Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering) in press
www.jzus.zju.edu.cn; www.springer.com/journal/11582
E-mail: jzus_a@zju.edu.cn

Research Article

https://doi.org/10.1631/jzus.A2400522

Preliminary study on evaluation indicators for urban engineering system sustainability

Junjie WU[1,2], Duanyang ZHUANG[1,2]✉, Xuecheng BIAN[1,2], Yunmin CHEN[1,2]

[1]*Institute of Hypergravity Science and Technology, Zhejiang University, Hangzhou 310058, China*
[2]*MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou 310058, China*

Abstract: China's Urbanization has entered a mid-to-late phase, and is characterized by high-density urban engineering projects that form systems coupled to geotechnical environments. These systems exhibit significant vulnerability due to strong spatiotemporal coupling, which hampers sustainable urban development. Traditional approaches to urban engineering design, construction, and maintenance tend to focus on individual projects, and lack the ability to comprehensively evaluate system-level sustainability. Thus with current methods, it is difficult to optimize the renewal and operation of high-density urban engineering systems. In this study, the constituent elements and key features of high-density urban engineering systems are discussed, and urban engineering system sustainability evaluation indicators are comprehensively reviewed. Viewed from perspectives of resilience, low-carbon development, and ecological impact, 66 performance indicators describing urban engineering systems are selected. The Decision Making Trial and Evaluation Laboratory based Analytic Network Process Method (DANP) and the Entropy Weight Method (EWM) are utilized to calculate these indicators' subjective and objective weights, respectively. Furthermore, the coupling relationships between evaluation indicators are explored, aiding the construction of an urban engineering sustainability evaluation index system. Finally, empirical analysis is conducted across six megacities in China (Tianjin, Hangzhou, Shanghai, Wuhan, Chongqing, and Shenzhen) to validate the effectiveness of the evaluation indicators. The findings reveal significant imbalances in the sustainability of urban engineering systems in China. Accordingly, potential strategies and indicators for targeted enhancement of these systems are discussed.

Key words: Urban engineering system; Geotechnical environment; Spatiotemporal coupling; Sustainability; Evaluation indicators

Unedited

1 Introduction

By the end of 2022, China's urbanization rate had reached 65.2%, signaling a transition to the mid-to-late urbanization stage. Meanwhile, the population density of Chinese megacities significantly exceeds the global average (Hou et al., 2023), and rapid urbanization has driven the development of complex urban engineering systems. In these systems, surface structures, underground spaces, transportation networks, and energy facilities are intricately connected through geotechnical bodies and the environment. Such systems provide physical support for city operations, ensure proper functioning of urban activities, promote economic and social development, and improve the environment in which humans live. However, the growing density of cities and aging infrastructure have created strong interdependencies and complex co-evolution phenomena among urban engineering projects. As a result, a failure or malfunction in one project can rapidly spread to interconnected projects, and potentially the entire system, posing significant threats to the stability and sustainability of a city. For instance, in Zhengzhou, China on July 20, 2021, there was extreme rainfall which reached 201.9 mm/h. The local drainage system, which was designed for a once-in-50-year event, could only handle 32% of this rainfall rate. Consequently, the rainfall formed torrents that spread danger to other urban engineering projects, leading to severe road damage, traffic

✉ Duanyang ZHUANG, zhuangdy@zju.edu.cn
Duanyang ZHUANG, https://orcid.org/0000-0002-5431-0691

Received Nov. 10, 2024; Revision accepted May 26, 2025; Crosschecked

© Zhejiang University Press 2025

disruptions, and catastrophic failures in underground spaces. The situation was also exacerbated by delayed emergency responses, imprecise measures, and lack of unified command, ultimately resulting in 380 fatalities and direct economic losses amounting to 40.9 billion Chinese Yuan (Li et al., 2023b; Zhang et al., 2022a). Similar incidents in other cities have highlighted the urgent need to address such systemic vulnerabilities.

Traditional urban engineering design, construction, and maintenance primarily focus on individual projects, thus neglecting urban engineering systems and lacking comprehensive system-level optimization. Therefore, systemic urban vulnerability tends to increase, leading to issues such as disaster mismanagement, carbon emission imbalances, and pollution disorders. To specify, disaster mismanagement refers to the increased intensity and frequency that urban engineering projects are facing from natural and human-made disasters, making it difficult to prevent and mitigate the induced damage (Gordon et al., 2019). Carbon emission imbalances are characterized by environmental degradation in dense urban areas and aging districts, as a result of uncoordinated and excessive carbon emissions during construction, renovation, and maintenance projects (Chen et al., 2020a; Wang et al., 2022b). Pollution disorders refer to increasingly complex and unmanageable pathways of pollution in high-density urban engineering projects, which result in a heightened risk of environmental deterioration (Tang et al., 2022).

To address the challenges above, it is imperative to promote sustainable construction and operation in the context of urban engineering systems. The aim is to meet contemporary urban functional needs without compromising the quality-of-life or resource demands of future generations, while meeting constraints of specific urban resources (Ding et al., 2016a). By prioritizing sustainable development in urban engineering systems, impacts from potential disruptions can be mitigated, thereby enhancing long-term system performance. A comprehensive assessment of current research in urban engineering system sustainability is fundamental to achieving these goals, as it would help identify critical engineering projects that require protection, and enable improved allocation of limited resources across various subsystems. However, current research on urban sustainability assessment mainly focuses on economic, social, and ecological aspects, with few studies addressing sustainability assessment indicators for urban engineering systems (Sharifi, 2021). Moreover, since the factors influencing urban sustainability are multidimensional, it remains uncertain how factors interrelate and which factors operate independently. Thus, there is an urgent need for multi-scale and multidimensional research to develop a system of sustainability assessment indices. This would help decision-makers monitor and evaluate the operational status of urban engineering systems, and provide metrics for policy-makers to evaluate strategies for enhancing sustainability.

This study focuses on the components and characteristics of high-density urban engineering systems that impact sustainable development. By reviewing current research on urban engineering system sustainability assessment, shortcomings in existing assessment frameworks are identified, and a novel configuration of sustainability assessment indicators for urban engineering systems are proposed. These are subsequently applied for empirical analysis of six Chinese megacities: Tianjin, Hangzhou, Shanghai, Wuhan, Chongqing, and Shenzhen. This application is performed to validate the proposed assessment methodology, and provide recommendations for enhancing urban engineering system sustainability in these particular cities.

2 Overview of urban engineering systems

2.1 Components of urban engineering systems

System science categorizes systems into simple systems, simple giant systems, and complex giant systems based on the level of complexity, which includes the number and types of subsystems, the complexity of the relationships among subsystems, and structural differences (Qian et al., 1993). We posit that an urban engineering system is an open, complex, and giant system composed of multiple subsystems with specific functions. These subsystems interact continuously through the geotechnical environment, exchanging materials, energy, and information, and collectively forming the physical foundation of a city. Urban engineering systems can

Unedited

be divided into Functional Building System, Underground Space System, and Infrastructure based on their constituent elements. Functional Building System and Underground Space System provide space for human habitation and productive activities, while Infrastructure supplies the necessary energy and materials for societal operations. Infrastructure can be further subdivided into six subsystems based on functional characteristics. These components are summarized in Table 1.

Table 1 Components of urban engineering systems

Constituent elements		Specific composition
Infrastructure	Energy Facility System	Power supply system, heating system, etc.
	Water Supply and Drainage System	Water supply system, sewage system, etc.
	Communication System	Postal system, broadcast television system, etc.
	Disaster Prevention and Mitigation System	Fire protection system, emergency system, etc.
	Environmental Facility System	Greening system, waste recycling system, etc.
	Transportation System	Road system, shipping system, etc.
Functional Building System		Residential buildings, public buildings, etc.
Underground Space System		Underground buildings, utility tunnels, etc.

2.2 Characteristics of urban engineering systems

As an open complex giant system, urban engineering systems exhibit numerous characteristics, among which the most important are coupling, openness, and dynamicity. Various characteristics complicate evaluating the sustainability of these systems, necessitating the establishment of a comprehensive multilevel evaluation and management methodology. Since scientific evaluation methods are often the basis for decision-making and management, the current challenge is how to effectively assess urban engineering system sustainability, and provide guidance for efficient synergistic operation during renewal and maintenance of such systems.

2.2.1 Coupling

As cities become denser and more modernized, coupling relationships between the above components have become increasingly complex (Fig. 1). The geotechnical environment leads to various urban engineering projects being tightly coupled, and working synergistically at a physical level. Moreover, the couplings generated by functional coordination between different subsystems further expands the scope of impact, forming a large-scale spatiotemporal coupling mechanism (Li et al., 2022). When a single subsystem experiences a disturbance, such coupling mechanisms can amplify or generate new effects, creating a complex chain of cascading failures. This results in disturbances gradually spreading from smaller to larger urban areas, ultimately leading to significant vulnerabilities in terms of resilience, carbon emissions, and ecological impact.

From the perspective of resilience, increased coupling heightens the risk of complex emergencies. When a single aspect of an urban engineering system encounters a disaster or malfunction, the resulting functional failures often trigger cascading effects, causing continuous propagation of losses that are difficult to predict (Ouyang, 2014). Both natural disasters (e.g., typhoons or earthquakes) and man-made disasters (e.g., terrorist attacks or industrial accidents) can trigger cascading failures. For example, when Typhoon Hato landed in Macau, China on August 23, 2017, the high proportion of land used for construction significantly increased the vulnerability of local urban engineering system (Lin and Li, 2022). Therefore, the level-14 typhoon immediately caused seawater to backflow, leading to widespread flooding and power outages. The failures of the local drainage system and energy system quickly resulted in cascading collapses of communication and transportation facilities, causing underestimated human casualties and economic losses (Chow et al., 2019).

