	√	√	√	-	-	-	-	-	√	√	-	-	-	-	-	-
Mode II	-	-	-	√	√	√	√	√	√	-	-	√	√	√	√	√
Mode III	-	-	-	-	-	-	-	-	√	-	√	√	√	√	√	√
Mode IV	-	-	-	-	-	-	-	-	-	-	-	√	√	√	√	√

"-" indicates that the mode has general requirements for the corresponding indices, and " √ " indicates that the mode has high requirements for the corresponding indices.

3) N sampling using a Python random number generator generates N sets of random number sequences $\{x_1^i, x_2^i, \ldots, x_n^i\}$, $(i = 1, 2, \ldots, N)$ and finally N random numbers of $\{y_1, y_2, \ldots, y_n\}$

$$\begin{cases} y_1 = f\left(x_1^1, x_2^1, \ldots, x_n^1\right) \\ y_2 = f\left(x_1^2, x_2^2, \ldots, x_n^2\right) \\ \ldots \\ y_N = f\left(x_1^N, x_2^N, \ldots, x_n^N\right). \end{cases}$$

4) When the simulation number N is large enough, this set of sampling data can be used for statistical analysis to calculate the statistical characteristic values (average, maximum, minimum, etc.) of Y.

Weight sampling was performed using the Saltelli sampling method [60], which requires running the TOPSIS evaluation model $N \times (n + 2)$ times, where N is the number of MCS samples and n is the number of indices. In this article, n was 16, and N was set to 5000, which generated a mixed matrix of $N \times (n + 2) \times n = 90\,000 \times 16$ as the input of the MCS. MCS was performed 90 000 times, and 90 000 TOPSIS evaluation results were obtained.

The final UMICU potential was determined based on the statistical characteristic values of the large number of simulation evaluation results. The specific classification method is as follows: the maximum, minimum and average values are divided into three levels (high, medium and low values) by the GIS standard classification method, and the UMI plots with high average values and high minimum values in a large number of simulations (i.e., these plots always have high evaluation values) are classified as high-potential areas; the UMI plots with low average values and low maximum values (i.e., these plots always have low evaluation values) are classified as low-potential areas; other UMI plots are classified as medium-potential areas.

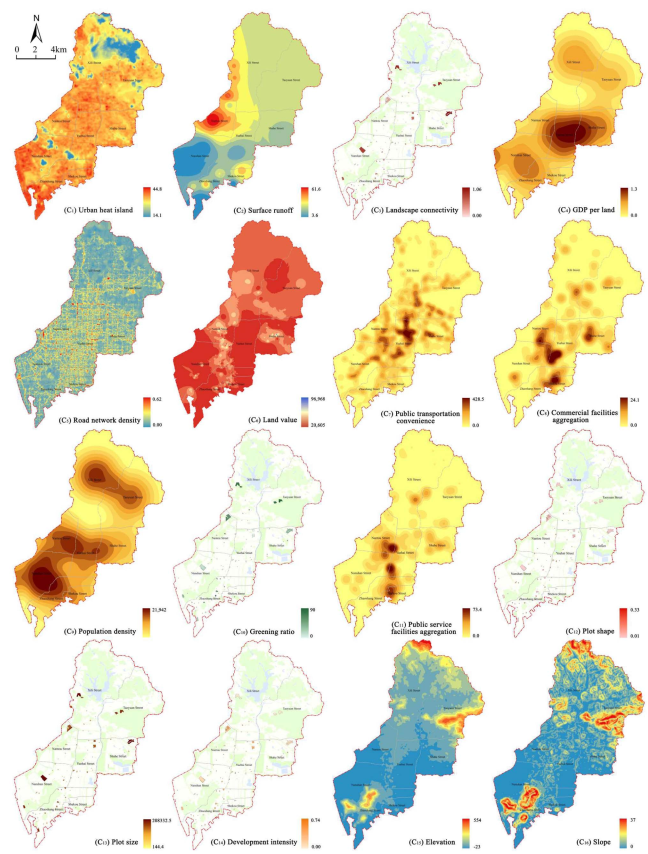

Fig. 3. Quantitative values of UMICU potential indices.

