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Evaluating and prioritizing interdependent strategies for construction land reduction in China with interdependent sustainability criteria: an integrated multi-criteria decision-making approach

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Construction land reduction (CLR) represents China's ambitious attempt to promote intensive and sustainable land use, yet its implementation faces challenges due to intricate interdependences within land use systems. Under limited management resources, effective strategies must be allocated differentiated efforts and implemented in an optimal sequence. This study proposes a novel integrated multi-criteria decision-making (MCDM) approach to systematically evaluate and prospectively prioritize interdependent alternative strategies with interdependent sustainability criteria. An empirical study of CLR in Shanghai is conducted to demonstrate the practicality of the proposed approach. Using the triple bottom line sustainability dimensions, the study identifies economic, environmental, and social goals as sustainability criteria to evaluate 20 alternative strategies sourced through multiple channels. The findings highlight extensive interdependences between criteria and strategies, and reveal eight priority strategies — involving overall design, financial mobilization, profit motivation, and multi-party co-governance — requiring substantial upfront investment, alongside two long-term strategies addressing system reform necessitating sustained resource allocation. This study provides methodological advancements in strategy evaluation and prioritization while offering managerial insights into CLR practices and sustainable land use.

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Introduction

Land resources are finite natural resources essential for human survival and development, with their sustainable use serving as the foundation for economic prosperity, environmental protection, and social well-being (Hurni, 2000). With the continuous surge in global population and accelerating pace of urbanization, excessive expansion of construction land has been observed worldwide. Global construction land area has nearly doubled over the past three decades (Gong et al., 2020; van Vliet et al., 2024) and is projected to continue for decades driven by socioeconomic factors (Gao and O'Neill, 2020). However, such expansion often occurs at the expense of large-scale encroachment of arable land and massive loss of ecological land (van Vliet, 2019), resulting in a range of adverse consequences including food security threats (Barthel et al., 2019), biodiversity loss (Seto et al., 2012), habitat quality degradation (Chen et al., 2025), carbon imbalance (Zhang and Jin, 2024), and climate change (Ouyang et al., 2022; Huang et al., 2024), which collectively impede sustainable land use (Li et al., 2020; Deng, 2021).

As one of the largest developing countries with a substantial population, China previously followed a crude economic growth pattern and an extensive land use pattern (Song et al., 2018; Yang et al., 2020). Over the past two decades, construction land in China expanded by 147,300 km^2 (Zhou et al., 2023), characterized by a fragmented layout, low land use efficiency, and ecological environmental deterioration (Lin et al., 2022; Niu et al., 2023; Zhang and Han, 2024). Such a traditional incremental development pattern has become increasingly unsustainable, necessitating an urgent shift to an intensive land use pattern aligned with high-quality development. Against this background, construction land reduction (CLR) was proposed as a distinctive national means for China to promote intensive and sustainable land use (Ministry of Land and Resources of the People's Republic of China, 2014), gaining rapid traction primarily in economically developed regions. The core logic of CLR is to rehabilitate inefficient and idle construction land outside urban development boundaries into arable or ecological land through demolition, reclamation, and restoration (Liu et al., 2015; Zheng et al., 2017), thereby creating opportunities for subsequent construction within urban development boundaries (Guo and Tian, 2016). While CLR's overall goal of land use adjustment appears straightforward, the inherent complexity of land use systems — characterized by intertwined economic, environmental, and social dimensions — poses substantial challenges for policymakers. To effectively address these challenges, a series of effective strategies must be identified and implemented to ensure continuous progress and smooth promotion of CLR over a long period. Nevertheless, due to the scarcity of management resources in reality, allocating equal effort simultaneously to all alternative strategies is impractical. Therefore, it is of managerial importance to evaluate and prioritize these strategies to determine optimal resource allocation and implementation sequence from a systemic perspective.

Previous studies have offered valuable insights into CLR, proposing strategies from various perspectives including grassroots response (Zhang et al., 2019), location choice (Wang et al., 2020), sustainable economic development (Wang et al., 2021), rural transformation (M. Xu et al., 2021), key success factors (Li et al., 2022), conflict coordination (Zhou et al., 2022a), barrier management (Zhou et al., 2022b), and risk response (Mu et al., 2024). Despite these contributions, these strategies remain overly detailed and fragmented, lacking systematic organization and arrangement. This requires strategy evaluation and prioritization, which is fundamentally a multi-criteria decision-making (MCDM) problem as it involves evaluating performances and establishing the ordering of alternative strategies based on multiple criteria (Wallenius et al., 2008; Khan, 2018; Xu et al., 2020). Although various MCDM frameworks have been developed and applied (Polat et al., 2017; Fernandez Portillo et al., 2019; Ahmad et al., 2021), they fail to simultaneously handle both criteria and strategic interdependences. As systems theory posits that constituent elements of any system have connections and interrelationships with each other (von Bertalanffy 1968), ignoring these interdependences can distort criteria weights and strategy performances, ultimately leading to suboptimal decisions.

To fill these gaps, this study proposes a novel integrated MCDM approach to systematically evaluate and prospectively prioritize interdependent alternative strategies for CLR with interdependent sustainability criteria under limited management resources. The proposed approach consists of a performance evaluation process — synthesizing fuzzy numbers, best-worst method, fuzzy measures, and decision-making trial and evaluation laboratory — and a strategic planning process realized through a strategic planning matrix. To demonstrate the practicality of the approach, we conduct an empirical study in Shanghai, which has been pioneering the exploration and practice of CLR at the provincial level in response to critical land use pressures resulting from rapid urban expansion. This study contributes methodologically and practically to strategy decision-making studies and CLR practices. Methodologically, the approach is probably unprecedented in integrating both criteria and strategic interdependences into strategy evaluation and prioritization, providing a more comprehensive and accurate depiction of real-world conditions and enabling more reliable strategic decision-making. While applied to Shanghai's CLR in this study, the approach is broadly applicable to other strategy decision-making scenarios. Practically, empirical findings from strategy evaluation and prioritization provide essential managerial guidance for optimal resource allocation and implementation sequence, thereby advancing CLR practices and maximizing their effects on sustainable land use.

The novel integrated approach

Problem conceptualization. According to pluralism theory, policy goals in democratic societies are inherently diverse (Dahl, 1984), particularly in land use policies that broadly target sustainability. The triple bottom line (TBL) sustainability framework transcends the traditional single-bottom-line perspective by integrating economic, environmental, and social dimensions, providing a comprehensive theoretical stance for sustainability performance evaluation (Elkington, 1997). As shown in Fig. 1a, CLR goals align with the TBL sustainability framework, as CLR policies aim to simultaneously address economic efficiency, environmental protection, and social equity (Gu et al., 2022). These three dimensions have been widely adopted as evaluation criteria for CLR projects (Wang et al., 2020; Zhou et al., 2022a, 2022b, 2024; He et al., 2024). Research evidence also demonstrates CLR's far-reaching impacts across all three dimensions: promoting rural financial development, industrial restructuring (Li et al., 2021), improving land use efficiency, reducing pollution intensity (Wang et al., 2021), optimizing egret habitat networks (Wu et al., 2018), and enhancing social mobility (Lu et al., 2023). Moreover, these dimensions exhibit complex interdependences: economic development may conflict with environmental protection, while social considerations can complicate both economic and environmental outcomes (Gu et al., 2022). As pathways to achieving these dimensional goals, CLR strategies should be adopted in an optimal sequence, as earlier strategies can facilitate the implementation of subsequent ones (Chandra et al., 2022).