From the perspective of low-carbon development, varying construction times and lifecycles of individual projects, which are strongly coupled through the geotechnical environment, often complicate the understanding of performance evolution over the lifespan of dense urban engineering projects. This can significantly increase

Unedited

the difficulty of synergistic operation and maintenance of multi-stage urban projects. Currently, the service performance of densely constructed areas in China tends to be poor, and urban engineering carbon emissions account for a high proportion of total city carbon emissions. For instance, Shanghai's per capita CO_2 emissions (11.9 tons) in 2019 were significantly higher than those of other major international cities such as London (9.6 tons) and Tokyo (4.89 tons) (Ji et al., 2023), with construction and transportation operations accounting for 25% of the total energy-related carbon emissions (Huang et al., 2019; Tian et al., 2024). This highlights the need for synergistic updates that promote energy conservation and carbon reduction.

From the perspective of ecological impact, coupling increases the vulnerability of the urban ecological environment. Failures in various urban engineering projects often lead to the spread of pollutants, resulting in complex pollution sources and emission pathways, and ineffective regulation of urban groundwater and soil pollution. For example, since systemic effects were not properly considered in early urban planning, municipal pipelines are often shallowly buried and chaotically arranged. This can lead to sewage leaks during long-term service, causing uneven stress in nearby pipelines and chain leakage (Wang et al., 2021). Statistics show that China's current sewage pipeline network has a COD (Chemical Oxygen Demand) penetration rate of 66%, meaning over half of the pollutants enter the groundwater and soil through pipeline leaks (Cao et al., 2019).

Urban engineering systems also exhibit coupling relationships and feedback mechanisms across the above dimensions, with a failure in any dimension potentially triggering cascading failures in others. For example, if an urban engineering system is inadequately resilient to an earthquake, it could lead to leaks in pipelines, septic tanks, pumping stations, and wastewater treatment facilities (Wells et al., 2013), causing pollution and negatively affecting the system's ecological status.

Unedited

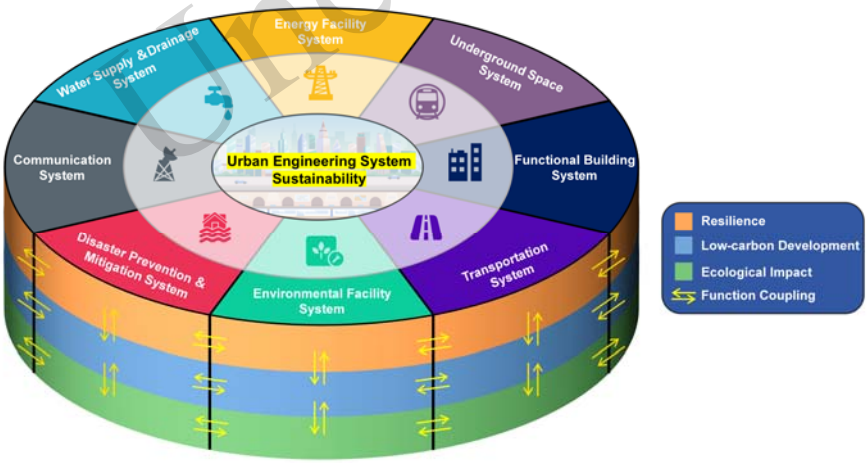

Fig. 1 Conceptual framework of urban engineering system sustainability

2.2.2 Openness

The formation and evolution of urban engineering systems follows similar laws as living systems, where individual and group evolutions are achieved via constant material and energy exchange with the outside world (Shi et al., 2021). The operation and development of all subsystems are influenced by external factors including climate conditions, natural environmental changes, international political and economic dynamics, national and regional policies and laws, population movements, cultural exchanges, and the flow of information. This openness necessitates that a single urban engineering system should effectively exchange and aggregate resources with other systems. For example, urban infrastructure must comply with international environmental agreements like the Paris Agreement on climate change, which requires cities to reduce greenhouse gas emissions and transition toward renewable energy sources (Kılkış, 2022); this might include upgrading the transportation system to promote public transit and cycling, retrofitting

buildings for improved energy efficiency, and implementing sustainable waste management practices.

The openness of urban engineering systems introduces additional complexity into urban engineering design, construction, and maintenance. External factors may lead to profound and unpredictable impacts on system functionalities, thus requiring the system to be robust in all dimensions. Consequently, it is necessary to build a comprehensive evaluation system that can quantify how different factors may influence the system's sustainability.

2.2.3 Dynamicity

Urban engineering systems are constantly evolving in response to both internal developments and external changes. By undergoing continuous transformations influenced by technological advancements, policy shifts, environmental changes, and social dynamics, engineering projects may ultimately serve a different purpose from what was envisioned (Guma, 2022). The dynamicity of urban engineering systems adds complexity, necessitating top-level designs that are both scalable and adaptable. Scalability ensures that the system can adjust its capacity to meet changing demands, while adaptability allows it to modify functionalities to address new challenges. For example, the integration of renewable energy technologies into existing power grids necessitates systems that can accommodate variable inputs without compromising stability.

In order to effectively manage dynamicity, it is essential to develop a comprehensive evaluation system, which can monitor and evaluate the performance of urban engineering systems amidst continuous change. Such an evaluation system would enable governments to assess how well urban engineering systems are responding to growing or changing demands, and how their functionalities need to be modified to meet new challenges.

3 Research status on urban engineering system sustainability assessment

3.1 Origin of the urban sustainability concept

The concept of sustainable development first appeared in 1987 in the United Nations report entitled "Our Common Future" (WCED, 1987). It was defined as "the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs" (Mebratu, 1998). This definition has since become a new reference point in environmental science research. The Earth Summit held in Rio de Janeiro, Brazil in 1992 introduced 27 principles to guide global sustainable development, marking another milestone (Kori and Gondo, 2012). Since then, the concept of sustainable development has been incorporated into international treaties, national constitutions, and the laws of various countries (Luke, 2005; Redclift, 2005), serving as a conceptual framework for addressing issues in business (Amran et al., 2015), agriculture (Zhang et al., 2022b), industry (Mayyas et al., 2012), and urban development (Ahern, 2013).

In the 21st century, with the intensification of climate change and environmental issues, the concept of urban sustainability has evolved further. The United Nations General Assembly's 2015 adoption of the "2030 Agenda for Sustainable Development" specifically calls for the creation of inclusive, safe, and disaster-resilient sustainable cities, introducing new ideas for urban development (Kumar et al., 2016). Subsequently, researchers have undertaken extensive work to investigate potential strategies that further this goal. This has included the widely adopted concept of urban resilience, which has been applied in areas such as disaster impact simulation, infrastructure risk assessment, and urban function loss prediction (Glaeser, 2022).

3.2 Research on urban engineering system performance evaluation

Currently, scholars have developed distinctive urban engineering performance evaluation systems based on different theoretical frameworks. Such evaluation systems can be analyzed from the following perspectives:

(1) From the perspective of evaluation objects, existing performance evaluation systems are primarily divided into two categories: evaluations of individual urban engineering subsystems, and evaluations of interconnected urban engineering subsystems. The former focuses on examining specific subsystem performance indicators in detail, providing a basis for targeted improvements. For

Unedited

example, Mahmoud (2022) utilized a generic sustainability rating tool within a multi-objective optimization model to evaluate and enhance surface building sustainability, focusing on life cycle cost and sustainability trade-offs. However, this type of evaluation tool overlooks the risk of cascading failures due to coupling between different subsystems, leading to the potential overestimation of subsystem performance, and creation of unsafe biases in engineering design and maintenance.

Evaluation systems that target interconnected urban engineering subsystems focus on the relationships among subsystems, and evaluate the overall performance by analyzing failure risk evolution mechanisms. For instance, Wang (2012) developed a framework to assess the vulnerability of power and water supply systems, and proposed system design strategies based on multiple indicators. Although such an evaluation system does consider the coupling features between subsystems, it only covers certain types of engineering projects, and overlooks the mediating role of the geotechnical environment. Additionally, due to the high cost of simulating complex coupling issues, some studies ignore implicit logical relationships between indicators and treat indicators as independent (Bi and Little, 2022).

(2) From the perspective of evaluation dimensions, existing evaluation systems explore multiple aspects including resilience (Blagojević et al., 2023), carbon emissions (Yang et al., 2022a), ecology (Zhang et al., 2022b), economics (Sun et al., 2017), and social impacts (Yang et al., 2022b). While these studies provide field-specific insights, they fail to comprehensively consider performance coupling and feedback mechanisms between different dimensions. This limits precise enhancement of system functions and makes it challenging to achieve optimal renewal and maintenance of high-density urban engineering systems. Establishing systematic assessment dimensions is crucial for evaluating sustainability, as focusing on a single dimension may compromise sustainability in others.

(3) In terms of evaluation frameworks and methods, existing studies can primarily be divided into three types: The first type is based on qualitative analysis, utilizing expert opinions, case studies, and literature reviews to explore and understand various phenomena and trends within urban engineering systems, and to propose countermeasures. For example, Jiang and Tan (2022) analyzed 378 cases of underground infrastructure failures related to heavy rainfall, summarizing general features affected by drainage facility performance, climate conditions, and engineering geology. While such qualitative analysis does offer a deep understanding of research issues, it is highly subjective and difficult to verify as statistically significant.