IV. RESULTS

A. Spatial Distribution of Potential Land for UMICU

Fig. 1 shows the spatial distribution of UMI suitable for compound use considering livelihood safety, public health, and technical feasibility. A total of 128 UMI plots were identified, with a total area of 185.85 hm^2, accounting for 1.52% of the total area of urban construction land in Nanshan District in 2021. The spatial distribution of these plots was unevenly distributed, mainly concentrated in Nanshan Street (25 plots), Zhaoshang Street (28 plots) and Nantou Street (17 plots), covering areas of 50.69, 27.72, and 25.11 hm^2, respectively. In comparison, Shekou Street had the smallest area of potential plots for UMICU, with 7 plots covering an area of 1.54 hm^2.

B. Quantitative Results of UMICU Potential Indices

The calculation results of the UMICU potential index are shown in Fig. 3. The surface temperature in Nanshan District ranged from 14.1 to 44.8 °C (C_1), with the ultrahigh temperature area concentrated in the southwestern part of Nanshan and Shekou streets and the low-temperature area was mainly in the northern hill basin area with high plant cover (C_{10}). Surface runoff varied significantly among streets under the 2-year return

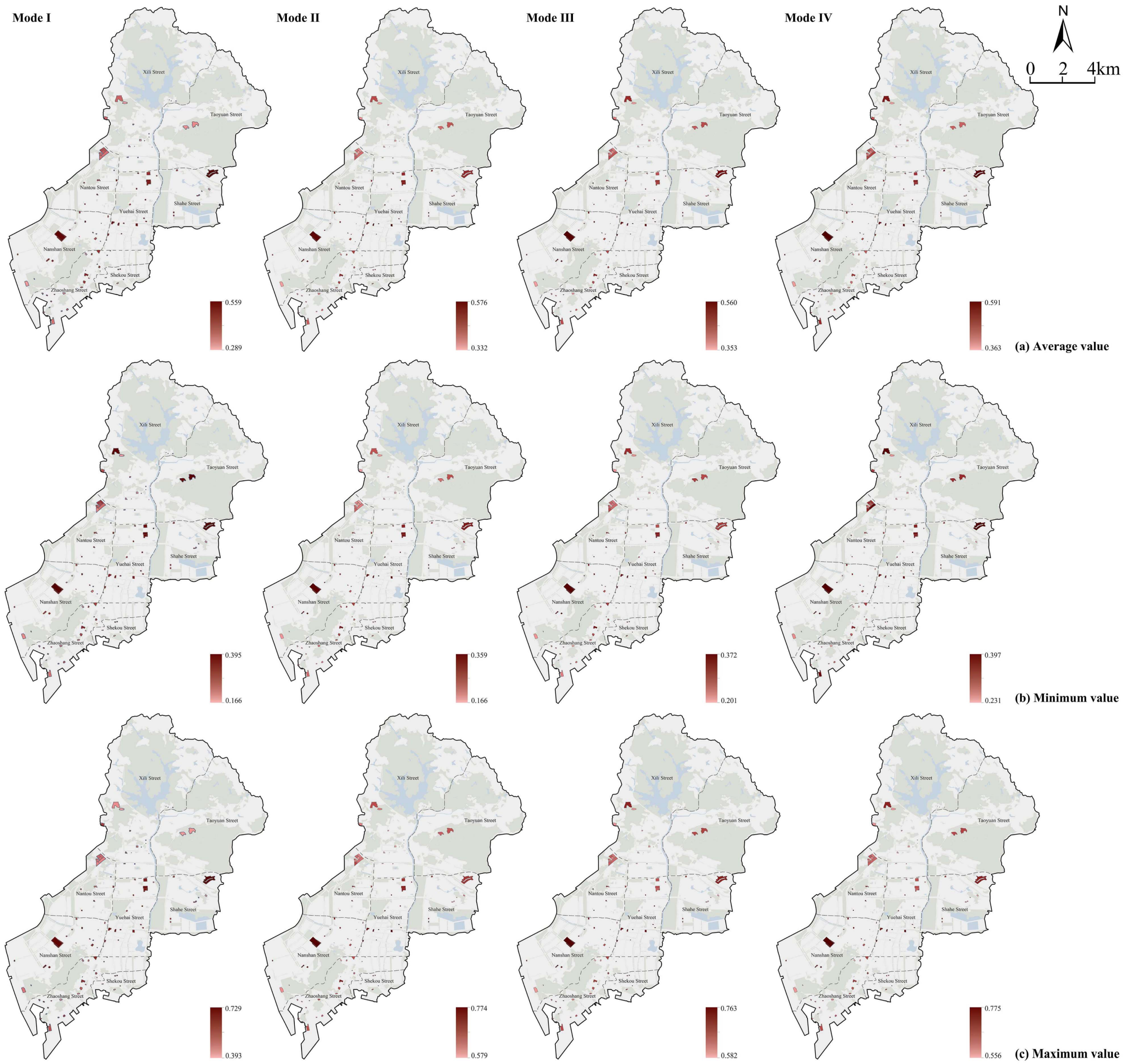

Fig. 4. Statistical characteristic values of UMICU potential under four compound use mode.