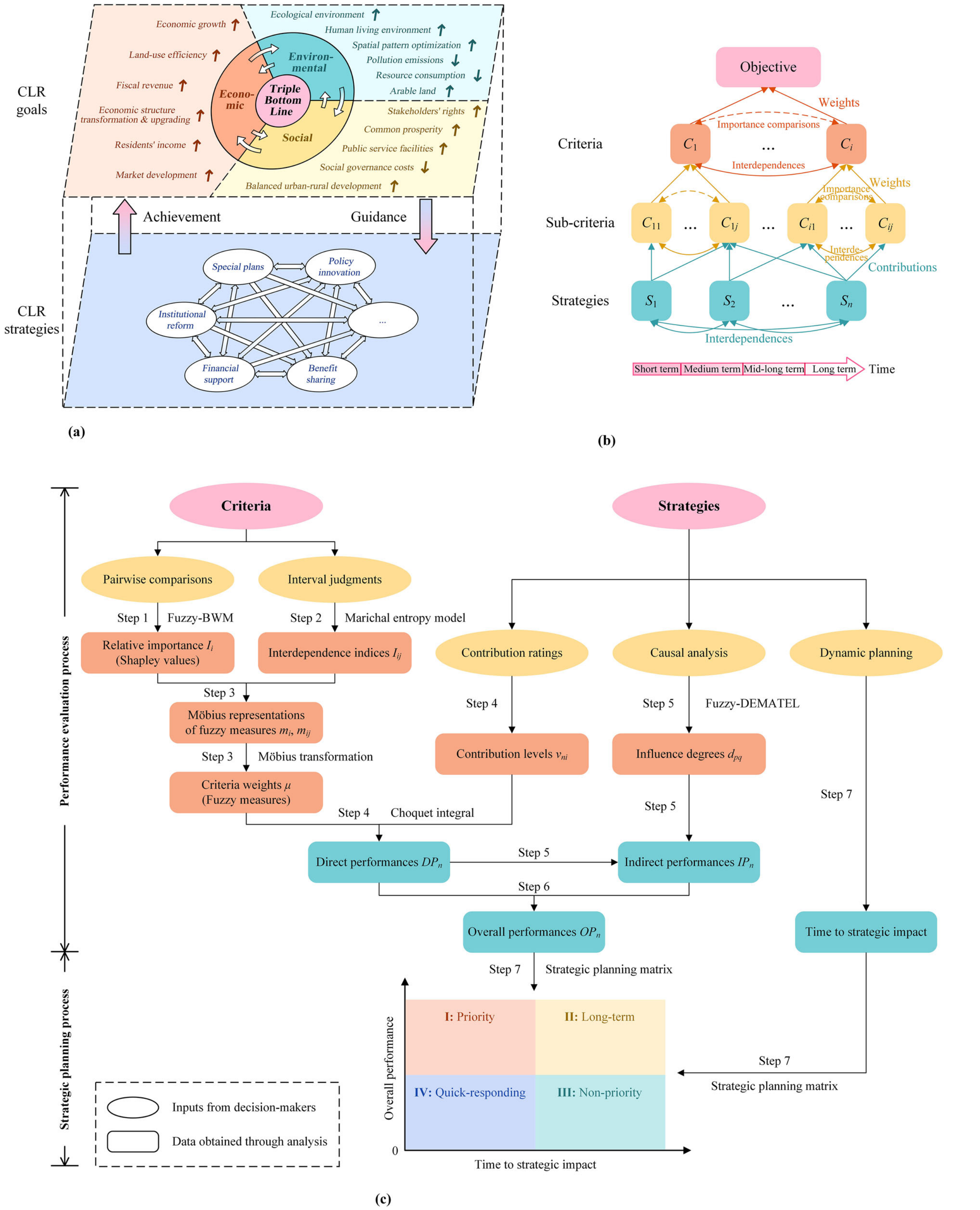

Fig. 1 The proposed novel integrated approach. a Relationships between CLR goals and strategies under TBL sustainability framework. **b** Conceptualized novel MCDM framework. **c** Flowchart of the proposed integrated approach.

This real-world issue is further conceptualized as a novel MCDM problem, as shown in Fig. 1b. The objectives comprise multiple criteria, each with its relative importance and interdependences. Therefore, determining criteria weights requires comparisons of their importance and assessment of their interdependence indices. As strategies aim to achieve multiple criteria, their contribution levels with respect to criteria and influence degrees on other strategies together form the basis for evaluating their performances. Incorporating strategy performances with temporal considerations further facilitates prospective strategic planning. As detailed in Supplementary Material S1.1, the major novelty of this MCDM problem lies in simultaneously handling criteria and strategic interdependences, a limitation that current mainstream MCDM methods cannot resolve, thereby necessitating a novel integrated approach.

Methodological framework. The proposed integrated approach consists of a performance evaluation process and a strategic planning process, as illustrated in the flowchart in Fig. 1c.

The purpose of the first process is to evaluate the performances of interdependent alternative strategies for CLR with interdependent sustainability criteria. In the absence of historical data, decision information in MCDM methods typically derives from decision-makers' judgments. However, the complexity and uncertainty of objective things, combined with the fuzziness of human thinking, lead to imprecise decision information (Guo and Zhao, 2017). Fuzzy set theory, introduced by Zadeh (1965), models uncertainty by allowing for partial membership in sets, offering a better way to represent incomplete decision information (Bellman and Zadeh, 1970). Therefore, the foundation of the performance evaluation process is rooted in fuzzy set theory. As a fundamental component of fuzzy set theory, triangular fuzzy numbers (TFNs) are characterized by triplets (l, m, u), representing the lowest possible, most likely, and highest possible values, offering a favorable balance between computational simplicity and interpretative effectiveness (Zadeh, 1965). In Step 1, TFNs are integrated into the best-worst method (Fuzzy-BWM), a recent pairwise comparison technique with advantages of fewer comparisons and reduced redundancy (Guo and Zhao, 2017), to assess the relative importance of criteria. As another key component of fuzzy set theory, fuzzy measures replace traditional additivity with weaker monotonicity and continuity (Sugeno, 1974), enabling the modeling of both individual criterion importance and collective importance of criteria sets (Xu et al., 2018). Focusing on pairwise interdependences, 2-additive fuzzy measures simplify complex fuzzy measures while retaining the expressiveness of criteria interdependences (Grabisch, 1997), thereby significantly reducing the number of judgments required and facilitating decision-makers' rating process. As such, 2-additive fuzzy measures are employed to identify interdependence indices between criteria pairs in Step 2, and to integrate the relative importance and interdependence indices to establish interdependent criteria weights in Step 3. Based on the criteria weights, the Choquet integral, a non-linear integration operator for fuzzy measures (Choquet, 1954), is employed in Step 4 to aggregate decision-makers' assessed contribution levels to determine the direct performances of strategies. For strategic interdependences, TFN-based decision-making trial and evaluation laboratory (Fuzzy-DEMATEL) is considered an effective method for analyzing causal relationships between complex factors. By constructing relation matrices, this method converts the interrelationships between factors into an understandable system structure, thereby clarifying logical connections between factors and quantifying the influence degrees of causal factors on effect factors (Wu and Lee, 2007). In Step 5, Fuzzy-DEMATEL is thus applied to measure the influence degrees between strategies and integrate them with direct performances to derive indirect performances of strategies. By summing direct and indirect performances, the overall performances of strategies are derived in Step 6.

The purpose of the second process is to prioritize and plan the strategies to be implemented under limited management resources, which is achieved through a strategic planning matrix. The strategic planning matrix is a structured tool that helps organizations to prioritize and plan their strategies by systematically integrating various dimensions (David, 1986), and can be adapted to different situations (Chang et al., 2007; Y. Xu et al., 2021; Zhou et al., 2022b). Therefore, in Step 7, depending on their overall performance and time to strategic impact, all strategies are categorized into different zones of a strategic planning matrix with varying priorities.

Preliminary knowledge of all fundamental methods employed and detailed explanations of their applicability are provided in Supplementary Material S1.2. The specific steps of the proposed integrated approach are as follows.

Performance evaluation process. Suppose that a finite set C of criteria C_i ($i = 1, 2, \ldots, K$) and a finite set S of strategies S_n ($n = 1, 2, \ldots, N$) have been provided by decision-makers.

Step 1: Assessing the relative importance of criteria to measure Shapley values. The assessment of relative importance of criteria relies on the decision-makers' selection of reference criteria and fuzzy reference comparisons. From the criteria set C, the most important criterion and least important criterion are first identified by the decision-makers as the best criterion C_B and worst criterion C_W, respectively. By using the linguistic terms of decision-makers listed in Table 1a, the fuzzy preferences $\tilde{a}_{Bi}$ of the best criterion C_B over all the criteria and the fuzzy preferences $\tilde{a}_{iW}$ of all the criteria over the worst criterion C_W are determined. The following optimization model is then constructed to derive the optimal relative importance I_i of criteria that best aligns with all fuzzy preferences.

$$\min \tilde{\xi} \quad s.t. \begin{cases} \left|\frac{\tilde{I}_B}{\tilde{I}_i} - \tilde{a}_{Bi}\right| \leqslant \tilde{\xi} \\ \left|\frac{\tilde{I}_i}{\tilde{I}_W} - \tilde{a}_{iW}\right| \leqslant \tilde{\xi} \\ \sum_{i=1}^{K_i} I_i = 1 \\ l_i \leqslant m_i \leqslant u_i \\ l_i \geqslant 0 \\ i = 1, 2, \cdots, \mathrm{K_i} \end{cases}, \tag{1}$$

where $\tilde{\xi} = (l_\xi, m_\xi, u_\xi)$ represents the maximum absolute deviation between the ratios of all optimal relative importance values and their fuzzy preferences, which should be minimized; $\tilde{a}_{Bi} = (l_{Bi}, m_{Bi}, u_{Bi})$ and $\tilde{a}_{iW} = (l_{iW}, m_{iW}, u_{iW})$ are fuzzy preferences; $\tilde{I}_B = (l_B, m_B, u_B)$, $\tilde{I}_i = (l_i, m_i, u_i)$, and $\tilde{I}_W = (l_W, m_W, u_W)$ are fuzzy relative importance; $I_i = \frac{l_i + 4m_i + u_i}{6}$ are crisp relative importance.

As the obtained optimal importance reflects the marginal contribution of criteria to the overall criteria set, coupled with the consistency of mathematical properties, relative importance has been considered an effective measure of Shapley values (Zhang and Yang, 2013). Therefore, the values of relative importance

Table 1 Linguistic terms and transformation rules for decision-makers' judgments.