The second type of evaluation system is based on quantitative analysis, which estimates objective variables through data and statistical methods (Shin et al., 2018). The main methods of this group include scenario analysis (Silva et al., 2018), model simulation (Leng et al., 2020), and system performance curves (Bao et al., 2020; Yang et al., 2021). Due to the spatial network characteristics of urban engineering systems, network-based modeling methods are commonly used in analyzing disaster damage and recovery progress. For example, Zhang (2018) proposed an evaluation framework for probabilistically predicting the functional loss of community buildings after earthquakes; the progression of urban building functionality failure was calculated by quantifying post-earthquake functional losses in the topology of water and electricity infrastructure. Also, Liu (2020) calculated changes in greenhouse gas emissions before and after the implementation of green infrastructure, successfully assessing the contribution of green infrastructure to low-carbon urban drainage systems and the city overall. Quantitative analysis offers objective conclusions, but places higher demands on quantitative verification methods, which must be researched in greater depth.

The third type is based on semi-qualitative and semi-quantitative analysis, which mainly involves the use of indicator systems (Moslem et al., 2020). Because of the low empirical and technical requirements, this approach has been used to develop a range of self-service performance evaluation tools (Reed et al., 2009), such as the BREEAM (Building Research Establishment Environmental Assessment Methodology) method (Umdu et al., 2021), and the PEOPLES (Population and Demographics, Environmental and Ecosystem, Organized Governmental Services, Physical Infrastructures, Lifestyle and Community Competence, Economic

Unedited

Development, and Social-Cultural Capital) urban resilience evaluation system (Cimellaro et al., 2010). However, limitations arise from the strong subjectivities involved in indicator scoring and standard setting for such methods. Currently, there is no unified method for quantifying urban engineering system sustainability in terms of statistical indicators. Additionally, since existing evaluation frameworks have mainly been established in developed countries, some of these indicators fail to integrate with the setting in China.

Overall, research on the evaluation of urban engineering system sustainability is still in the exploratory stage. Although the existing evaluation systems enable performance assessment of certain subsystems based on different research backgrounds, there is still a lack of a comprehensive evaluation system covering various subsystems and different dimensions.

3.3 Validation of urban engineering system performance indicators

Limited by the complexity of urban engineering systems, traditional experimental methods under normal gravity are insufficient for simulating performance evolution on the scale of a city (Chen et al., 2020b). Additionally, due to the scarcity of real data on such performance changes, existing sustainability assessments of urban engineering systems have not been practically validated. Hypergravity physical simulation is a revolutionary engineering tool currently addressing these challenges, which can replicate the evolution of multiphase media over large scales and long durations; it operates under normal gravity in a laboratory scale, and within an observable time frame (Chen et al., 2022c; van Loon et al., 2008).

Western countries have taken early initiatives to study hypergravity physical simulations of urban engineering system coupling mechanisms. In 1991, the U.S. Army Corps of Engineers built the world's current largest capacity centrifuge (1200 g·t) (Ledbetter et al., 1991), which has been used to simulate the dynamic responses of geotechnical infrastructure under seismic or explosive conditions, as well as the long-term migration of contaminants in the environment. This centrifuge has successfully simulated the internal flooding disaster chain observed in New Orleans, Louisiana during hurricane conditions (Ubilla et al., 2008; Blume and Burroughs, 2009). However, the current capacity of hypergravity centrifuges in China is insufficient, limiting the modeling of complex scenarios, intelligent renewal, and maintenance of urban engineering systems. There is thus an urgent need to develop similar large-scale spatiotemporal simulation devices.

4 Urban engineering system sustainability evaluation indicators

4.1 Selection of evaluation indicators

Since urban engineering system sustainability is a multidimensional issue, the most challenging task is the choice of evaluation indicators. To address this complexity, the indicators chosen in this study were rigorously screened through bibliometric analysis, which examined existing evaluation indices of different subsystems. Meanwhile, in order to incorporate the openness and dynamicity of urban engineering systems, the selected indicators were grounded in quantifiable and standardized statistical variables. This enables the capture of temporal variations in urban evolution while ensuring applicability across cities of varying scales. Meanwhile, statistical variables with insufficient data were removed or replaced.

A set of typical indicators and their corresponding statistical variables are summarized in Section S4 of the electronic supplementary materials (ESM), and the attributes indicate whether the given variable enhances (+) or diminishes (−) the urban engineering system sustainability. The indicators were selected based on the subsystems defined in Section 1.1, and could be considered as a detailed description of different cities' resilience (32 indicators), low-carbon development (17 indicators), and ecological impact (17 indicators). Indicators in the resilience dimension were prioritized to quantify system robustness against disruptions, reflecting the capacity to maintain critical services during crises; indicators in the low-carbon development dimension were chosen to reflect sustainability transitions that align urban growth with emission reduction targets; indicators in the ecological impact dimension were selected to monitor environmental feedback to

Unedited

engineering operations.

4.2 Indicator weight calculation method

The evaluation indicators are weighted to signify their importance, with common weighting methods being divided into subjective and objective approaches. In this study, the subjective and objective weights were calculated by the Decision Making Trial and Evaluation Laboratory based Analytic Network Process Method (DANP) and the Entropy Weight Method (EWM), respectively. The integrated weights were then calculated using the Maximizing Deviation Method (MDM). The calculation process of the evaluation indicator system is illustrated in Fig. 2.

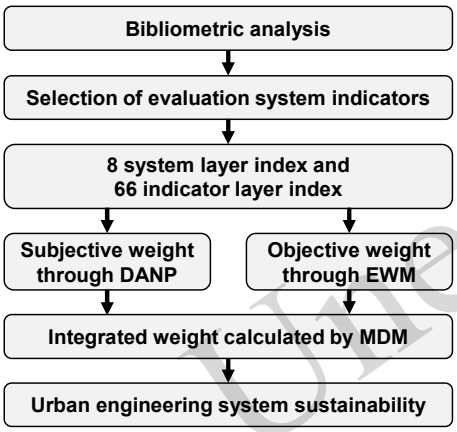

Fig. 2 Schematic flowchart of the methodology

4.2.1 Subjective weight calculated by DANP

Subjective weighting plays a critical role in sustainability assessments, as it captures expert insights into systemic priorities and interdependencies. Traditional methods like Analytic Hierarchy Process (AHP) assume unidirectional hierarchical relationships among criteria (Nefeslioglu et al., 2013), and fail to address feedback loops or bidirectional influences that are prevalent in complex urban engineering systems. Although the Analytic Network Process (ANP) partially resolves this problem by accommodating network-like interactions, its reliance on pairwise comparisons alone often leads to oversimplified causal structures, as well as computational intractability in large-scale systems (Liu, 2022a). Therefore, in order to express the coupling relationships among selected indicators, the DANP was employed to calculate the subjective weights. The DANP is a decision support tool that can reveal relationships and interdependence between various subjects, so as to facilitate problem-solving. By utilizing graph theory and matrix tools to quantify the direct and indirect relationships between indicators, the DANP can calculate the cause and effect relationship of each factor, and convert the relationships among the factors into a structural model that enables visual representation of the interdependencies (Jiang et al., 2022). Referencing the research of Lin et al. (2022), five experts from the field of urban engineering construction were invited to participate in a survey that collected their assessments of the direct impact levels between evaluation indicators. The constructed evaluation system network hierarchy and the main steps of the DANP are described in Section S1 of the ESM.

4.2.2 Objective weight calculated by EWM

Objective weighting is essential to counterbalance expert subjectivity, and enhance the credibility of the evaluation system. To accurately differentiate evaluation objects and maximize the informational value of indicators, the EWM was used to determine the objective weights. Referencing the research of Luo et al. (2020), higher weights were assigned to indicators with greater data variability, with the goal of quantifying the uncertainty of each indicator.

4.2.3 Integrated weight calculated by MDM

Combined weighting is critical for reconciling the strengths of expertise and data variability, ensuring a balanced evaluation framework that mitigates the biases inherent in standalone methods. Therefore, the Maximizing Deviation Method was employed to optimize weight integration, by maximizing the total deviation across evaluation objects. By formulating a constrained optimization problem to autonomously determine integration coefficients, this method preserves the casual nuances of DANP, while prioritizing entropy-driven disparities. The specific calculation steps can be referenced from Yi et al. (2019).

5 Empirical analysis

5.1 Selection of evaluation cities

A city cluster refers to a compact urban agglomeration centered around a megacity, and

Unedited

includes at least three large cities or metropolitan areas connected by transportation and communication networks. Currently, China has five major city clusters: Beijing-Tianjin-Hebei, Yangtze River Delta, Middle Yangtze, Chengdu-Chongqing, and the Pearl River Delta (Tao et al., 2019). To comprehensively explore sustainability differences within China, six megacities from these clusters were selected to carry out an empirical analysis: Tianjin, Hangzhou, Shanghai, Wuhan, Chongqing, and Shenzhen.

It is worth noting that the urban engineering system sustainability discussed in this paper is limited to normal city operation scenarios, but the same methods could also be applied to analyze extreme disaster scenarios or other special circumstances.

5.2 Data sources and pre-processing

The data used for each indicator variable mainly came from the China City Statistical Yearbook, China Urban Construction Statistical Yearbook, China Energy Statistical Yearbook, China Statistical Yearbook on Environment, National Economic and Social Development Statistical Bulletin, the website of the National Bureau of Statistics, Statistics Yearbooks of selected prefectural cities, and official documents recognized by relevant governmental departments. The sample period was 2021, and missing data were filled in through linear interpolation of historical data.

To eliminate the differences in magnitude, size, and range between indicators, all data were scaled from 0 to 1 through normalization to ensure that different indicators can be compared straightforwardly.