period rainfall event, with the highest average surface runoff in Nantou Street, implying a higher risk of flooding, and the smallest was in Nanshan Street (C_2). The size of the evaluation unit and the distance from the green space directly affected its landscape connectivity (C_3). The Shenzhen Bay CBD located in Yuehai and Shahe streets had the highest GDP per land (C_4), and the road network was generally dense in the middle and gradually decreased in density toward the north and south, with traffic convenience gradually deteriorating (C_5). Land values were significantly lower in the north than in the south. Among them, Yuehai Street had the highest land value (C_6) and the highest public-transportation convenience (C_7) and was a high-tech industrial development zone with a concentration of universities and high-tech industries. The spatial distribution of commercial facilities (C_8) and public-service facilities (C_{11}) was similar, mainly concentrated in Shekou, Yuehai, and Nantou streets, while Nanshan Street was the most densely populated (C_9). In addition, the shape (C_{12}), size (C_{13}), development intensity (C_{14}), elevation (C_{15}), and slope (C_{16}) of the evaluation unit directly reflect the development potential of the plot.

C. UMICU Potential Analysis Under Different Compound Use Modes

Under four compound use modes, park renovation (mode I), commercial development (mode II), public-service compound (mode III), and municipal compound mode (mode IV), 90 000 MCSs generated 90 000 scores for each evaluation unit, and the statistical characteristic values of these scores could be calculated (see Fig. 4). The relative ranking value of UMICU potential