(a) Criteria pairwise comparisons

Linguistic term	Equally important		Weakly important		Moderately important		Strongly important		Extremely important
TFN	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(3, 4, 5)	(4, 5, 6)	(5, 6, 7)	(6, 7, 8)	(7, 8, 9)	(8, 9, 10)

(b) Criteria interdependence judgments

Linguistic term	Completely substitutive (CS)	Strongly substitutive (SS)	Moderately substitutive (MS)	Weakly substitutive (WS)	Non-interdependent (N)	Weakly complementary (WC)	Moderately complementary (MC)	Strongly complementary (SC)	Completely complementary (CC)
Interval	$[-l^B_{ij}, -7/9l^B_{ij}]$	$[-7/9l^B_{ij}, -5/9l^B_{ij}]$	$[-5/9l^B_{ij}, -3/9l^B_{ij}]$	$[-3/9l^B_{ij}, -1/9l^B_{ij}]$	$[-1/9l^B_{ij}, 1/9l^B_{ij}]$	$[1/9l^B_{ij}, 3/9l^B_{ij}]$	$[3/9l^B_{ij}, 5/9l^B_{ij}]$	$[5/9l^B_{ij}, 7/9l^B_{ij}]$	$[7/9l^B_{ij}, l^B_{ij}]$

(c) Strategic contribution ratings

Linguistic term	None (N)	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)
Value	0	1	2	3	4	5

(d) Strategic interdependence judgments

Linguistic term	No influence (N)	Low influence (L)	Medium influence (M)	High influence (H)	Very high influence (VH)
TFN	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.75, 1, 1)

The TFNs (1, 2, 3), (3, 4, 5), (5, 6, 7), and (7, 8, 9) in the criteria pairwise comparisons correspond to the importance between linguistic terms on the neighboring sides. According to Definition 3.4 in Supplementary Material S1.2, $l^B_{ij} = \min\left\{\frac{2I_p}{K-1}, \frac{2I_q}{K-1}\right\}$.

serve as the Shapley values I_i of criteria required for fuzzy measures in our approach.

Step 2: Assessing the interdependence indices between criteria. The assessment of criteria interdependences combines decision-makers' subjective interval judgments with objective entropy maximization, ensuring reliable evaluation of intangible complex interactions. The interdependent effect of criteria pair C_i, C_j ($i, j = 1, 2, \ldots, K, i \neq j$) is assessed by using the linguistic terms of decision-makers listed in Table 1b to obtain the interval $[l_{ij}, u_{ij}]$ of interdependence index of the criteria pair. To specify the optimal interdependence index I_{ij} of the criteria pair, the following optimization model is developed to maximize the Marichal entropy, which is meant to achieve the maximization of the amount of information and uncertainty contained in 2-additive fuzzy measures (Marichal, 1998; Marichal and Roubens, 1999).

$$\max \sum_{i=1}^{K} \sum_{S \subset C \setminus C_i} \frac{(K-|S|-1)!|S|!}{K!} \cdot h\left[I_i - \sum_{C_j \in C \setminus S} \frac{I_{ij}}{2} + \sum_{C_j \in S} \frac{I_{ij}}{2}\right], \quad s.t. \begin{cases} I_{ij} \in [l_{ij}, u_{ij}] \\ C_i, C_j \in C, \ i \neq j \end{cases} \tag{2}$$

where $h(x) = -x\ln(x)$.

Step 3: Calculating fuzzy measures to obtain the weights of criteria. Based on the Shapley value I_i of each criterion and interdependence index I_{ij} of each criteria pair, the Möbius representations m_i, m_{ij} of 2-additive fuzzy measures for individual criteria and criteria pair is obtained as

$$\begin{cases} m_{ij} = I_{ij} \\ m_i = I_i - \sum \frac{m_{ij}}{2} \end{cases}. \tag{3}$$

The 2-additive fuzzy measures $\mu(S)$ of subsets S of the criteria set C ($S \subset C$) are derived through the transformation from Möbius representations as

$$\mu(S) = \sum_{i \in S} m_i + \sum_{i,j \in S} m_{ij}. \tag{4}$$

Due to their ability to simultaneously capture both the relative importance of criteria and interdependence indices, fuzzy measures serve as criteria weights with criteria interdependence consideration. When criteria system consists of multiple levels, criteria weights are calculated separately at each level.

Step 4: Measuring the direct performances of strategies. The direct performance of a strategy is obtained by aggregating the contribution levels of the strategy with respect to each criterion. The linguistic terms of decision-makers listed in Table 1c are used by decision-makers to rate the contribution levels v_{ni} of strategy S_n with respect to criterion C_i. Using the corresponding criteria weights obtained in Step 3 to aggregate these contribution levels, the direct performance DP_n of S_n is derived by applying the Choquet integral as

$$DP_n = \sum_{i=1}^{K} \left[v_{n(i)} - v_{n(i-1)}\right] \cdot \mu(S_{(i)}), \tag{5}$$

where (i) is the subscript of $v_{n(i)}$ that satisfies $0 \leq v_{n(i)} \leq \ldots \leq v_{n(K)}$; $S_{(i)} = \{C_{(i)}, \cdots, C_{(K)}\}$; $v_{n(0)} = 0$. When multiple criteria levels are involved, direct performances are calculated progressively from lower to higher hierarchical levels.

Step 5: Measuring the indirect performances of strategies. The indirect performance of a strategy through other strategies it influences is determined by its total influence degrees on other

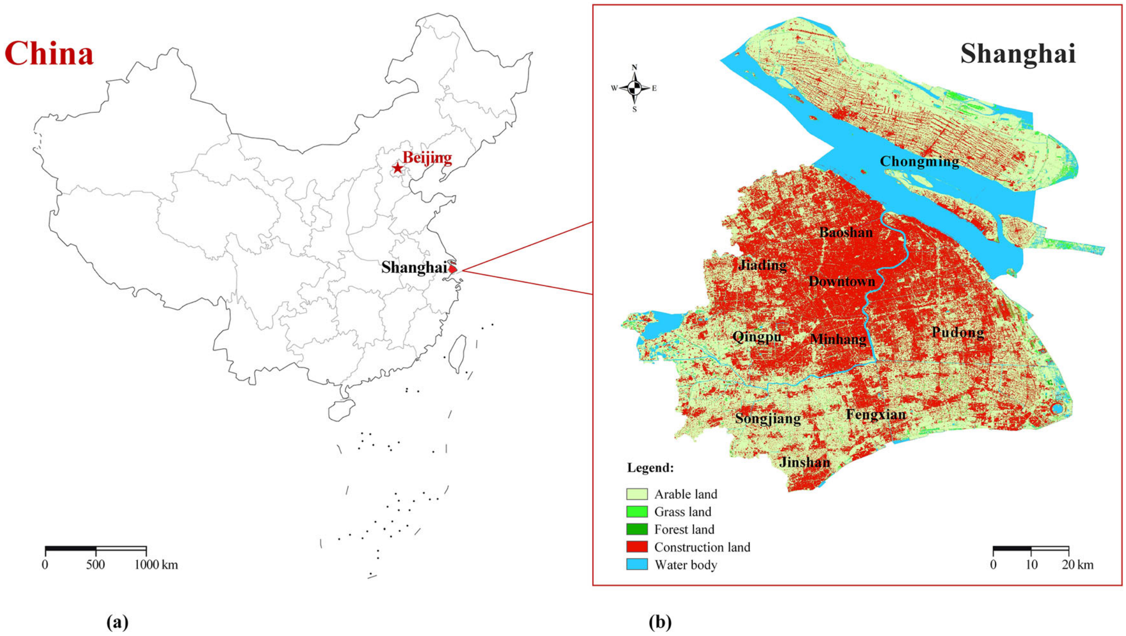

Fig. 2 Study area. a Geographical location of the study area. **b** Land use distribution in the study area in 2020.

strategies and the direct performances of the influenced strategies. Total influence degrees are determined by direct influence degrees and matrix calculations of mediating effects through Fuzzy-DEMATEL.

The fuzzy direct influence degree $\widetilde{d}_{pq} = (l_{pq}, m_{pq}, u_{pq})$ of strategy S_p on strategy S_q (p, $q = 1, 2, \ldots, N$) is first assessed using the linguistic terms of decision-makers listed in Table 1d, which is then defuzzified into the crisp direct influence degree d_{pq} as

$$d_{pq} = \alpha m_{pq} + (1-\alpha)[(1-\beta)l_{pq} + \beta u_{pq}], \quad (6)$$

where $\alpha, \beta \in [0, 1]$ represent the α-cut value and attitude index, respectively. These parameters indicate the certainty and attitude of decision-makers' assessment, with larger values representing a higher degree of certainty and a more optimistic attitude, respectively. Typically, a median value of 0.5 is used to represent a moderate degree of certainty and a neutral attitude (Yeh and Xu, 2012). Next, the direct-relation matrix D, formed by the crisp direct influence degrees d_{pq}, is calculated to derive the total-relation matrix T as

$$A = D \times \min\left(\frac{1}{\max \sum_{q=1}^{N} d_{pq}}, \frac{1}{\max \sum_{p=1}^{N} d_{pq}}\right), \quad (7)$$

$$T = A \times (I - A)^{-1}, \quad (8)$$

where A is the normalized direct-relation matrix, I is $N \times N$ unit matrix, and t_{pq} in T represents the total influence degree of strategy S_p on strategy S_q. Finally, the indirect performance IP_p of strategy S_p is obtained by summing all the products of the total influence degrees t_{pq} of strategy S_p on strategies S_q influenced by S_p and the direct performances DP_q of strategies S_q as

$$IP_p = \sum_{q=1}^{N} t_{pq} \cdot DP_q. \quad (9)$$

Step 6: Obtaining the overall performance of strategies. The overall performance OP_n of strategy S_n is determined by summing its direct performance DP_n and indirect performance IP_n as

$$OP_n = DP_n + IP_n. \quad (10)$$

Strategic planning process

Step 7: Prospective planning of strategies. As shown in the strategic planning process in Fig. 1c, a strategic planning matrix for CLR is constructed with overall performance as the vertical axis and time to strategic impact as the horizontal axis. Such a setting helps to clarify the priorities of strategies by balancing their effectiveness and efficiency under limited management resources. The strategic planning matrix is divided into four strategic planning zones by the arithmetic mean of the overall performances and the medium time to strategic impact - (I) Priority zone, (II) Long-term zone, (III) Non-priority zone, and (IV) Quick-responding zone. Given the overall performances obtained in Step 6 and the time to strategic impact assessed by decision-makers, the strategies are categorized into the four strategic planning zones, and can be selected for implementation with different priorities.