5.3 Results and analysis

5.3.1 Calculation results of indicator weights

Taking power supply stability (A11) as an example to illustrate the calculation process of indicator weights, A11 obtained subjective and objective weights of 0.0194 and 0.0110 through the DANP and EWM, respectively, indicating that the integrated weight constraints range from [0.0110, 0.0194]. To maximize the variance of scores among evaluation objects while meeting the normalization constraint of all indicator weights, the calculated integrated weight for this indicator was 0.0194. Other indicator weights were similarly calculated and the results are listed in Section S5 of the ESM.

5.3.2 Reliability validation

A reliability test of the evaluation system was conducted using Cronbach's α, which is a common means of assessing reliability. It works by comparing the amount of shared variance among the items making up an instrument, to the amount of overall variance. Cronbach's α typically ranges from 0 and 1, with values closer to 1 indicating higher reliability of the evaluation results (Pinto et al., 2014). The overall Cronbach's α for the evaluation results is 0.8811, demonstrating that the constructed evaluation system reliably, consistently, and stably reflects the performance of each evaluation object regarding urban engineering system sustainability.

5.3.3 Evaluation results for different subsystems

Based on the established evaluation system and normalized data, the sustainability scores for each evaluation object were calculated. The ranking results for the overall system and the individual subsystems are shown in Fig. 3.

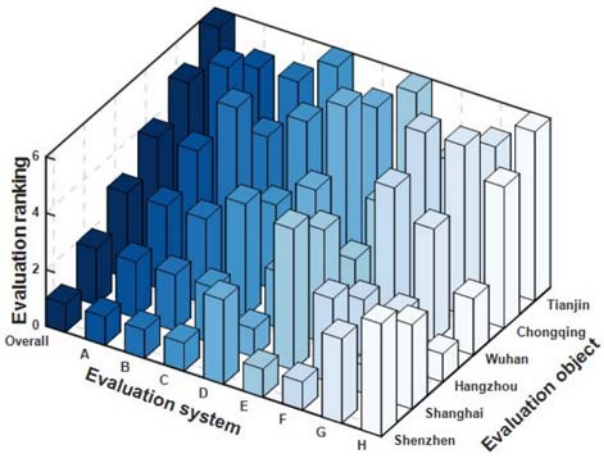

Fig. 3 Evaluation results ranking the different subsystems

Shenzhen leads in five out of eight subsystems, exhibiting strong sustainability synergies. For instance, Shenzhen's low-carbon public transport scale (F22) reduces reliance on fossil fuels, and lowers energy intensity (A22). Meanwhile, Shanghai dominates the Disaster Prevention and Mitigation System (D) and Functional Building System (G). In contrast, Chongqing and Tianjin show weaker performance; the reasons for this can be attributed to: the coupling characteristics inevitably trigger cascading risks, the openness characteristic amplifies

Unedited

systemic vulnerability across different regions, and the dynamicity characteristic increases uncertainty during system operations. For instance, Tianjin's inefficient construction industry resource utilization (G21) intensifies the energy intensity (A22) and worsens air pollution control (E32); it also increases resource dependency on other cities.

5.3.4 Evaluation results across different dimensions

The normalized scores for each city across different dimensions are displayed in Fig. 4. The results reveal a significant disparity in overall evaluation scores: Shenzhen and Shanghai attain the highest scores (0.63 and 0.60), while Chongqing and Tianjin demonstrate lower performance (0.34 and 0.32). Notably, Shanghai's top resilience score (0.3357) is directly attributed to its leading performance in the Disaster Prevention and Mitigation System (D), since this means the city has strong adaptation to uncertainties from the dynamicity characteristic.

Performance imbalance is also found across different dimensions within the same city. For example, Shanghai ranks second overall, but first in the resilience dimension, which is likely due to the different attention given to various dimensions during city policy formulation.

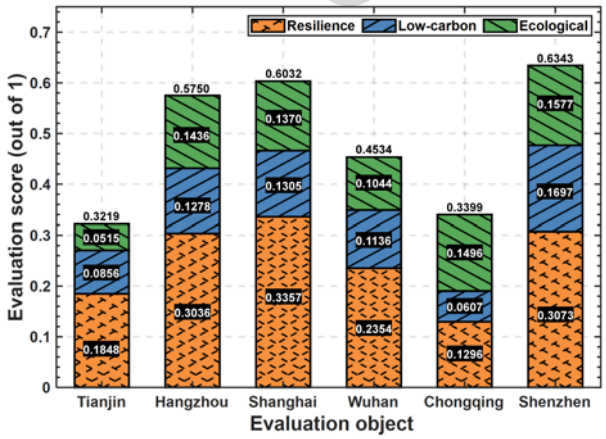

Fig. 4 Evaluation scores across different dimensions

5.3.5 Enhancement measures and recommendations

As described in Section S5 of the ESM, the geological disaster forecast accuracy (D12) and mobile communication assurance (C13) are the most critical indicators affecting urban engineering system sustainability, with their integrated weights being 0.0264 and 0.0243, respectively. In contrast, the road traffic connectivity (F11) and Internet transmission efficiency (C21) rank as the lowest indicators, with integrated weights of 0.0093 and 0.0087, respectively.

For specific cities, it is essential to analyze sustainability in different subsystems and dimensions of each urban engineering system. Taking Hangzhou as an example, its overall ranking among the selected cities is third, but its rankings across all subsystems are 3, 3, 4, 2, 4, 2, 2, and 1, respectively, indicating that Hangzhou currently places a high priority on the development of the Underground Space System (H). However, improvements should be made in the sustainability of its Communications System (C) and Environmental Facilities System (E); some of these improvements might include implementing stricter electromagnetic radiation management measures, enhancing broadband network assurance, and strengthening environmental protection efforts. Hangzhou's ranking across different dimensions is uniformly third, indicating a balanced development across all dimensions.

As shown in Fig. 5, a comparative analysis between Hangzhou and Wuhan was conducted based on the scores of all indicators. There are notable differences in indicators between the selected cities: Hangzhou has significant advantages in the resilience of water supply stability (B12), emergency resettlement (D13), green building development (G31), and underground space utilization (H21). On the other hand, Wuhan performs better in pipeline network safety (B11), Internet transmission efficiency (C21), environmental risk management (E12), and construction industry efficiency (G11). Comparative analyses are beneficial for cities to learn from each other and avoid implementing "one size fits all" policies. For example, Hangzhou could learn from Wuhan's expertise in pipeline network modernization and industrialized construction techniques in order to enhance water infrastructure resilience and resource efficiency, while synergizing these advancements with its own strengths in underground space utilization to improve urban sustainable development.

Unedited

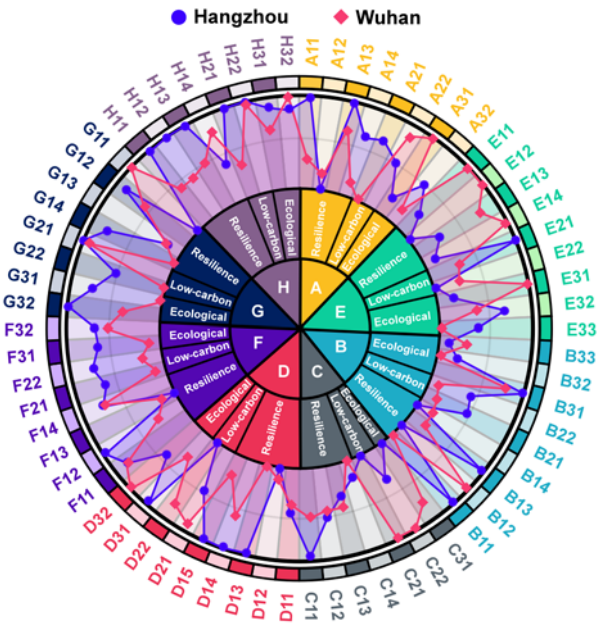

Fig. 5 Indicator scores of Hangzhou and Wuhan

6 Discussion

6.1 Analysis of indicator coupling relationships

The influential relationships and causal positioning between indicators within each layer were calculated by the DANP, in order to make a preliminary analysis of the interdependency among different indicators. However, it should be acknowledged that the interaction mechanisms among high-density urban engineering projects are complex. The DANP employed in this study provides a subjective simplification of these interactions, which may not capture all the intricacies of the real-world system.

6.1.1 System layer

By calculating the Prominence and Relationship value of each subsystem, an influential network relation map is created, as shown in Fig. 6.

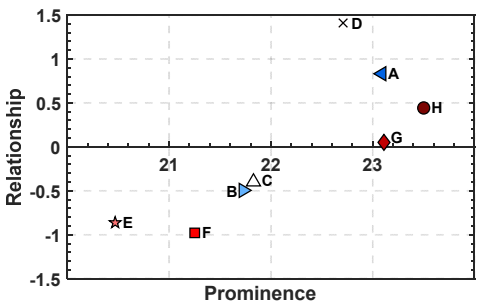

Fig. 6 System layer influential network relation map

The results of the DANP reveal that the Underground Space System (H) has the highest Prominence value, indicating that efficient utilization of underground spaces can significantly promote the sustainable development of urban engineering systems. On the contrary, the Environmental Facility System (E) has the lowest Prominence value, likely because impacts from failures in environmental facilities usually take a long time to become apparent.

Relationship values categorize indicators into cause-and-effect classes. The Disaster Prevention and Mitigation System (D), which has the highest Relationship value, exerts the strongest influence on other subsystems because it determines the city's capabilities in disaster reduction, emergency response, and post-disaster reconstruction. Conversely, the Transportation System (F), which has the lowest Relationship value, shows the weakest impact on other indicators when disturbed, as it primarily responds to demands and changes in other subsystems.

6.1.2 Indicator layer

Similarly, an influential network relation map for indicator layer index under conventional conditions is created, as illustrated in Section S2 of the ESM.