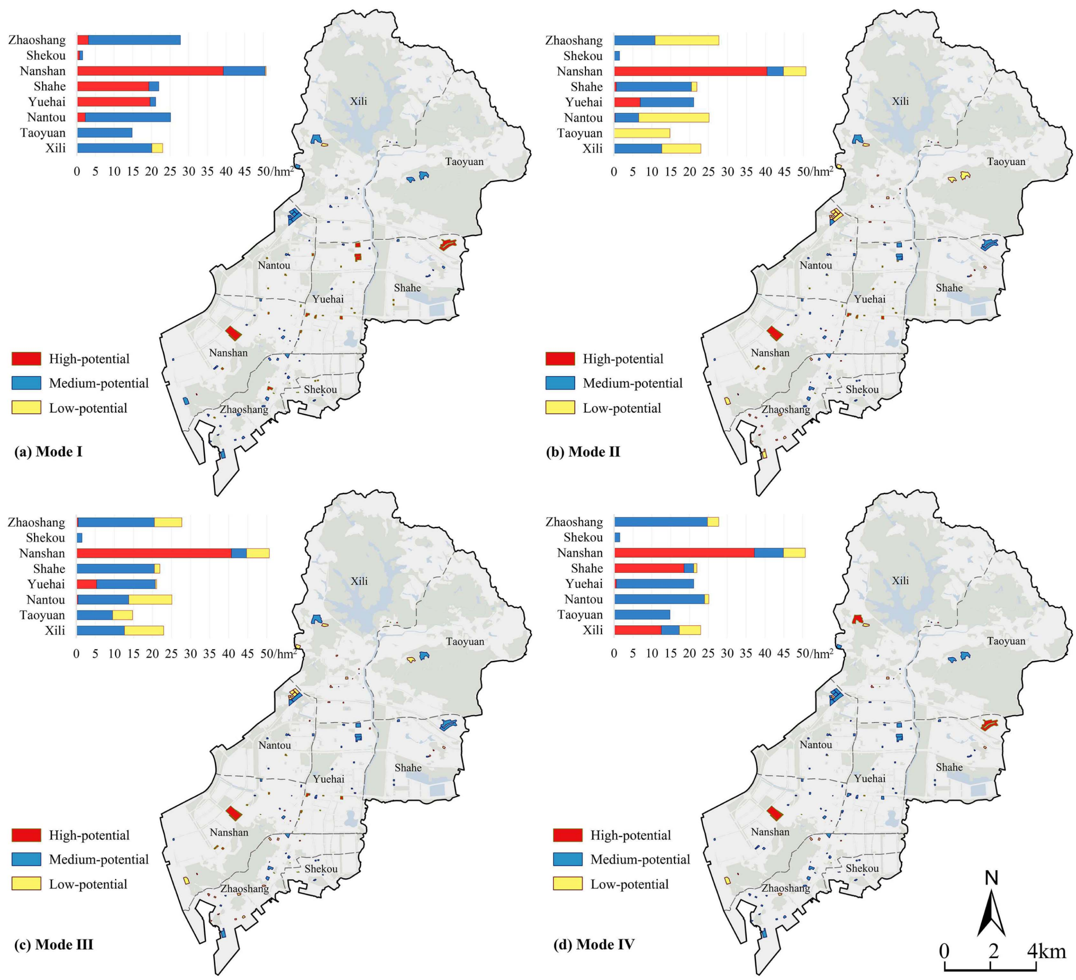

Fig. 5. Classification of UMICU potential under four compound use modes.

is more meaningful than the absolute score for decision-makers. Therefore, the average value of 90 000 scores was the final potential ranking value [see Fig. 4(a)]. In addition, high-value units of the average value and of the minimum value [see Fig. 4(b)] were classified as the high-potential area; low-value units of the average value and of the maximum value [see Fig. 4(c)] were classified as the low-potential area; and the others were classified as the medium-potential area.

Under the park renovation mode [mode I, Fig. 5(a)], the areas of high-, medium-, and low-potential plots were 84.28, 98.45, and 3.12 hm^2, accounting for 45.3%, 53.0%, and 1.7%, respectively, indicating that most evaluation units in the study area had higher potential for park renovation. Among them, there were 46 high-potential plots, mainly located in Qianhai with a significant heat-island effect and Yuehai Street with insufficient green space. Under the commercial development mode [mode II, Fig. 5(b)], the areas of high-, medium-, and low-potential plots were 48.54, 69.46, and 67.85 hm^2, respectively, which were relatively balanced. Among them, the high-potential plots were concentrated in the Shenzhen Bay CBD, which has good transportation conditions, perfect facilities and obvious location advantages. Under the public-service compound mode [mode III, Fig. 5(c)], the areas of high-, medium- and low-potential plots were 47.26, 96.70, and 41.89 hm^2, respectively. High-potential plots were concentrated in densely populated Nanshan and Yuehai streets. Under the municipal compound mode [mode IV, Fig. 5(d)], the high-, medium- and low-potential areas were 69.02, 100.50, and 16.32 hm^2, accounting for 37.1%, 54.1%, and 8.8%, respectively, and the high-potential plots were mostly used for large-scale UMI.

Street statistics showed that under all four compound use modes, the area of high-potential plots of Nanshan Street, where Qianhai is located, was the highest. The area of low-potential plots under the park transformation mode was the lowest, which is located in Nanshan and Xili streets, while under the commercial development mode, the area of low-potential plots was the highest, mainly concentrated in Zhaoshang, Nantou, and Taoyuan streets.

V. Discussion

A. Methods of UMICU Potential Evaluation

To maximize the benefits of construction land, the compound use potential of inefficient UMI must be evaluated, especially in high-density cities with limited land resources and prominent NIMBY effects [8], [14]. Our proposed approach considers the demand and supply levels and classifies the potential for UMICU into three categories, high, medium, and low potential, under four compound use modes. The presented workflow can be easily applied in other contexts, as the proposed approach allows for the adjustment of the weights and even dimensions by managers and experts. They can modify the proposed dimensions, indices, and weighting relationships according to specific conditions of the unique area or portfolio or given the aims of the prioritization exercise.

In addition, the proposed approach has some advantages when compared with previous research. On one hand, previous research on the compound use of construction land focused on a single optimization mode under the orientation of economic interests [52]. However, there are various optimization modes under different orientations for high-quality development in high-density cities, and different modes have different requirements for indices. In this article, the UMICU potential was evaluated considering four different optimization modes. The results applied to the study area indicated that considering various optimization modes can accurately determine the UMICU orientation. Therefore, the examination of various optimization modes should be incorporated into future renewal and optimization of UMI in high-density cities. On the other hand, the determination of index weights is an important step in UMICU potential evaluation. Most existing evaluation methods regard index weights as a fixed value without considering their uncertainty, which inevitably leads to a certain subjectivity of the results [1]. Therefore, considering the uncertainty of the index weights, a coupled TOPSIS-MCS model was constructed, the weights were simulated stochastically using MCS, and the TOPSIS method was repeated extensively to obtain stable results through the statistical characteristic values of a large number of evaluated values.