Empirical study

Study area. To demonstrate the practicality of the approach, we conduct an empirical study in Shanghai, a typical CLR area. As China's largest economic center, Shanghai has undergone unprecedented urban expansion following its rapid economic growth. Despite land use efficiency being at the forefront within China (Guo et al., 2025), Shanghai's current construction land approaches 50% of its total land area (Fig. 2), significantly exceeding the 20–30% benchmark observed in other global metropolises such as London, Paris, and Tokyo. Shanghai's past development progressed at the expense of high industrial land consumption and inadequate arable and ecological land resources, potentially approaching the carrying limits of resources and the environment. Moreover, Shanghai's escalating land transaction values signal substantial demand for construction land driven by continued population influx. To transform the city's development patterns and further enhance land use efficiency, Shanghai has been pioneering the exploration and practice of CLR at the provincial level in China (Wang et al., 2016; Zhang et al., 2019). These efforts have yielded

Table 2 Sustainability criteria for evaluating CLR strategies.

Criterion		Sub-criterion		Definition	Key references
C_1	Economic	C_{11}	Promoting economic growth	Although CLR may temporarily suppress regional economic growth through the closure of inefficient or highly polluting enterprises, it generates long-term effects by stimulating corporate innovation and productivity, ultimately driving regional economic growth.	Wang et al. (2019)
		C_{12}	Improving land use efficiency	CLR is expected to improve land use efficiency by strictly controlling the total amount of construction land, gradually reducing the scale of new construction land, improving the turnover efficiency of construction land turnover quota, optimizing the stock of construction land, and improving the quality of construction land.	Zhang et al. (2019), Wang et al. (2020)
		C_{13}	Increasing fiscal revenue	CLR is expected to contribute to revenue growth by generating high land grant revenues in the short term and expanding the tax base in the long term.	Wang et al. (2019)
		C_{14}	Increasing residents' income	CLR is expected to increase the value of residential housing and income from land rentals, land turnover, house rentals, wages, etc.	Guo and Tian (2016)
		C_{15}	Promoting economic structure transformation and upgrading	CLR is expected to eliminate backward industries and optimize regional resource allocation, thereby promoting economic structural transformation and upgrading.	Wang et al. (2020), Li et al. (2021)
		C_{16}	Promoting land market development and real estate market development	CLR is expected to increase the supply of high-quality construction land and boost the entry of collective construction land into the land market, thereby promoting land market development and real estate market development.	Guo (2020)
C_2	Environmental	C_{21}	Protecting arable land	CLR is expected to increase the area of arable land and improve the quality of arable land through engineering techniques such as land reclamation.	Wang et al. (2016), Gu et al. (2022)
		C_{22}	Reducing pollution emissions	CLR is expected to shut down or renovate highly polluting industrial enterprises, thereby reducing pollution emissions including air pollution, water pollution, soil pollution, noise pollution, etc.	Zhang et al. (2019), Wang et al. (2021)
		C_{23}	Reducing resource consumption	CLR is expected to shut down or renovate energy-intensive industrial enterprises, thereby reducing resource consumption.	Xu et al. (2021)
		C_{24}	Improving ecological environment	CLR is expected to improve the ecological environment in the implemented areas, including improving soil, increasing vegetation cover, beautifying the surrounding landscape, increasing biodiversity, improving ecosystem service functions, etc.	Liu et al. (2015), Zhang et al. (2019), Wang et al. (2020), Xu et al. (2021)
		C_{25}	Improving human living environment	CLR is expected to improve the human living environment in the implemented areas, including improving housing conditions, neighborhood environment, urban environment, etc.	Guo and Tian (2016), Gu et al. (2022)

Table 2 (continued)

Criterion	Sub-criterion		Definition	Key references
	C_{26}	Optimizing the spatial pattern of land development and protection	CLR is expected to execute spatial planning, optimize spatial structure and spatial layout, thereby optimizing the spatial pattern of land development and protection.	Liu et al. (2015), Wang et al. (2020)
C_3 Social	C_{31}	Improving infrastructure and public service facilities	CLR is expected to improve infrastructure and public service facilities such as transportation facilities, water and electricity facilities, commercial facilities, cultural and educational facilities, medical facilities and other supporting facilities.	Zhang et al. (2019), Xu et al. (2021)
	C_{32}	Reducing social governance costs	CLR is expected to reduce the social governance costs arising from the misconduct of floating population and backward industrial enterprises.	Zhang et al. (2019), Xu et al. (2021)
	C_{33}	Protecting stakeholders' rights	CLR is expected to provide complete guarantees to ensure stakeholder participation and protection of stakeholder rights.	Li et al. (2022)
	C_{34}	Promoting balanced urban and rural development	CLR is expected to reduce the gap between urban and rural areas by promoting balanced allocation and orderly flow of resources, thereby promoting balanced urban and rural development.	Wang et al. (2016)
	C_{35}	Advancing common prosperity	CLR is expected to reduce income disparities and promote social justice, thereby contributing to common prosperity.	Guo (2022)

substantial outcomes over the past decade, including a 114 km^2 reduction in inefficient construction land outside urban development boundaries, creation of over 45 km^2 of new farmland, and establishment of more than 35 km^2 of forest area (Shanghai Municipal Bureau of Planning and Natural Resources, 2024). However, Shanghai now faces increasing challenges as readily reclaimable low-efficiency construction land diminishes (Li et al., 2021), necessitating urgent adoption of innovative strategies to ensure sustainable CLR success. In light of this, Shanghai's existing practical experience and future pathbreaking initiatives can provide valuable insights for nationwide CLR implementation.

Data sources. The preliminary evaluation criteria and alternative strategies are organized through literature review and on-site investigation. Specifically, 270 CLR-related academic papers sourced from Web of Science (WOS), Scopus, and China National Knowledge Infrastructure (CNKI), 468 policy and project documents collected from government websites, and textual materials from field surveys conducted in Shanghai during 2021 and 2022 are manually reviewed to extract evaluation sub-criteria and alternative strategies advocated by scholars or applied in various practical scenarios.

Decisions in the empirical study are collectively determined by decision-makers with specialized knowledge and extensive experience using the Delphi method. The Delphi method is a structured decision support approach for obtaining consensus knowledge from anonymous experts (Linstone and Turoff, 1975). In the absence of official or reliable data, the Delphi method proves to be the optimal choice for collecting decision information for CLR. While the Delphi method has no precise standard for the number of decision-makers (Vernon, 2009; Avella, 2016), 10–12 is generally considered the safest number (Johnson, 1976; Paliwoda, 1983). Considering that excessive participants could complicate evaluation consistency, we recruit 10 decision-makers familiar with CLR through our research group's expert database and snowball sampling method (Goodman, 1961). The decision-makers' profiles are presented in Supplementary Material S2. All decision-makers hold senior positions with extensive tenure across different backgrounds, ensuring the diversity and expertise of the Delphi group. Two separate Delphi processes are conducted via questionnaires to gather qualitative and quantitative information, respectively. In the qualitative process, the 10 decision-makers endorse the preliminary evaluation criteria and alternative strategies in the first round, with one suggesting the addition of strategy S_{18} relating to human resource development. After providing feedback to the remaining decision-makers, all decision-makers agree to add this strategy in the second round, thus determining the final evaluation criteria and alternative strategies. In the quantitative process, the 10 decision-makers complete the assessments as required by the proposed approach. After all questionnaires are collected, Kendall's W coefficient is calculated to measure consensus levels (Schmidt, 1997). W ranges from 0 (no consensus) to 1 (complete consensus), with values $\geq$ 0.7 indicating satisfactory concordance (Okoli and Pawlowski, 2004; von der Gracht, 2012). With W of 0.524 and 0.678, respectively, the first and second round results are returned to the decision-makers for reassessment. The third round achieved a W of 0.829, indicating high consensus, and the majority decisions are adopted as final decisions.

Implementation and results. The TBL sustainability framework guides our selection of economic, environmental, and social dimensions as sustainability criteria to evaluate the performance of alternative strategies for CLR. Through literature review, on-

Table 3 Alternative strategies for CLR.