The Prominence value for underground space planning (H12) is the highest, reflecting the role of underground spaces in alleviating urban land resource constraints. Conversely, the Prominence value for traffic noise control (F31) is the lowest, possibly due to the complex causes of urban traffic noise and the lack of efficient measures to manage such noise.

Weather forecast accuracy (D11) has the highest Relationship value and exerts the strongest impact on other indicators, mainly because of the increasing frequency of extreme weather events; this enhances the risk of unconventional emergencies such as power outages, transportation paralysis, and water shortages. The Relationship value of the construction industry efficiency (G11) is the lowest, which is consistent with its high dependency on providing construction resources to other subsystems.

6.2 Sensitivity analysis

The results of an evaluation system are generally related to different types of errors and uncertainty,

Unedited

including weighting criteria, data, knowledge of the system, and influential expert decisions (Foroozesh et al., 2022). Therefore, it is vital to assess the impact of uncertainty on the outcomes. To test the robustness of the established evaluation system, a sensitivity analysis using the OAT (one-at-a-time) method was conducted. The weight of a single indicator was modified by ±10% and ±20%, while other indicators lost proportional shares to keep the weight sum unchanged. The sensitivity analysis results are displayed in Section S3 of the ESM.

The sensitivity analysis results indicate that the evaluation system exhibits different sensitivities to alterations of different indicator weights. The highest change rate is observed with changes in the weights of geological disaster forecast accuracy (D12) and heating security (A13), while the lowest change rate occurs with weight changes in mobile communication coverage (C12) and medical resource integration (D22). Despite these fluctuations in indicator weights, the relative rankings remained stable, confirming the system's robustness to weighting uncertainties.

6.3 Future research directions

While a systematic approach was employed in our proposed evaluation system for urban engineering system sustainability, it is important to acknowledge that the unavailability of certain statistical data, such as maximum load rate on the power grid, fire station density, and per-capita carbon emissions from transportation, has imposed limitations on this study. For instance, lacking information on fire station density hinders assessment of the city's preparedness and responsiveness to emergencies. Similarly, the absence of per-capita carbon emission data from transportation impedes the ability to accurately measure the environmental impact and effectiveness of policies aimed at reducing emissions. In order to address these data limitations, future research should prioritize the collection and integration of comprehensive datasets that encompass a broader range of sustainability indicators. Collaborations with government agencies, urban planners, and utility companies could facilitate access to proprietary or difficult-to-obtain data.

Since this study only considered statistical data in 2021, future studies should also integrate multi-year data to explore how urban engineering system sustainability evolves over time. Longitudinal analyses could further investigate temporal feedback mechanisms, such as whether improvements in low-carbon public transport scale (F22) consistently reduce energy intensity (A22) or the effect eventually plateaus. Real-time data could also complement longitudinal investigations by revealing short-term anomalies and adaptive behaviors. Therefore, the development of advanced data collection technologies, such as IoT (Internet of things) sensors and real-time monitoring systems, would not only resolve current data gaps but also empower predictive modelling that aids policy development.

7 Conclusions

China is presently facing greater vulnerabilities in urban engineering systems due to strong coupling in the geotechnical environments of densely-populated areas. However, current urban engineering design, construction, and maintenance efforts primarily rely on technical specifications and standards developed for individual projects, which lack systematic evaluations of sustainability. This, in turn, poses challenges for renewal and maintenance work in high-density urban engineering systems. Focusing on the interconnected nature of high-density urban engineering systems, we systematically reviewed existing literature on urban engineering system performance evaluation indicators, selecting 66 indicators reflecting the performance of urban engineering systems across three dimensions: resilience, low-carbon development, and ecological impact. The methods of DANP and EWM are then used to calculate the subjective and objective weights of each indicator, respectively, and accordingly constructed an urban engineering system sustainability evaluation index system. Furthermore, an empirical analysis of six Chinese megacities (Tianjin, Hangzhou, Shanghai, Wuhan, Chongqing, and Shenzhen) is conducted. The following findings were obtained:

1. The proposed evaluation indicator system effectively quantified the sustainability of urban engineering systems in each evaluated city. Notably, geological disaster forecast accuracy and mobile communication assurance were identified as the most critical indicators influencing urban engineering

Unedited

system sustainability.

2. Significant imbalances were also observed in the comprehensive scores of the selected megacities. Shenzhen and Shanghai achieved the highest scores (0.6343 and 0.6032), while Chongqing and Tianjin had the lowest (0.3399 and 0.3219). Moreover, substantial variations in performance across different dimensions were observed within the same city, indicating intra-city disparities.

Acknowledgments

The research work described herein was financially supported by the Fundamental Research Funds for the Central Universities (Grant No. 226-2024-00242), the Excellent Research Groups Project (Grant No. 52588202), and the National Science Fund for Distinguished Young Scholars of China (Grant No. 52125803).

Author contributions

Yunmin CHEN, Xuecheng BIAN and Duanyang ZHUANG designed the research. Junjie WU and Duanyang ZHUANG processed the corresponding data. Junjie WU wrote the first draft of the manuscript. Duanyang ZHUANG helped to organize and revise the manuscript. Xuecheng Bian revised and edited the final version.

Conflict of interest

Junjie WU, Duanyang ZHUANG, Xuecheng BIAN, and Yunmin CHEN declare that they have no conflict of interest.

Unedited

References

Ahern J, 2013. Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landscape ecology*, 28(6):1203–1212. https://doi.org/10.1007/s10980-012-9799-z

Amran A, Ooi SK, Mydin RT, et al., 2015. The impact of business strategies on online sustainability disclosures. *Business Strategy and the Environment*, 24(6):551–564. https://doi.org/10.1002/bse.1837

Bai MY, Zhang YF, Wang CJ, et al., 2022. Risk evaluation model for power tower sharing operation. Seventh International Conference on Electromechanical Control Technology and Transportation (ICECTT 2022), p.1118–1122. https://doi.org/10.1117/12.2645795

Bao ML, Ding Y, Sang MS, et al., 2020. Modeling and evaluating nodal resilience of multi-energy systems under windstorms. *Applied Energy*, 270:115136. https://doi.org/10.1016/j.apenergy.2020.115136

Bi CY, Little JC, 2022. Integrated assessment across building and urban scales: A review and proposal for a more holistic, multi-scale, system-of-systems approach. *Sustainable Cities and Society*, 82:103915. https://doi.org/10.1016/j.scs.2022.103915

Bian X, Gao ZY, Zhao P, et al., 2024. Quantitative analysis of low carbon effect of urban underground space in Xinjiekou district of Nanjing city, China. *Tunnelling and Underground Space Technology*, 143:105502. https://doi.org/10.1016/j.tust.2023.105502

Blagojević N, Hefti F, Henken J, et al., 2023. Quantifying disaster resilience of a community with interdependent civil infrastructure systems. *Structure and Infrastructure Engineering*, 19(12):1696–1710. https://doi.org/10.1080/15732479.2022.2052912

Blume P, Burroughs G, 2009. Centrifuge DAQ system reinforces New Orleans levees. *EE-Evaluation Engineering*, 48(10):42–46

Böse M, Papadopoulos AN, Danciu L, et al., 2022. Loss‐Based Performance Assessment and Seismic Network Optimization for Earthquake Early Warning. *Bulletin of the Seismological Society of America*, 112(3):1662–1677. https://doi.org/10.1785/0120210298

Cao YS, Tang JG, Henze M, et al., 2019. The leakage of sewer systems and the impact on the "black and odorous water bodies" and WWTPs in China. *Water Science and Technology: A Journal of the International Association on Water Pollution Research*, 79(2):334–341. https://doi.org/10.2166/wst.2019.051

Chen M, Jiang Y, Wang ED, et al., 2022a. Measuring Urban Infrastructure Resilience via Pressure-State-Response Framework in Four Chinese Municipalities. *Applied Sciences*, 12(6):2819. https://doi.org/10.3390/app12062819

Chen X, Shuai C, Wu Y, et al., 2020a. Analysis on the carbon emission peaks of China's industrial, building, transport, and agricultural sectors. *Science of the Total Environment*, 709:135768. https://doi.org/10.1016/j.scitotenv.2019.135768

Chen XS, Jiang SL, Xu LS, et al., 2023. Resilience assessment and obstacle factor analysis of urban areas facing waterlogging disasters: a case study of Shanghai, China. *Environmental Science and Pollution Research*, 30(24):65455–65469. https://doi.org/10.1007/s11356-023-26861-1

Chen YL, Chen ZL, Guo DJ, et al., 2022b. Underground space use of urban built-up areas in the central city of Nanjing: Insight based on a dynamic population distribution. *Underground Space*, 7(5):748–766. https://doi.org/10.1016/j.undsp.2021.12.006

Chen YM, Ma PC, Tang Y, 2020b. Constitutive models and hypergravity physical simulation of soils. *Chinese Journal of Theoretical and Applied Mechanics*, 52(4):901–915. https://doi.org/10.6052/0459-1879-20-059

Chen YM, Tang Y, Ling DS, et al., 2022c. Hypergravity experiments on multiphase media evolution. *Science China Technological Sciences*, 65(12):2791–2808. https://doi.org/10.1007/s11431-022-2125-x

Chow ECH, Wen M, Li L, et al., 2019. Assessment of the

environmental and societal impacts of the category-3 typhoon Hato. *Atmosphere*, 10(6):296. https://doi.org/10.3390/atmos10060296

Cimellaro GP, Renschler C, Reinhorn AM, et al., 2016. PEOPLES: a framework for evaluating resilience. *Journal of Structural Engineering*, 142(10): 4016063. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001514

Cui LL, Liang JH, Fu HB, et al., 2020. The contributions of socioeconomic and natural factors to the acid deposition over China. *Chemosphere*, 253:126491. https://doi.org/10.1016/j.chemosphere.2020.126491