B. UMICU-Targeted Strategy Analysis

UMICU is not a blind function combination; it needs to ensure the original professional functions of UMI while allowing citizens to reasonably participate in the use of public functions. Based on the evaluation results, targeted strategies for UMICU need to be developed in conjunction with the selection of compound use mode directions and the guidance for construction-form classification.

Regarding the selection of compound use mode directions, for the plots with high potential under a single compound use mode, the development timing under this mode can be determined according to the ranking results, while for plots with high potential under various compound use modes, priority can be given to the mode with a higher potential score, or a comprehensive development integrated with multiple modes can be carried out in combination with the actual situation of the plots.

In terms of the guidance for construction-form classification, the construction forms of UMICU include four types: separate construction, joint construction, close neighboring construction, and stratified construction (see Fig. 6). Separate construction refers to the state in which different functional facilities or buildings are built separately on the same land plane. Joint construction refers to the state in which different functional facilities or buildings are built together in the same building, but it should be noted that the process flow of this layout may involve special production and operation equipment, such as high temperature and high pressure; therefore, its joint construction has higher process requirements, and the compound construction of such processes should be subject to special studies. Close neighboring construction refers to the state in which different functional facilities or buildings are built adjacent to each other on the same land plane when they meet the requirements of relevant safety production and fire prevention codes. Stratified construction refers to the state of layered construction of different functional facilities or buildings in the vertical space of the same land [10].

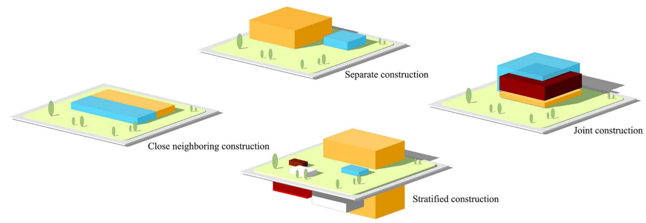

Fig. 6. Construction-form classification for UMICU.

C. Implications for Urban Planning and Design

UMI with large coverage and specialized functions, is recognized as a crucial resource for high-density cities to facilitate urban renewal. However, the increasing social demand for UMICU often clashes with the limited availability of public funds. Therefore, urban planners and managers must prioritize the UMICU based on its potential for compound use. The methodological framework proposed in this paper is of great significance for the scientific planning of UMICU modes, the rational development of design strategies, and the orderly guidance of UMICU practices. On one hand, the measurement results of the potential indicators guide the selection of UMICU modes and the proposal of targeted design strategies, which effectively leverage the unique characteristics of different UMI. On the other hand, the quantitative results of potential evaluation values provide a direct basis for determining the near- and long-term phases of construction. UMICU is prioritized based on their potential value, and a phased construction plan is developed to ensure the flow of funds and alleviate the pressure on investment and finance in a "rolling development from easy to difficult" approach.

D. Directions for Future Research

Future research prospects include the following three aspects. First, with the progress of technical means, the data and information obtained will be enriched, and the evaluation indices should be more reasonable. This study only selects quantitative data and lacks consideration of public willingness and satisfaction. In the future, the index system should be further improved, and the evaluation method and model should be revised to make the evaluation results more scientific and reasonable. Second, regional difference mechanism analysis can be carried out to study influential mechanisms in terms of human factors and physical characteristics of UMICU in the future, which will provide a better understanding of the relationship between input and output variables and will support decision-makers in properly considering and using the results [31]. Third, UMICU is inseparable from the formulation of policies, and the greatest challenge in applying this approach is the property rights division of compound space, while there is a lack of relevant policies in China to give clear guidance to the 3-D development and compound use of construction land. Therefore, laws and regulations, policy systems, and benefit guarantee mechanisms are crucial, and although they are not part of the current study, they are necessary for the implementation of UMICU in high-density cities and should be the focus of future work.

VI. Conclusion

Selecting suitable compound use modes is essential for the high-quality sustainable development of UMI, especially in high-density cities where land resources are scarce and the NIMBY effect is prominent. This article proposes an analytical framework for UMICU, starting from an analysis of suitable UMI-use direction. The framework is divided into four parts, potential land definition, use mode classification, index system calculation, and potential evaluation and grading, forming a complete process from the identification of potential land for UMICU to final optimization strategy development. The empirical results from Shenzhen, China, show that the framework is feasible and effective, and the findings indicate the following.