Strategy		Definition	Key references
S_1	Developing CLR special plans	Taking the spatial master plan as the basis, short-term and long-term special plans for CLR should be formulated in accordance with local development.	Mu et al. (2024), Zhou et al. (2024)
S_2	Improving and innovating CLR policies	Although a series of policies have been introduced to support CLR in recent years, there are still certain weaknesses to be improved, especially in terms of policy incentives, implementation standards, emergency response, effectiveness assessment, etc.	Zhang et al. (2019)
S_3	Reforming the land tenure system	Under China's current urban-rural dual land tenure system, urban state-owned land is far more expensive and richer in land rights than rural collective-owned land, while rural collective-owned land can only be converted to urban state-owned land through the only means of government expropriation. The conversion of land ownership in CLR results in huge profits for the government and a loss of bargaining power for collectives and farmers. To overcome this problem, land tenure system reform should be promoted by allowing the marketization of rural collective-owned commercial construction land, implementing the reform of rural homesteads, etc.	Guo (2020), Li et al. (2021)
S_4	Increasing public financial support	The government should increase public financial support to cover the upfront investment costs of CLR and to motivate grassroots efforts.	Wang et al. (2021), Mu et al. (2024)
S_5	Broadening funding sources	As the government currently bears all the costs of CLR and has been under constant financial strain, relying solely on government financial allocation is likely to cause delays in CLR progress of CLR. Therefore, funding sources should be broadened, such as public-private partnerships, green financing.	Liu et al. (2015), Wang et al. (2021), Lu et al. (2022), Mu et al. (2024)
S_6	Establishing a market-based benefit sharing mechanism	Taking into account regional characteristics, stakeholders' willingness and implementation costs, a mature benefit sharing mechanism with market allocation, policy incentives and social participation should be established.	Gu et al. (2022)
S_7	Providing diversified settlement options	The government should provide land-expropriated farmers and industrial enterprises with diversified options, including unified resettlement to centralized residential communities or industrial parks with limited subsidies, and large one-time compensation for the withdrawal of collective rights and interests.	Zhou et al. (2024)
S_8	Properly settling land-expropriated farmers and industrial enterprises	The government should give adequate compensation to land-expropriated farmers and industrial enterprises timely, relocate farmers and industrial enterprises in accordance with individual wishes, enhance public services and welfare for farmers, and guide the re-employment of the unemployed population.	Li et al. (2021)
S_9	Establishing a long-lasting income generation mechanism	The transfer of land development rights in CLR necessitates a more sustainable approach to compensating collectives and farmers for their long-term production and livelihoods. Therefore, a long-lasting income generation mechanism should be established through reasonable retention of construction land, introduction of high-quality industries to rural areas, equity participation, etc.	Guo and Tian (2016), Wang et al. (2021), Lu et al. (2022, 2023)
S_{10}	Establishing a cross-regional CLR quota trading mechanism	Currently, CLR quotas for new construction projects are limited to redeployment by the government within the specified area, with a series of problems such as narrow trading range, insufficient marketization and improper pricing. Therefore, on the premise of conforming to spatial plans, a CLR quota trading market and a CLR quota trading management system should be established to realize cross-regional trading of CLR quotas.	Liu et al. (2017), Wang et al. (2019), Guo (2020), Wang et al. (2020), Li et al. (2021), Wang et al. (2021)
S_{11}	Standardizing the administrative organizational operation system	The operation of CLR requires coordinated efforts among multiple departments at multiple levels of government. A coordinated organizational operation system should be established with the natural resource management department taking the lead and the participation of various departments at the city, district, and town levels.	Lu et al. (2022)

Table 3 (continued)

Strategy		Definition	Key references
S_{12}	Encouraging multi-party participation	A cooperative governance mechanism led by the government and participated by multiple parties should be established. Government leadership ensures the seriousness of decision-making on CLR. The participating parties should include both stakeholders and non-stakeholders. The participation of stakeholders, including government, collectives, farmers, industrial enterprises, etc., can fully express their interests and ensure democratic decision-making; non-stakeholders, consisting of people of different economic levels, social classes, and occupations, can ensure more adequate and objective decision-making and reduce the negative externalities of CLR.	Wang et al. (2016), Zhou et al. (2022a)
S_{13}	Improving the information disclosure mechanism	The government should establish a centralized information platform for organizing and releasing information about CLR. The requisite information should include details about CLR plans, approval of new projects, implementation of established projects, compensation and resettlement to farmers and industrial enterprises, use of government funds, CLR effects, etc.	Wang et al. (2016)
S_{14}	Strengthening advocacy and interpretation efforts	The government should widely publicize the objectives and benefits of CLR and patiently explain CLR policies to the public, thereby stimulating public awareness and support for CLR.	Liu et al. (2017), Xu et al. (2021)
S_{15}	Improving the supervision and feedback mechanism	The government should establish a strict internal and external supervision mechanism, broaden the public's supervision and feedback channels, and provide positive feedback and rewards for the public's effective supervision and reporting.	Liu et al. (2017), Zhou et al. (2022a)
S_{16}	Performing routine land surveys and monitoring activities	Regular land surveys and monitoring should be conducted to clarify the scale and distribution of inefficient and fragmented construction land as a basis for CLR plans, and to track land use changes as an assessment of the effectiveness of CLR.	Hu et al. (2018)
S_{17}	Expanding CLR range	The present focus of CLR is primarily on illegal and poorly profitable industrial enterprises and idle and fragmented rural homesteads on collective-owned construction land, but little of such land is still available. It is worth considering expanding the range of CLR in due course, such as industrial enterprises on state-owned land.	Li et al. (2021)
S_{18}	Strengthening CLR-related human resource development	Training and guidance for CLR-related personnel should be strengthened to improve their professional knowledge and skills, and professional CLR teams should be established, thereby providing talent support for CLR.	Added by the decision-makers
S_{19}	Innovating CLR-related technologies	Innovative technologies are needed to drive CLR. For example, technologies such as big data, cloud computing, and machine learning can be used to facilitate intelligent CLR management; technologies such as land reclamation and ecological restoration can be used to rehabilitate inefficient and fragmented construction land to concentrated patches of high-quality arable land and ecological land.	Wang et al. (2016), Zhou et al. (2022b)
S_{20}	Strengthening post-CLR land management	The reclaimed arable land and the restored ecological land should be managed continuously to strictly prevent the utilization of arable land for non-food production and safeguard the quality of the ecosystem.	Zhu (2021)

site investigation, and the Delphi method, 17 sub-criteria belong to the TBL criteria and 20 alternative strategies for CLR are identified, as shown in Tables 2 and 3.

In the performance evaluation process, by applying Step 1, the best and worst criteria, along with their fuzzy preferences relative to other criteria, are determined through the Delphi method. By solving Eq. (1), the optimal Shapley values of all criteria and sub-criteria are obtained, as shown in Table 4. The environmental criterion is the most important in CLR, followed by economic. The importance of sub-criteria varies, with improving ecological environment, improving land use efficiency, and protecting stakeholders' rights ranking as the most crucial under the environmental, economic, and social dimensions, respectively.

By implementing Step 2 to solve Eq. (2), the interdependence indices of criteria are obtained, as shown in Fig. 3a. The results reveal prevalent interdependences between all criteria pairs. Notably, 83.7% of the criteria pairs demonstrate complementary effects, while the remaining 16.3% exhibit substitutive effects observed in C_1 - C_2, C_2 - C_3, C_{14} - C_{15}, C_{32} - other sub-criteria.

Table 4 Criteria weights.

Criterion C_i	C_1	C_2	C_3			
Best criterion C_2	(1,2,3)	(1,1,1)	(2,3,4)			
Worst criterion C_3	(1,2,3)	(2,3,4)	(1,1,1)			
Shapley value I_i	0.310	0.519	0.171			
Möbius representation m_i	0.333	0.580	0.152			
Sub-criterion C_{1i}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
Best sub-criterion C_{12}	(1,2,3)	(1,1,1)	(2,3,4)	(2,3,4)	(2,3,4)	(3,4,5)
Worst sub-criterion C_{16}	(2,3,4)	(3,4,5)	(1,2,3)	(1,2,3)	(1,2,3)	(1,1,1)
Shapley value I_{1i}	0.202	0.333	0.129	0.129	0.129	0.078
Möbius representation m_{1i}	0.161	0.294	0.084	0.112	0.089	0.049
Sub-criterion C_{2i}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}
Best sub-criterion C_{24}	(1,2,3)	(2,3,4)	(4,5,6)	(1,1,1)	(2,3,4)	(2,3,4)
Worst sub-criterion C_{23}	(3,4,5)	(2,3,4)	(1,1,1)	(4,5,6)	(2,3,4)	(2,3,4)
Shapley value I_{2i}	0.202	0.139	0.058	0.324	0.139	0.138
Möbius representation m_{2i}	0.166	0.098	0.049	0.269	0.094	0.100
Sub-criterion C_{3i}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	
Best sub-criterion C_{33}	(1,2,3)	(3,4,5)	(1,1,1)	(2,3,4)	(1,2,3)	
Worst sub-criterion C_{32}	(2,3,4)	(1,1,1)	(3,4,5)	(1,2,3)	(2,3,4)	
Shapley value I_{3i}	0.213	0.082	0.353	0.139	0.213	
Möbius representation m_{3i}	0.173	0.110	0.290	0.103	0.165	

Based on the Shapley values and interdependence indices, the Möbius representations and fuzzy measures of criteria are derived by performing Step 3, with results shown in Tables 4 and S.6. Due to the prevalence of criteria interdependences, the Shapley values and Möbius representations differ across all criteria.

By applying Step 4, the contribution levels of strategies with respect to the criteria are assessed with the Delphi method. As shown in Fig. 4, each strategy aims to achieve multiple goals. The direct performances of strategies are then obtained by aggregating their contribution levels based on the fuzzy measures of criteria, with the results shown in columns 2–5 of Table 5. S_{17} has the strongest direct impact, particularly in environmental impact. S_{10} exhibits the strongest direct economic impact, while S_6 has the largest direct social impact.

By executing Step 5, total influence degrees between strategies are calculated using Eqs. (6–8), with results shown in Fig. 3b. Based on the direct performances and total influence degrees, the indirect performances of strategies are calculated using Eq. (9), as displayed in column 6 of Table 5. The results show that S_2 demonstrates substantially superior indirect performance, followed by S_{12}, S_4, and S_5.