Dang X, Zhang Y, Feng W, et al., 2020. Comparative study of city-level sustainability assessment standards in China and the United States. *Journal of Cleaner Production*, 251:119622 https://doi.org/10.1016/j.jclepro.2019.119622

Dianat H, Wilkinson S, Williams P, et al., 2022. Choosing a holistic urban resilience assessment tool. *International Journal of Disaster Risk Reduction*, 71:102789. https://doi.org/10.1016/j.ijdrr.2022.102789

Ding L, Shao ZF, Zhang HC, et al., 2016a. A comprehensive evaluation of urban sustainable development in China based on the TOPSIS-Entropy method. *Sustainability*, 8(8):746. https://doi.org/10.3390/su8080746

Ding Z, Wang Y, Zou PXW, 2016b. An agent based environmental impact assessment of building demolition waste management: Conventional versus green management. *Journal of Cleaner Production*, 133:1136–1153. https://doi.org/10.1016/j.jclepro.2016.06.054

Foroozesh F, Monavari SM, Salmanmahiny A, et al., 2022. Assessment of sustainable urban development based on a hybrid decision-making approach: Group fuzzy BWM, AHP, and TOPSIS–GIS. *Sustainable Cities and Society*, 76:103402. https://doi.org/10.1016/j.scs.2021.103402

Gao Y, Tian XL, 2020. Prefabrication policies and the performance of construction industry in China. *Journal of Cleaner Production*, 253:120042. https://doi.org/10.1016/j.jclepro.2020.120042

Glaeser EL, 2022. Urban resilience. *Urban Studies*, 59(1):3–35. https://doi.org/10.1177/00420980211052230

Gordon M, Fysh A, Katsanakis R, et al., 2019. UN Global Assessment Report on Disaster Risk Reduction 2019 (GAR 2019)

Grellier J, Rushton L, Briggs DJ, et al., 2015. Assessing the human health impacts of exposure to disinfection by-products — A critical review of concepts and methods. *Environment International*, 78:61–81. https://doi.org/10.1016/j.envint.2015.02.003

Guma PK, 2022. The Temporal Incompleteness of Infrastructure and the Urban. *Journal of Urban Technology*, 29(1):59–67. https://doi.org/10.1080/10630732.2021.2004068

Guo Q, Wang Y, Dong X, 2022. Effects of smart city construction on energy saving and CO2 emission reduction: Evidence from China. *Applied Energy*, 313:118879 https://doi.org/10.1016/j.apenergy.2022.118879

He G, Jiang HY, Zhu YN, 2024. The effect of digital technology development on the improvement of environmental governance capacity: A case study of China. *Ecological Indicators*, 165:112162. https://doi.org/10.1016/j.ecolind.2024.112162

Heng BB, Zhang R, Wang ZB, et al., 2021. Occurrence and risk assessment of volatile halogenated disinfection by-products in an urban river supplied by reclaimed wastewater. *Ecotoxicology and Environmental Safety*, 211:111912. https://doi.org/10.1016/j.ecoenv.2021.111912

Hou XR, Lv T, Xu J, et al., 2021. Energy sustainability evaluation of 30 provinces in China using the improved entropy weight-cloud model. *Ecological Indicators*, 126:107657. https://doi.org/10.1016/j.ecolind.2021.107657

Hou YL, Kuang WH, Dou YY, 2023. Observing the compact trend of urban expansion patterns in global 33 megacities during 2000–2020. *Journal of Geographical Sciences*, 33(12):2359–2376. https://doi.org/10.1007/s11442-023-2180-0

Hu XW, Su YQ, Ren KF, et al., 2021. Measurement and influencing factors of urban traffic ecological resilience in developing countries: A case study of 31 Chinese cities. *Regional Sustainability*, 2(3):211–223. https://doi.org/10.1016/j.regsus.2021.10.001

Huang BJ, Chen YX, McDowall W, et al., 2019. Embodied GHG emissions of building materials in Shanghai. *Journal of Cleaner Production*, 210:777–785. https://doi.org/10.1016/j.jclepro.2018.11.030

Ji LQ, Xin J, Zhao CC, 2023. Energy consumption and carbon emissions: Measurement and analysis—The case of Shanghai in China. *Waste and Biomass Valorization*, 14(1):365–375. https://doi.org/10.1007/s12649-022-01876-w

Jiang HB, Lin YX, Luo X, et al., 2022. Understanding the selection of cross-border import e-commerce platforms through the DANP and TOPSIS techniques: A multi-study analysis. *Journal of Global Information Technology Management*, 25(1):26–53. https://doi.org/10.1080/1097198X.2021.2022397

Jiang WZ, Tan Y, 2022. Overview on failures of urban underground infrastructures in complex geological conditions due to heavy rainfall in China during 1994–2018. *Sustainable Cities and Society*, 76:103509. https://doi.org/10.1016/j.scs.2021.103509

Kang LG, Wu XJ, Yuan XX, et al., 2022. Performance indices review of the current integrated energy system: From history and projects in China. *Sustainable Energy Technologies and Assessments*, 53:102785. https://doi.org/10.1016/j.seta.2022.102785

Unedited

Kim S, Chang S, Castro-Lacouture D, 2020. Dynamic modeling for analyzing impacts of skilled labor shortage on construction project management. *Journal of Management in Engineering*, 36(1):04019035. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000720

Kılkış Ş, 2022. Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems. *Renewable and Sustainable Energy Reviews*, 167:112733. https://doi.org/10.1016/j.rser.2022.112733

Kori E, Gondo T, 2012. Environmental sustainability: Reality, fantasy or fallacy. 2012 2nd International Conference on Environment and BioScience, p.28–29 https://doi.org/10.7763/IPCBEE.2012.V44.22

Kumar S, Kumar N, Vivekadhish S, 2016. Millennium Development Goals (MDGs) to Sustainable Development Goals (SDGs): Addressing unfinished agenda and strengthening sustainable development and partnership. *Indian Journal of Community Medicine : Official Publication of Indian Association of Preventive & Social Medicine*, 41(1):1–4. https://doi.org/10.4103/0970-0218.170955

Ledbetter R, Hughes S, Rollings M, et al., 1991. Large centrifuge: A critical army capability for the future

Leng LY, Mao XH, Jia HF, et al., 2020. Performance assessment of coupled green-grey-blue systems for Sponge City construction. *Science of The Total Environment*, 728:138608. https://doi.org/10.1016/j.scitotenv.2020.138608

Li B, Han SW, Wang YF, et al., 2020a. Feasibility assessment of the carbon emissions peak in China's construction industry: Factor decomposition and peak forecast. *Science of The Total Environment*, 706:135716. https://doi.org/10.1016/j.scitotenv.2019.135716

Li J, Wang L, Lin XS, et al., 2020b. Analysis of China's energy security evaluation system: Based on the energy security data from 30 provinces from 2010 to 2016. *Energy*, 198:117346. https://doi.org/10.1016/j.energy.2020.117346

Li N, Wang F, Magoua JJ, et al., 2022. Interdependent effects of critical infrastructure systems under different types of disruptions. *International Journal of Disaster Risk Reduction*, 81:103266. https://doi.org/10.1016/j.ijdrr.2022.103266

Li W, Jiang S, Zhao Y, et al., 2023a. Comprehensive evaluation and scenario simulation of water resources carrying capacity: A case study in Xiong'An New Area, China. *Ecological Indicators*, 150:110253. https://doi.org/10.1016/j.ecolind.2023.110253

Li Y, Ye SS, Wu QZ, et al., 2023b. Analysis and countermeasures of the "7.20" flood in Zhengzhou. *Journal of Asian Architecture and Building Engineering*, 22(6):3782–3798. https://doi.org/10.1080/13467581.2023.2208195

Lin SH, Zhang HJ, Li JH, et al., 2022. Evaluating smart office buildings from a sustainability perspective: A model of hybrid multi-attribute decision-making. *Technology in Society*, 68:101824. https://doi.org/10.1016/j.techsoc.2021.101824

Lin Y, Li HX, 2022. An analysis of urban vacant land on the Macau Peninsula. *Journal of Geographical Research*, 5(3):13–21. https://doi.org/10.30564/jgr.v5i3.4595

Liu B, Zhang FL, Qin XS, et al., 2021a. Spatiotemporal assessment of water security in China: An integrated supply-demand coupling model. *Journal of Cleaner Production*, 321:128955. https://doi.org/10.1016/j.jclepro.2021.128955

Liu BS, Yang ZQ, Xue B, et al., 2022a. Formalizing an integrated metric system measuring performance of urban sustainability: Evidence from China. *Sustainable Cities and Society*, 79:103702. https://doi.org/10.1016/j.scs.2022.103702

Liu J, Wang J, Ding XY, et al., 2020. Assessing the mitigation of greenhouse gas emissions from a green infrastructure-based urban drainage system. *Applied Energy*, 278:115686. https://doi.org/10.1016/j.apenergy.2020.115686

Liu JJ, Chen NC, Chen ZQ, et al., 2022b. Towards sustainable smart cities: Maturity assessment and development pattern recognition in China. *Journal of Cleaner Production*, 370:133248. https://doi.org/10.1016/j.jclepro.2022.133248

Liu Q, 2022. Identifying and correcting the defects of the saaty analytic hierarchy/network process: A comparative study of the saaty analytic hierarchy/network process and the markov chain-based analytic network process. *Operations Research Perspectives*, 9:100244. https://doi.org/10.1016/j.orp.2022.100244

Liu SC, Peng FL, Qiao YK, et al., 2021b. Evaluating disaster prevention benefits of underground space from the perspective of urban resilience. *International Journal of Disaster Risk Reduction*, 58:102206. https://doi.org/10.1016/j.ijdrr.2021.102206