1) The compound use direction of inefficient UMI should be reasonably determined by combining the environmental, social, and economic benefits at the demand level and the land conditions and geological conditions at the supply level. UMICU can be subdivided into park renovation, commercial development, public-service compound, and municipal compound mode, and the corresponding compound use potential is related to the evaluation results characterizing the land location conditions, traffic convenience, service facility aggregation, and land attributes of evaluation units.
2) In the study area in Nanshan District, Shenzhen, the evaluation scores of UMICU potential under the four compound use modes were calculated by MCSs and the TOPSIS method based on multisource datasets such as geospatial datasets, socioeconomic datasets, remote sensing image datasets, and POI datasets. These multisource datasets comprehensively described the influential factors of the differences in UMICU potential. A total of 90 000 MCS scores helped to select stable, high-potential UMI by voting and finally obtained the potential ranking of all UMI in Nanshan District. Relatively speaking, the area of low-potential plots under the park renovation mode accounted for the lowest percentage (1.7%), while the area of low-potential plots under the commercial development mode accounted for the highest percentage (36.5%). Under all four compound use modes, the area of high-potential plots of Nanshan Street was the highest.
3) The framework proposed in this article can quickly evaluate UMICU potential, rank UMICU evaluation results under different compound use modes in a large-scale area, and provide urban planners and government departments with information on the location, spatial distribution and index values of existing high-potential UMI plots, to scientifically determine the final and most appropriate solutions.

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Jing Dong received the B.S. degree in architecture from Chongqing University, Chongqing, China, in 2014, and the M.S. degree in architecture and the Ph.D. degree in urban and rural planning from Tianjin University, Tianjin, China, in 2016 and 2021, respectively.

Since 2021, she has been a Postdoctoral Researcher with the School of Architecture and Fine Art, Dalian University of Technology, Dalian, China. Her research interests include urban renewal, resilient cities, and ecological city planning.

Bin Zhang received the B.S. degree in civil engineering from Dalian University of Technology, Dalian, China, in 2003, and the M.S. degree in architecture and civil engineering (part-time) from Shenzhen University, Shenzhen, China, in 2008.

Since 2008, he has been a Senior Engineer with the Shenzhen Municpial Engineering Consulting Center Company, Ltd., Shenzhen, China. His research interests include municipal infrastructures, urban renewal, and transportation planning.

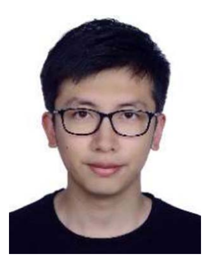
Fei Guo received the B.S. degree in architecture, and the M.S. and Ph.D. degrees in architectural technology science from Tongji University, Shanghai, China, in 2003, 2005 and 2008, respectively.

Since 2008, he has been with the School of Architecture and Fine Art, Dalian University of Technology, Dalian, China, first as a Lecturer, an Associate Professor, since 2011, and a Professor, since 2018. His research interests include building energy efficiency, urban climate, and urban disaster prevention.

Ruonan Guo received the B.S. degree in urban and rural planning from the Hebei University of Engineering, Handan, China, in 2019, and the M.S. degree in urban and rural planning from the Dalian University of Technology, Dalian, China, in 2022. She is currently working toward the Ph.D. degree in architecture in the School of Architecture and Fine Art, Dalian University of Technology.

Jun Cai received the B.S. degree in urban planning from Shandong Jianzhu University, Jinan, China, in 1994, and the M.S. and Ph.D. degrees in urban planning from Tongji University, Shanghai, China, in 1997 and 2005, respectively.

Since 1997, he has been with the School of Architecture and Fine Art, Dalian University of Technology, Dalian, China, first as an Assistant, an Associate Professor, since 2006, and a Professor, since 2013. His research interests include urban and rural transportation planning and land use planning.



Hongchi Zhang received the B.S. degree in architecture from the Shenyang Jianzhu University, Shenyang, China, in 2013, and the M.S. and Ph.D. degrees in architecture from Dalian University of Technology, Dalian, China, in 2016 and 2020, respectively.

Since 2020, he has been a Lecturer with the School of Architecture and Fine Art, Dalian University of Technology, Dalian, China. His research interests include urban space quantification, historical street culture, and urban climate resilience.