By implementing Step 6, the overall performances of strategies are obtained using Eq. (10), with the results shown in columns 7–8 of Table 5. Among all strategies, S_2, S_{12}, S_4, S_1, and S_5, have top five overall performances.

In the planning process, the time to impact of strategies is assessed through the execution of Step 7. The medium time to strategic impact is set at 5 years, aligning with the planning cycles of both national and local governments in China. Given their overall performances and time to strategic impact, the 20 strategies are categorized into four strategic planning zones in the constructed strategic planning matrix. As shown in Fig. 5, eight strategies S_1, S_2, S_4, S_5, S_6, S_7, S_{12}, and S_{15} classified in the (I) Priority zone demonstrate both high overall performances and short time to impact, while two strategies S_3 and S_{11} in the (II) Long-term zone exhibit high overall performances despite requiring a long time to impact. Three strategies S_{18}, S_{19}, and S_{20} fall within the (III) Non-priority zone due to their low overall performances and persistent nature, and the remaining seven strategies S_8, S_9, S_{10}, S_{13}, S_{14}, S_{16}, and S_{17} are grouped into the (IV) Quick-responding zone characterized by easy responsiveness but limited performances.

Discussions

Managerial implications of CLR strategies with different priorities. To further quantify the allocation of management resources, the overall performances are evenly distributed across each year of strategy implementation, as shown in Fig. 6. Based on Table 5 and Figs. 5, 6, the eight priority strategies require substantial resource investment (averaging 40.6% annually) during the first five years due to their potential for rapid goal achievement. In the first year, the greatest effort (13.8%) should be dedicated to developing CLR special plans (S_1) as a crucial component of the territorial spatial planning system to provide overall guidance for future CLR. Beyond the current singular quantitative targets, CLR special plans should systematically outline overall objectives, annual targets, suitable areas, implementation sequence, and pathways. Funding guarantee requires significant attention in the second and third years to ensure adequate project funding. This involves increasing public financial support (S_4) through establishing special funds, prioritizing budgets, integrating cross-departmental funding, and reinvesting previous CLR revenues. Additionally, funding sources (S_5) can be broadened through public-private partnerships (PPP) and green financing. Providing diversified settlement options (S_7) requires

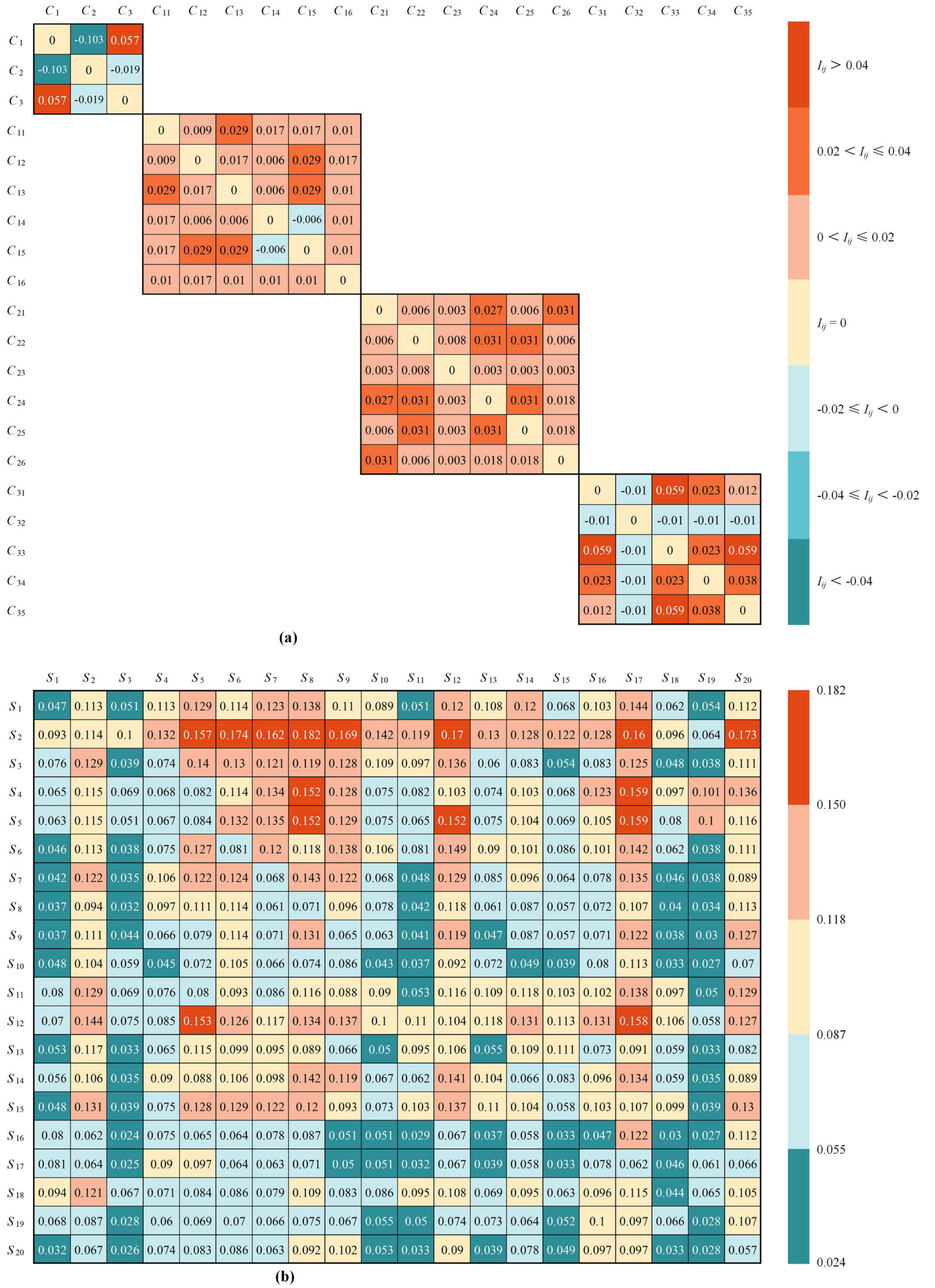

Fig. 3 Criteria and strategic interdependences. a Interdependence indices between criteria. **b** Total influence degrees between strategies.

the second-highest resource allocation in the initial two years. Beyond the existing single compensation standard, governments should offer a range of settlement options including monetary compensation, centralized resettlement, housing vouchers, off-site relocation, equity participation, and employment arrangements to address diverse stakeholder needs and enhance support from land-expropriated farmers and enterprises. Improving the supervision and feedback mechanism (S_{15}) is another primary strategy in the third year. This involves establishing both top-down governmental oversight and bottom-up public feedback channels through hotlines, petitions, online platforms, community follow-ups, and third-party assessments to enhance governance efficiency and bolster public trust. Given the current deficiencies in addressing market risks and stakeholder equity (Guo, 2020; Gu et al., 2022), establishing a market-based benefit-sharing mechanism (S_6) is essential within the first three years. Referring to the game theory approach (Zhou et al., 2024), a fair and unified set of rules should be established to determine the benefit distributions for individual projects based on market returns. With the second-highest indirect and overall performances, S_{12} can take effect in the fourth year, building upon S_1, S_5, S_6, and S_7 to create a cooperative governance mechanism involving government leadership and participation from collectives, farmers, enterprises, citizens, etc. Despite having the highest indirect and overall performances, improving and innovating CLR policies (S_2) requires support from S_7, S_{12}, and S_{15} to take effect due to complex policy objectives and formulation procedures. Given that existing CLR policies were introduced fragmentally across different periods, a comprehensive policy framework should be established in the short term, encompassing responsibility allocation, planning requirements, funding management, implementation standards, market transactions, risk management, and performance assessment. After policy stabilization, innovative policies should be introduced in the medium term, such as allowing marketized floor area ratio transfers and developing integrated CLR modes with cultural, tourism, or ecological restoration. These innovative policies should be pilot-tested in selected regions, with successful approaches incorporated into the policy framework to sustain CLR vitality.

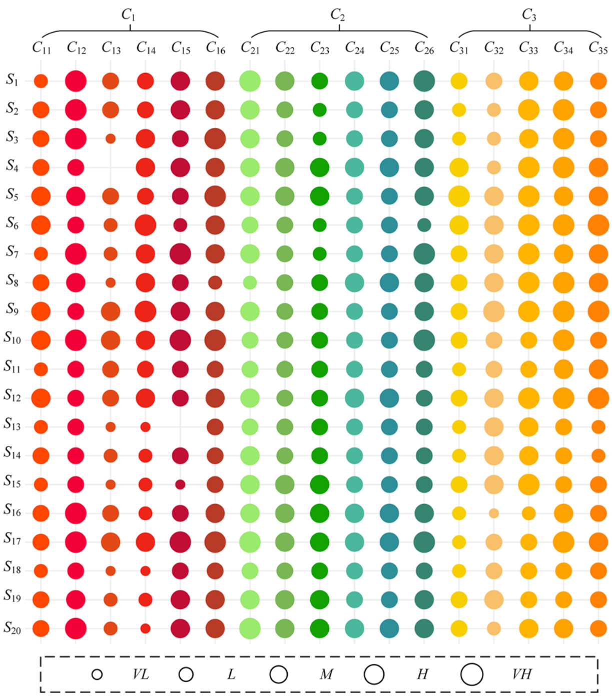

Fig. 4 Contribution levels of strategies with respect to criteria.