Lu C, Shi L, Zhao XC, et al., 2021a. Evaluation and planning of urban geological and ecological environment quality. *Arabian Journal of Geosciences*, 14(2):71. https://doi.org/10.1007/s12517-020-06335-1

Lu XH, Zhang YW, Lin CR, et al., 2021b. Analysis and comprehensive evaluation of sustainable land use in China: Based on sustainable development goals framework. *Journal of Cleaner Production*, 310:127205. https://doi.org/10.1016/j.jclepro.2021.127205

Luke TW, 2005. Neither sustainable nor development: reconsidering sustainability in development. *Sustainable development*, 13(4):228–238. https://doi.org/10.1002/sd.284

Luo J, Chen SY, Sun X, et al., 2020. Analysis of city centrality based on entropy weight TOPSIS and population mobility: A case study of cities in the Yangtze River Economic Belt. *Journal of Geographical Sciences*, 30(4):515–534. https://doi.org/10.1007/s11442-020-1740-9

Unedited

Luo XY, Ren MY, Zhao JH, et al., 2022. Life cycle assessment for carbon emission impact analysis for the renovation of old residential areas. *Journal of Cleaner Production*, 367:132930. https://doi.org/10.1016/j.jclepro.2022.132930

Lyu HM, Shen SL, Zhou A nan, et al., 2020. Risk assessment of mega-city infrastructures related to land subsidence using improved trapezoidal FAHP. *Science of The Total Environment*, 717:135310. https://doi.org/10.1016/j.scitotenv.2019.135310

Ma CX, Peng FL, Qiao YK, et al., 2022. Evaluation of spatial performance of metro-led urban underground public space: A case study in Shanghai. *Tunnelling and Underground Space Technology*, 124:104484. https://doi.org/10.1016/j.tust.2022.104484

Mahmoud S, Hussein M, Zayed T, et al., 2022. Multiobjective optimization model for the life cycle cost-sustainability trade-off problem of building upgrading using a generic sustainability assessment tool. *Journal of Construction Engineering and Management*, 148(7):04022050. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002281

Mapar M, Jafari MJ, Mansouri N, et al., 2020. A composite index for sustainability assessment of health, safety and environmental performance in municipalities of megacities. *Sustainable Cities and Society*, 60:102164. https://doi.org/10.1016/j.scs.2020.102164

Marrero M, Puerto M, Rivero-Camacho C, et al., 2017. Assessing the economic impact and ecological footprint of construction and demolition waste during the urbanization of rural land. *Resources, Conservation and Recycling*, 117:160–174. https://doi.org/10.1016/j.resconrec.2016.10.020

Mayyas A, Qattawi A, Omar M, et al., 2012. Design for sustainability in automotive industry: A comprehensive review. *Renewable and sustainable energy reviews*, 16(4):1845–1862. https://doi.org/10.1016/j.rser.2012.01.012

Mebratu D, 1998. Sustainability and sustainable development: Historical and conceptual review. *Environmental Impact Assessment Review*, 18(6):493–520. https://doi.org/10.1016/S0195-9255(98)00019-5

Moslem S, Alkharabsheh A, Ismael K, et al., 2020. An integrated decision support model for evaluating public transport quality. *Applied Sciences*, 10(12):4158. https://doi.org/10.3390/app10124158

Mou Y, Luo Y, Su Z, et al., 2021. Evaluating the dynamic sustainability and resilience of a hybrid urban system: Case of Chengdu, China. *Journal of Cleaner Production*, 291:125719 https://doi.org/10.1016/j.jclepro.2020.125719

Nefeslioglu HA, Sezer EA, Gokceoglu C, et al., 2013. A modified analytical hierarchy process (M-AHP) approach for decision support systems in natural hazard assessments. *Computers & Geosciences*, 59:1–8. https://doi.org/10.1016/j.cageo.2013.05.010

Ouyang M, 2014. Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety*, 121:43–60. https://doi.org/10.1016/j.ress.2013.06.040

Pinto FST, Fogliatto FS, Qannari EM, 2014. A method for panelists' consistency assessment in sensory evaluations based on the Cronbach's alpha coefficient. *Food Quality and Preference*, 32:41–47. https://doi.org/10.1016/j.foodqual.2013.06.006

Qian XS, Yu JY, Dai RW, 1993. A new discipline of science — The study of open complex giant system and its methodology. *Journal of Systems Engineering and Electronics*, 4(2):2–12

Qiu WG, Liu Y, Lu F, et al., 2020. Establishing a sustainable evaluation indicator system for railway tunnel in China. *Journal of Cleaner Production*, 268:122150. https://doi.org/10.1016/j.jclepro.2020.122150

Redclift M, 2005. Sustainable development (1987–2005): an oxymoron comes of age. *Sustainable development*, 13(4):212–227. https://doi.org/10.1002/sd.281

Reed R, Bilos A, Wilkinson S, et al., 2009. International comparison of sustainable rating tools. *Journal of Sustainable Real Estate*, 1(1):1–22. https://doi.org/10.1080/10835547.2009.12091787

Sharifi A, 2021. Urban sustainability assessment: An overview and bibliometric analysis. *Ecological Indicators*, 121:107102. https://doi.org/10.1016/j.ecolind.2020.107102

Shehab MJ, Kassem I, Kutty AA, et al., 2022. 5G networks towards smart and sustainable cities: A review of recent developments, applications and future perspectives. *IEEE Access*, 10:2987–3006. https://doi.org/10.1109/ACCESS.2021.3139436

Shi YJ, Zhai GF, Xu LH, et al., 2021. Assessment methods of urban system resilience: From the perspective of complex adaptive system theory. *Cities*, 112:103141. https://doi.org/10.1016/j.cities.2021.103141

Shin S, Lee S, Judi DR, et al., 2018. A systematic review of quantitative resilience measures for water infrastructure systems. *Water*, 10(2):164. https://doi.org/10.3390/w10020164

Silva M, Leal V, Oliveira V, et al., 2018. A scenario-based approach for assessing the energy performance of urban development pathways. *Sustainable Cities and Society*, 40:372–382. https://doi.org/10.1016/j.scs.2018.01.028

Stefaniec A, Hosseini K, Xie J, et al., 2020. Sustainability assessment of inland transportation in China: A triple bottom line-based network DEA approach. *Transportation Research Part D: Transport and Environment*, 80:102258 https://doi.org/10.1016/j.trd.2020.102258

Su WH, Zhang DC, Zhang CH, et al., 2020. Sustainability assessment of energy sector development in China and European Union. *Sustainable Development*, 28(5):1063–1076.

Unedited

https://doi.org/10.1002/sd.2056

Sun L, Zhang T, Liu S, et al., 2021. Reducing energy consumption and pollution in the urban transportation sector: A review of policies and regulations in Beijing. *Journal of Cleaner Production*, 285:125339 https://doi.org/10.1016/j.jclepro.2020.125339

Sun SD, Jin JX, Xia M, et al., 2020. Vehicle emissions in a middle-sized city of China: Current status and future trends. *Environment International*, 137:105514. https://doi.org/10.1016/j.envint.2020.105514

Sun X, Liu XS, Li F, et al., 2017. Comprehensive evaluation of different scale cities' sustainable development for economy, society, and ecological infrastructure in China. *Journal of Cleaner Production*, 163:S329–S337. https://doi.org/10.1016/j.jclepro.2015.09.002

Tang WZ, Pei YS, Zheng H, et al., 2022. Twenty years of China's water pollution control: Experiences and challenges. *Chemosphere*, 295:133875. https://doi.org/10.1016/j.chemosphere.2022.133875

Tao Y, Li F, Crittenden J, et al., 2019. Measuring urban environmental sustainability performance in China: A multi-scale comparison among different cities, urban clusters, and geographic regions. *Cities*, 94:200–210. https://doi.org/10.1016/j.cities.2019.06.014

Tian YF, Zuo SD, Ju JH, et al., 2024. Local carbon emission zone construction in the highly urbanized regions: Application of residential and transport CO2 emissions in Shanghai, China. *Building and Environment*, 247:111007. https://doi.org/10.1016/j.buildenv.2023.111007

Ubilla J, Abdoun T, Sasanakul I, et al., 2008. New Orleans levee system performance during hurricane Katrina: London Avenue and Orleans Canal South. *Journal of Geotechnical and Geoenvironmental Engineering*, 134(5):668–680. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:5(668)

Umdu DÇ, Alakavuk E, Koyuncu A, 2021. BREEAM communities: Criteria aim, status, strengths and weaknesses. 2021 International Conference on Digital Age & Technological Advances for Sustainable Development (ICDATA), p.208–215. https://doi.org/10.1109/ICDATA52997.2021.00048

van Loon JJ, Krausse J, Cunha H, et al., 2008. The large diameter centrifuge, LDC, for life and physical sciences and technology. Proceedings of the 'Life in Space for Life on Earth Symposium', p.92.1-92.2.