The seven quick-responding strategies, despite exhibiting relatively low performances, require moderate effort (averaging 25.1% annually) in the first five years, leveraging their high quantity and ease of implementation to facilitate rapid CLR improvement. In the first year, strengthening advocacy and interpretation efforts (S_{14}) should be initiated through activities such as urban development forums, community outreach, media coverage, and public-private dialogs to rapidly gain collective and public understanding of CLR benefits. Additionally, routine land surveys and monitoring activities (S_{16}) should also be implemented in the first year by integrating high-precision multi-type base maps, artificial intelligence, drone technology, and manual verification to establish an intelligent sensing platform that can identify inefficient construction land in real time as suitable CLR areas and monitor implementation outcomes. In the second year, proper resettlement of land-expropriated farmers and enterprises (S_8) should be rigorously implemented according to settlement options provided in S_7, ensuring full compliance with legal and policy regulations to prevent involuntary demolition. In the third year, governments should establish a unified information disclosure platform (S_{13}) to disseminate CLR plans, policies,

Table 5 Performances of strategies.

Strategy	Direct performance value of each criterion			Direct performance value	Indirect performance value	Overall performance value	Overall performance ranking
	C_1	C_2	C_3				
S_1	3.539	4.230	3.416	3.917	6.758	10.675	4
S_2	3.782	3.230	3.509	3.472	9.297	12.769	1
S_3	3.522	3.230	3.197	3.312	6.581	9.894	6
S_4	2.742	4.000	4.306	3.686	7.029	10.714	3
S_5	3.589	3.469	4.522	3.675	6.983	10.658	5
S_6	3.158	2.759	4.678	3.206	6.617	9.823	7
S_7	3.634	3.330	4.036	3.556	6.062	9.618	9
S_8	2.966	3.293	4.162	3.331	5.260	8.592	14
S_9	3.740	3.297	4.493	3.652	5.245	8.897	12
S_{10}	4.488	3.200	3.206	3.631	4.534	8.165	16
S_{11}	2.757	3.000	3.053	2.938	6.552	9.490	10
S_{12}	3.360	3.594	4.425	3.653	7.826	11.478	2
S_{13}	1.731	3.000	2.883	2.621	5.433	8.054	17
S_{14}	2.686	3.166	2.883	2.991	6.100	9.091	11
S_{15}	2.046	3.329	3.675	3.014	6.617	9.631	8
S_{16}	3.508	4.000	2.355	3.640	4.205	7.845	20
S_{17}	4.245	4.297	3.156	4.068	4.156	8.225	15
S_{18}	2.174	3.000	2.747	2.729	5.970	8.700	13
S_{19}	3.174	3.469	3.110	3.333	4.656	7.989	18
S_{20}	2.322	4.166	3.361	3.530	4.443	7.973	19

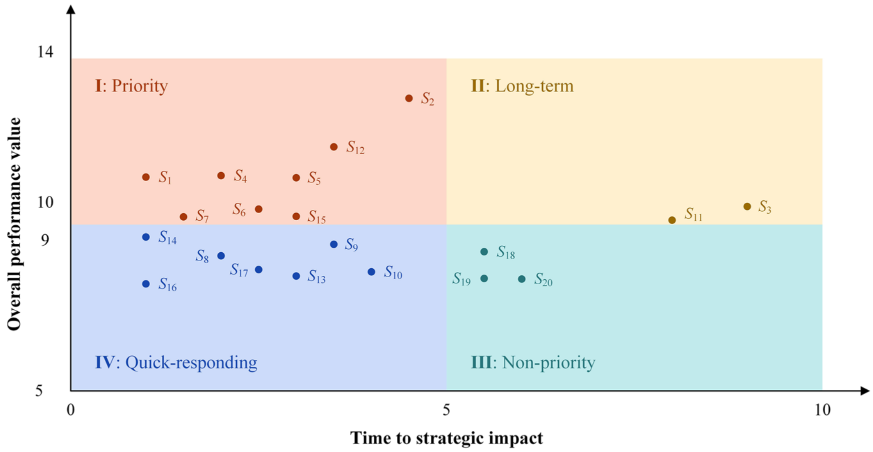

Fig. 5 Strategic planning results.

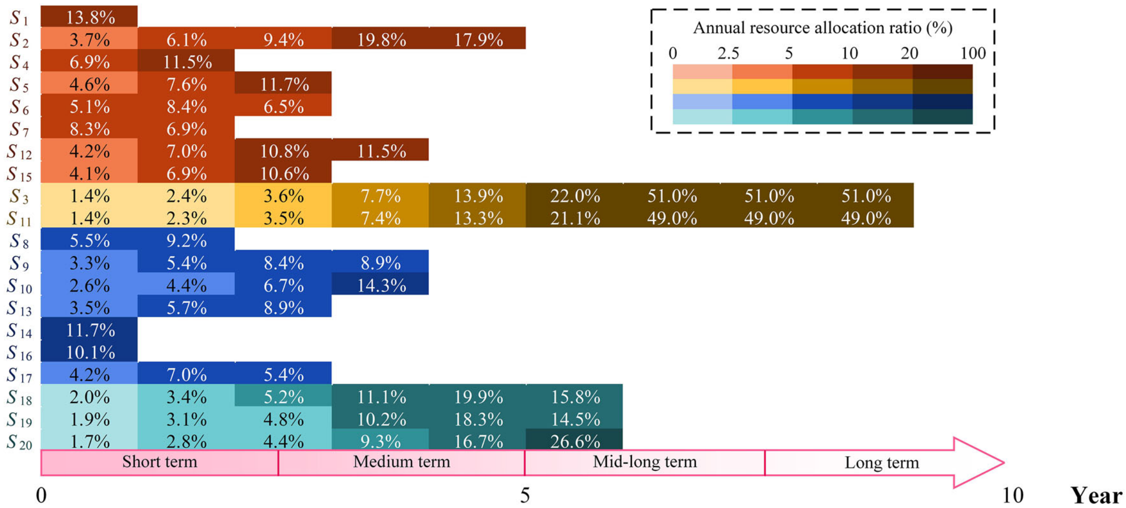

Fig. 6 CLR strategic timeline.

and schemes through online and on-site channels, thereby enhancing governmental decision-making transparency and safeguarding citizens' information rights. To generate scale effects that reduce costs and cluster arable and ecological land, CLR range (S_{17}) should be extended to state-owned industrial enterprises and peri-urban areas in the third year. To address long-term concerns of land-expropriated farmers and enterprises, a long-lasting income generation mechanism (S_9) should be established through reasonable retention of construction land, introduction of high-quality industries to rural areas, and equity participation in the fourth year. A cross-regional CLR quota trading mechanism (S_{10}) should also be established in the fourth year through the development of CLR quota markets, trading platforms, and regulatory systems. This mechanism allows areas with greater CLR potential to reduce more construction land in exchange for more financial benefits, thereby enhancing regional competition and optimal land resource allocation across regions (Guo, 2022).

The two long-term strategies, despite their high overall performances, cannot be easily implemented and thus require sustained resource investment. On the one hand, the huge CLR profits stem from the stark urban-rural land value disparities inherent in China's dual land system—an issue requiring long-term systematic reform (S_3) to resolve. Future reforms should focus on implementing the separation of homestead qualification rights and use rights, and realizing the free market entry of collective operational land, thereby narrowing urban-rural gaps. On the other hand, CLR is currently led by the natural resources department, but its goals are multifaceted and thus require coordination across multiple departments, including finance, agriculture and rural affairs, housing, and ecological environment. Given the complexity of cross-departmental and cross-level coordination, governments should standardize the organizational operation system (S_{11}) by establishing a dedicated CLR task force equipped with normalized working coordination mechanisms and information-sharing platforms, thereby improving the efficiency and effectiveness of CLR implementation.

The remaining three non-priority strategies require only routine resources. To enhance existing effects with minimal additional resources, human resource development (S_{18}) and technological innovation (S_{19}) require deepening government-university-enterprise collaborations, intensifying staff training, and proactively adopting advanced engineering and digital technologies. Post-CLR land management (S_{20}) can leverage spillover effects from higher-priority strategies (such as S_2, S_{15}, S_{16}) through policy guidance, public feedback, routine land surveys, and monitoring, etc.

While the above discussions are specific to Shanghai's context, such strategy evaluation and prioritization is applicable to other cities. Amid intensifying land use conflicts, many economically

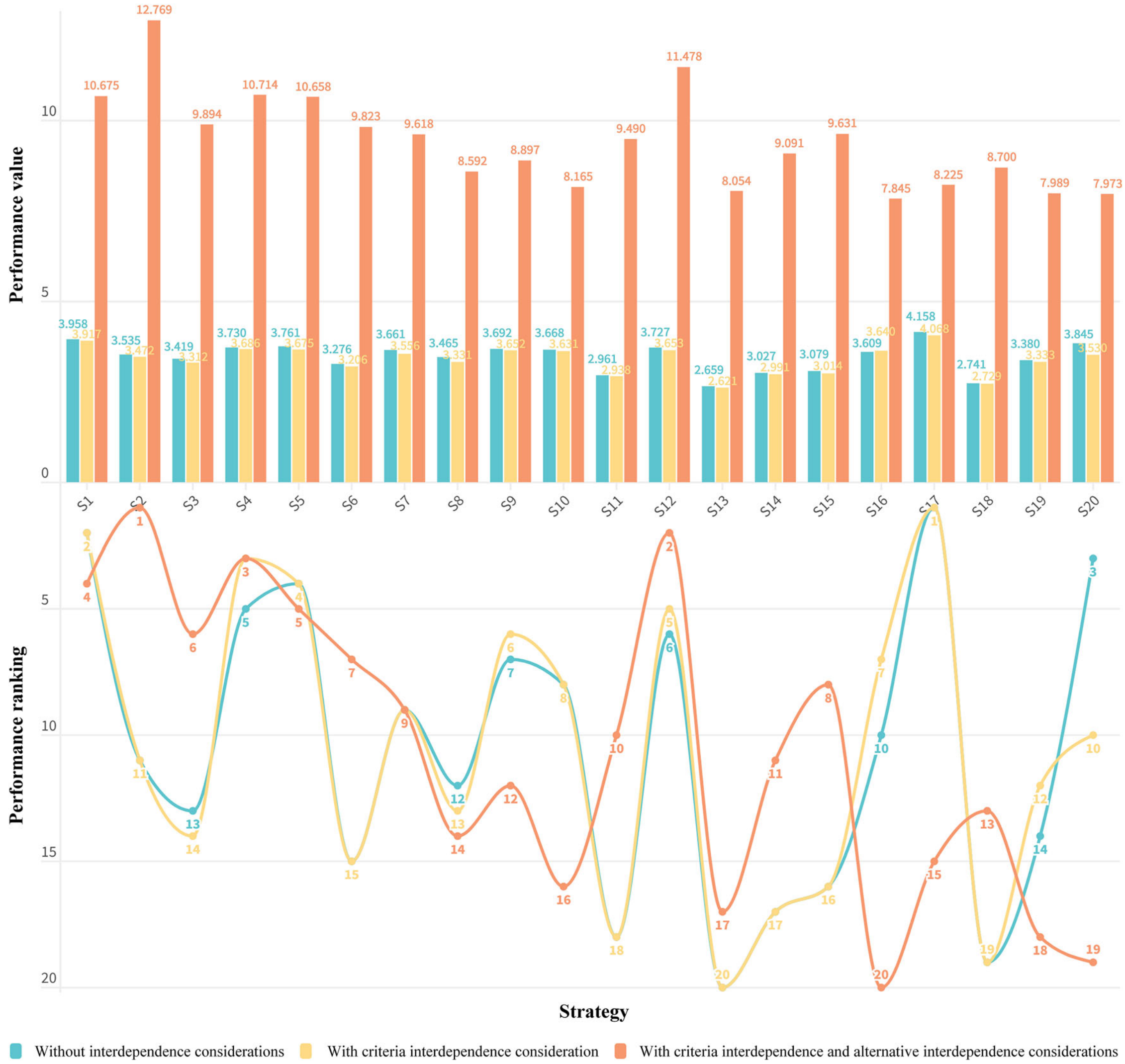

Fig. 7 Comparison of performance results under different interdependence considerations.

advanced metropolises have ambitious CLR targets. For instance, Guangzhou rehabilitated 31.73 km^2 of construction land in 2024, while Beijing aims to achieve a CLR target of 5.4 km^2 in 2025. Leveraging locality-specific data, the proposed approach enables optimal resource allocation and the implementation sequence of strategies tailored to individual cities. These strategies require careful adaptation to local conditions when implemented. For example, Guangzhou faces widespread historical issues of illegal land use, necessitating the incorporation of penalty and legalization provisions in CLR policies or prioritizing reductions in these areas in CLR plans. Similarly, Beijing's CLR policies and plans must pay special attention to the preservation of historical buildings and dispersal of non-capital functions. While smaller cities in less developed regions currently show limited enthusiasm for CLR due to construction land quotas exceeding economic development rates, the gradual liberalization of nationwide quota trading suggests an emerging trend toward CLR adoption in these regions. Consequently, smaller cities should proactively establish institutional frameworks for future CLR implementation by drawing lessons from metropolitan experiences.

Roles of criteria and strategic interdependencies in the proposed approach. As shown in Fig. 3, extensive interdependencies exist between criteria and strategies. To demonstrate the significance of considering these interdependences, we compare the performance and strategic planning results of this novel MCDM framework with two traditional MCDM frameworks (a and b in Fig. S.1), with results presented in Figs. 7 and S.3.

In terms of criteria interdependences, as shown in Fig. 3a, complementary effects dominate (83.7%), reflecting synergistic relationships among most CLR goals, while the remaining 16.3% exhibit conflicts primarily between economic-environmental, social-environmental, and intra-social criteria. As indicated in Table 4, after accounting for criteria interdependences, the weights of criteria with predominantly substitutive effects increase, while those with complementary effects decrease. Among TBL criteria, environmental (C_2) weight increases by 11.8%, attributed to its substitutive relationship with the other two criteria diminishing their marginal contributions. This can also be explained from a practical standpoint: environmental carrying capacity is the ultimate constraint on socioeconomic development, making environmental protection an increasingly critical prerequisite for economic and social benefits in CLR implementation. Sub-criteria weights follow similar patterns, notably with C_{32} increasing by 34.1%. As shown in Fig. 7, after considering criteria interdependences, most strategies' performance values slightly decrease, as numerous criteria weights decline. This suggests that treating criteria as independent oversimplifies the complexity of sustainable goals, typically overestimating strategy performances. Uniquely, S_{16} shows increased performance and the largest ranking improvement, as its distribution of contribution levels aligns closely with criteria interdependence patterns. Conversely, S_{20} experiences the most significant ranking decline due to economic and social vulnerabilities, indicating that post-CLR land management is less critical than traditionally perceived (ranked 3rd).

In terms of strategic interdependences, as shown in Fig. 3b, S_2, S_{12}, S_4, and S_5 demonstrate the highest influence on other strategies, and thus exhibit the greatest indirect performances in Table 5. Figure 7 reveals that strategies' indirect performances even exceed their direct performances, confirming widespread and strong strategic interdependences and indicating that strategies' overall performances are heavily reliant on indirect performances. After considering strategic interdependences, S_2, S_3, S_6, S_{11}, and S_{15} show significant ranking improvements due to high indirect performances, while S_9, S_{10}, S_{16}, S_{17}, and S_{20} experience substantial ranking declines due to low indirect performances. Comparing Figs. 5 and S.3 reveals that neglecting strategic interdependences would inappropriately alter strategic planning zones for these ten strategies, misclassifying priority strategies with quick-responding ones or long-term ones with non-essential ones, severely disrupting strategic priorities and implementation sequence.

The above analysis demonstrates that our novel MCDM framework effectively captures the intricate relationships between criteria and strategies in sustainable land use, providing a more comprehensive and accurate representation of real-world scenarios and enabling more reliable strategic decision-making.

Conclusions

This study proposes a novel integrated MCDM approach to evaluate and prioritize interdependent alternative strategies with interdependent sustainability criteria, with its practicality demonstrated in an empirical study of CLR in Shanghai.

The study identifies 17 specific CLR goals across economic, environmental, and social dimensions as evaluation criteria, as well as 20 alternative strategies for CLR. The performance evaluation process reveals extensive interdependencies between criteria and strategies. Environmental criteria emerge as the most important, particularly when considering substitutive effects with economic and social dimensions. The overall performances of strategies heavily rely on indirect performance resulting from strategic interdependencies. In the strategic planning process, the 20 strategies are categorized into four strategic planning zones in the strategic planning matrix, reflecting varying priorities and implementation sequence. Eight priorities strategies, focusing on overall design, financial mobilization, profit motivation, and multi-party co-governance, require substantial upfront investment. Two long-term strategies, centered on system reform, need sustained resource allocation. Seven quick-responding strategies, involving spatial preparation, information communication, and continued safeguards, warrant moderate initial efforts. Comparative analysis with traditional methods demonstrates our approach's superior capability to accurately capture complex interdependences inherent in real-world scenarios.

The approach is broadly applicable to other contexts through the customization of criteria weightings, interdependence analyses, and locality-specific strategies to address differentiated challenges. While our approach offers promising utility, potential limitations warrant consideration. When decision information stems from the Delphi method, ensuring the diversity and expertise of decision-makers is crucial. Furthermore, as the number of criteria and strategies increases, the exponential increase in required judgments may be impractical, potentially necessitating data-mining techniques such as association rule mining as an alternative source.

Data availability

The data that support the findings of this study are available within the paper and its supplementary materials in the form of figures and tables.

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Author contributions

Jia-He Zhou conceptualized the research, designed the methodology, developed the software, conducted formal analysis, curated data, created visualizations, wrote the original draft of the manuscript, and acquired funding. Chao-Yue Yu provided resources, validated the research, and reviewed and edited the manuscript. Zheng-Feng Zhang acquired funding, administered the project, supervised the research team, and reviewed and edited the manuscript. Lei He conducted the investigation, curated data, validated the research, and reviewed and edited the manuscript. Hong-Li Lin conducted the investigation, validated the research, and reviewed and edited the manuscript.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

According to Article 3 of the "Working Rules of the Academic Ethics Committee of Renmin University of China" released in January 2021, Renmin University of China does not require ethics approval for this study as it only involved the collection of decision information from decision-makers rather than medical research, experimental research involving human subjects, gene editing or cloning. Our research posed minimal risk to participants, did not involve personal or sensitive data collection, ensured anonymized data processing, and did not include any interventional procedures.

Informed consent

Written informed consent was obtained from all participants by Jia-He Zhou in May 2023 prior to their involvement in the study. All participants were thoroughly informed about the purpose of the study, the voluntary nature of participation, the right to withdraw at any time without consequences, the use of data for academic research and publication purposes, and the anonymity of reporting results.

Additional information

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