Wang J, Liu GH, Wang JY, et al., 2021. Current status, existent problems, and coping strategy of urban drainage pipeline network in China. *Environmental Science and Pollution Research*, 28(32):43035–43049. https://doi.org/10.1007/s11356-021-14802-9

Wang JQ, Ma XW, Zhang J, et al., 2022a. Impacts of digital technology on energy sustainability: China case study. *Applied Energy*, 323:119329. https://doi.org/10.1016/j.apenergy.2022.119329

Wang MZ, Tian SQ, Gao L, 2024. Comprehensive dynamic evaluation model and empirical research of provincial resilience in China. *Ecological Indicators*, 165:112208. https://doi.org/10.1016/j.ecolind.2024.112208

Wang SL, Hong L, Chen XG, 2012. Vulnerability analysis of interdependent infrastructure systems: A methodological framework. *Physica A: Statistical Mechanics and its Applications*, 391(11):3323–3335. https://doi.org/10.1016/j.physa.2011.12.043

Wang XC, Yang L, Wang YT, et al., 2022b. Imbalances in virtual energy transfer network of China and carbon emissions neutrality implications. *Energy*, 254:124304. https://doi.org/10.1016/j.energy.2022.124304

Wang YJ, Liu ZY, Huang L, et al., 2020. Development and evaluation of a scheme system of joint prevention and control of PM2.5 pollution in the Yangtze River Delta region, China. *Journal of Cleaner Production*, 275:122756. https://doi.org/10.1016/j.jclepro.2020.122756

Wang ZY, Chen ZQ, Ma CP, et al., 2022c. Nationwide evaluation of urban energy system resilience in China using a comprehensive index method. *Sustainability*, 14(4):2077. https://doi.org/10.3390/su14042077

WCED U, 1987. Our Common Future-Brundtland Report (No. UN Doc. A/42/427). *United Nations World Commission on Environment and Development*

Wells NS, Clough TJ, Condron LM, et al., 2013. Biogeochemistry and community ecology in a spring-fed urban river following a major earthquake. *Environmental Pollution*, 182:190–200. https://doi.org/10.1016/j.envpol.2013.07.017

Wu JS, Yi TY, Wang H, et al., 2022. Evaluation of medical carrying capacity for megacities from a traffic analysis zone view: A case study in Shenzhen, China. *Land*, 11(6):888. https://doi.org/10.3390/land11060888

Wu S, Sun K, Bi Y, et al., 2024. Carbon reduction potential of housing retrofits: Evidence from China. *Renewable and Sustainable Energy Reviews*, 200:114580

Xing YY, Wang K, Lu JJ, 2020. Exploring travel patterns and trip purposes of dockless bike-sharing by analyzing massive bike-sharing data in Shanghai, China. *Journal of Transport Geography*, 87:102787. https://doi.org/10.1016/j.jtrangeo.2020.102787

Xun XL, Yuan YB, 2020. Research on the urban resilience evaluation with hybrid multiple attribute TOPSIS method: an example in China. *Natural Hazards*, 103(1):557–577. https://doi.org/10.1007/s11069-020-04000-0

Yan DH, Wu SH, Zhou SL, et al., 2021. Healthy city development for Chinese cities under dramatic imbalance: evidence from 258 cities. *Sustainable Cities and Society*, 74:103157. https://doi.org/10.1016/j.scs.2021.103157

Yang HY, Zhang XR, Fu K, et al., 2023. Comprehensive evaluation of urban water supply security based on the

Unedited

VIKOR-TOPSIS method. *Environmental Science and Pollution Research*, 30(3):8363–8375. https://doi.org/10.1007/s11356-022-24493-5

Yang PJ, Peng S, Benani N, et al., 2022a. An integrated evaluation on China's provincial carbon peak and carbon neutrality. *Journal of Cleaner Production*, 377:134497. https://doi.org/10.1016/j.jclepro.2022.134497

Yang YY, Li J, Huang Q, et al., 2021. Performance assessment of sponge city infrastructure on stormwater outflows using isochrone and SWMM models. *Journal of Hydrology*, 597:126151. https://doi.org/10.1016/j.jhydrol.2021.126151

Yang Z, Clemente MF, Laffréchine K, et al., 2022b. Resilience of social-infrastructural systems: Functional interdependencies analysis. *Sustainability*, 14(2):606. https://doi.org/10.3390/su14020606

Yang ZS, Yang H, Wang H, 2020. Evaluating urban sustainability under different development pathways: A case study of the Beijing-Tianjin-Hebei region. *Sustainable Cities and Society*, 61:102226. https://doi.org/10.1016/j.scs.2020.102226

Yi PT, Dong QK, Li WW, 2019. Evaluation of city sustainability using the deviation maximization method. *Sustainable Cities and Society*, 50:101529. https://doi.org/10.1016/j.scs.2019.101529

Yuan X, Xue N, Han Z, 2021. A meta-analysis of heavy metals pollution in farmland and urban soils in China over the past 20 years. *Journal of Environmental Sciences*, 101:217–226. https://doi.org/10.1016/j.jes.2020.08.013

Yuan YW, Zhang Q, Chen SM, et al., 2022. Evaluation of comprehensive benefits of sponge cities using meta-analysis in different geographical environments in China. *Science of The Total Environment*, 836:155755. https://doi.org/10.1016/j.scitotenv.2022.155755

Zhang GR, Feng W, Lei Y, et al., 2022a. Generation and evolution mechanism of systemic risk (SR) induced by extreme precipitation in Chinese urban system: A case study of Zhengzhou "7 20" incident. *International Journal of Disaster Risk Reduction*, 83:103401. https://doi.org/10.1016/j.ijdrr.2022.103401

Zhang HR, Zhang JW, Song JF, 2022b. Analysis of the threshold effect of agricultural industrial agglomeration and industrial structure upgrading on sustainable agricultural development in China. *Journal of Cleaner Production*, 341:130818. https://doi.org/10.1016/j.jclepro.2022.130818

Zhang LL, Long RY, Li WB, et al., 2020. Potential for reducing carbon emissions from urban traffic based on the carbon emission satisfaction: Case study in Shanghai. *Journal of Transport Geography*, 85:102733. https://doi.org/10.1016/j.jtrangeo.2020.102733

Zhang P, Chen PR, Xiao F, et al., 2022c. The impact of information infrastructure on air pollution: empirical evidence from China. *International Journal of Environmental Research and Public Health*, 19(21):14351. https://doi.org/10.3390/ijerph192114351

Zhang SX, Li ZF, Ning X, et al., 2021. Gauging the impacts of urbanization on CO2 emissions from the construction industry: Evidence from China. *Journal of Environmental Management*, 288:112440. https://doi.org/10.1016/j.jenvman.2021.112440

Zhang WL, Lin PH, Wang NY, et al., 2018. Probabilistic prediction of postdisaster functionality loss of community building portfolios considering utility disruptions. *Journal of Structural Engineering*, 144(4):04018015. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001984

Zhang Y, Zhang YJ, Zhang H, et al., 2022d. Evaluation on new first-tier smart cities in China based on entropy method and TOPSIS. *Ecological Indicators*, 145:109616. https://doi.org/10.1016/j.ecolind.2022.109616

Zhao RD, Fang CL, Liu J, et al., 2022a. The evaluation and obstacle analysis of urban resilience from the multidimensional perspective in Chinese cities. *Sustainable Cities and Society*, 86:104160. https://doi.org/10.1016/j.scs.2022.104160

Zhao X, Li H, Qi Y, 2022b. Are Chinese Cities Prepared to Manage the Risks of Extreme Weather Events? Evidence from the 2021.07.20 Zhengzhou Flood in Henan Province

Zhao ZT, Cheng HM, Wang S, et al., 2022c. SCC-UEFAS, an urban-ecological-feature based assessment system for sponge city construction. *Environmental Science and Ecotechnology*, 12:100188. https://doi.org/10.1016/j.ese.2022.100188

Zhong M, Lin KR, Tang GP, et al., 2020. A framework to evaluate community resilience to urban floods: A case study in three communities. *Sustainability*, 12(4):1521. https://doi.org/10.3390/su12041521

Zhu DM, Chang YJ, 2020. Urban water security assessment in the context of sustainability and urban water management transitions: An empirical study in Shanghai. *Journal of Cleaner Production*, 275:122968. https://doi.org/10.1016/j.jclepro.2020.122968

Electronic supplementary materials

Sections S1-S5

中文概要

题　目：城市工程系统可持续能力评价指标初探

作　者：吴俊杰[1,2]，庄端阳[1,2]，边学成[1,2]，陈云敏[1,2]

机　构：[1]浙江大学，超重力科学与技术研究院，浙江杭州，310058；[2]浙江大学，软弱土与环境土工教育部重点实验室，浙江杭州，310058

目　的：我国城市化已进入中后期阶段，高密度城市工程通过岩土环境耦联形成城市工程系统，强烈

Unedited

的时空耦联性导致城市工程系统服役脆弱性显著，严重削弱了城市可持续能力。本文旨在构建多维度的城市工程系统可持续性评价指标体系，研究不同子系统间的耦联关系，为高密度城市工程系统可持续运维提供量化评估工具。

创新点： 1. 综述了城市工程系统可持续能力评价研究现状及验证方法，指出了既有评价研究的不足；2. 综合韧性、低碳及环保三种维度，构建了包含 66 项指标的城市工程系统可持续性评价指标体系。

方　法： 1. 通过文献计量与标准化筛选，基于 8 个城市工程子系统确定了 66 项指标，涵盖韧性、低碳与环保维度（补充材料 S4 部分）；2. 基于 DANP 法和熵权法分别确认了评价指标的主、客观权重，并利用最大离差法计算了指标组合权重（补充材料 S5 部分）；3. 通过对国内 6 个超大城市的实证分析，验证了所构建评价体系的合理性，并根据计算结果提出了对应城市工程系统可持续能力的提升方法。

结　论： 1. 本文构建的评价指标体系可以准确合理地量化分析各评价对象的城市工程系统可持续能力，其中地质灾害监测能力和移动通信保障能力是影响城市工程系统可持续能力最关键的两项指标；2. 所选国内超大城市的城市工程系统可持续能力综合评价呈现明显的不均衡性，同一城市在不同维度上的表现也有明显差异。

关键词： 城市工程系统；岩土环境；时空耦联；可持续能力；评价指标

Unedited