Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-024-03016-2 OPEN

Decomposing the comprehensive efficiency of major cities into divisions on governance, ICT and sustainability: network slack-based measure model

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The rapid urbanization and population growth in major cities have given rise to enduring urban challenges, prompting local governments to assess urban development performance and customize urban planning strategies to meet these challenges. This study aims to formulate an evaluation framework for the comprehensive efficiency of major cities, centering on governance, Information and Communication Technology (ICT), and sustainability as fundamental aspects. Distinct from prior research, the framework employs the network slack-based measure (SBM) to unravel efficiency, concurrently scrutinizing input/output slack and link efficiency. Utilizing the network SBM model, the study assesses the comprehensive operational efficiencies of 38 major Chinese cities spanning from 2015 to 2019. The application of the Kruskal–Wallis test discerns differences in comprehensive efficiency between coastal and inland areas. The results indicate that governance, ICT, and sustainability significantly influence the comprehensive operations of cities. In addition to general and short-term policies, the implementation of the National New-Type Urbanization Plan by the Chinese central government has led to an increase in the number of cities demonstrating sustainable efficiency. Despite fluctuations in the efficiency gap during the study period, coastal cities consistently outperform their inland counterparts in terms of efficiency. Persistent geographical disparities underscore the imperative for balanced development. While acknowledging positive strides in sustainable urbanization, the study emphasizes the ongoing necessity to address the adverse impacts of urban development, positioning governance, ICT, and sustainability as indispensable elements in confronting the multifaceted challenges inherent in urban development. The research findings contribute significantly to the field of urban efficiency evaluation, accentuating the collaborative impact of governance, ICT, and sustainability.

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Introduction

The onset of the Industrial Revolution has drastically transformed cities worldwide, driven by economic development and globalization. Urbanization, a global trend, is anticipated to surge, constituting 70% of the world's population by 2050 (Sodiq et al. 2019). China, as a leading developing country, has been actively promoting urbanization through its policies and economic growth. Between 1978 and 2019, the urbanization rate in China experienced substantial growth, rising from 17.9% to 60.6% (NBS 2020). Throughout this period, the Chinese government emerged as a pivotal force, actively steering the trajectory of government-led urbanization. However, negative impacts from urban development, such as environmental pollution, social injustice, and wasteful resource utilization, are evident from the experiences of other developed nations (Wang et al. 2014). This has led urban planners to focus on sustainable cities, which take into consideration sustainable goals such as energy conservation, energy efficiency, human capital development, building standards, and food waste management (Sodiq et al. 2019). Despite the Chinese government's efforts to promote urbanization, it has also resulted in numerous problems, including a crowded urban populace, employment difficulties, and wealth disparity, leading to a development crisis (Gries and Grundmann 2018; Zheng et al. 2014). To ensure the sustainability of each city, the Chinese government has formulated sustainable development plans, which are essential in promoting sustainable urbanization. The "National New-type Urbanization Plan (2014–2020)," introduced in March 2014, is an example of China's commitment to sustainable urbanization. This transformative plan signifies a shift from land-centered to people-centered urbanization, emphasizing a "human-centered and environmentally friendly path" for the upcoming decade (Chen et al. 2018; Taylor 2015). In addition to general and short-term policies, the National New-type Urbanization Plan is a nationwide, long-term, and far-reaching policy that warrants special attention for in-depth study. It establishes new developmental goals for China's robust urbanization process, outlining four primary objectives, including the enhancement of city sustainability (Chu 2020). Government policies and regulations exert a substantial impact on efficiency, exemplified by the influence of environmental regulatory policies on energy consumption efficiency (Chen and Gong 2017). Additionally, initiatives such as the Low Carbon City Pilot Project contribute to the overall improvement of carbon emission efficiency in pilot cities (Fu et al. 2021), while support policies for resource-depleted cities have significantly enhanced energy efficiency (Yu et al. 2022). By examining relative changes in cities within the context of the National New-Type Urbanization Plan, the external situation created by the policy becomes apparent. However, with the advancement of China's industrialization and urbanization, the focus of urban sustainability must extend beyond environmental assessment.

Effective governance is pivotal in steering urban development towards sustainability, as policies encompassing economic development, social welfare, and environmental protection profoundly influence urban sustainability. However, governance faces impediments such as centralization of power, political risks, and corruption, which can hinder the implementation of sustainable development policies (Neirotti et al. 2014). In tandem with governance, the integration of Information and Communication Technology (ICT) emerges as a transformative force in modern urban development (Odendaal 2003). As such, ICT presents an opportunity to address the problems of urbanization and is an effective means of realizing sustainable urban development and building eco-efficient smart cities. As the second-largest global economy, China has actively pursued the development of smart cities through substantial investments in ICT infrastructure. The information and communication technology (ICT) revolution has made cities more digitized and information-driven, with AI, digital currency and other services becoming a part of daily life (Yao et al. 2020; Yin et al. 2015). The government's focus on ICT aligns with global trends in smart city development, which leverage technology to address urban challenges and enhance overall urban well-being (Chourabi et al. 2012). Sustainable development, encompassing economic growth, environmental sustainability, and social inclusion, stands as the overarching goal in contemporary urban planning (Roseland 2000). The choice of governance, ICT, and sustainable development as the evaluation framework is rooted in their synergistic impact on urban sustainability. Effective governance is essential for creating and implementing policies that foster sustainability. ICT acts as an enabler, facilitating efficient resource management, data-driven decision-making, and smart solutions for urban challenges. Sustainable development, with its triple bottom line approach, provides a comprehensive lens to evaluate the economic, social, and environmental facets of urban systems.

Data Envelopment Analysis (DEA) is a non-parametric method assessing the efficiency of decision-making units (DMUs) through multiple inputs and outputs, enabling a quantifiable evaluation of a city's sustainability and efficiency. The literature suggests diverse indicator systems for sustainable cities, constructed with various DEA models. While common indicators like air quality and economic development exist, specific ones such as carbon emission reduction and energy efficiency have gained attention (Sheng et al. 2021; Hu and Wang 2006). Traditionally, traditional DEA models treated DMUs as "black boxes," focusing on slack in input or output spaces (Suzuki and Nijkamp 2017). However, network DEA breaks down internal organizational efficiency, evaluating both system and process efficiency (Kao 2009; Yang 2016). Despite the widespread use of traditional DEA models, the advanced network DEA approach is underutilized. For instance, Suzuki and Nijkamp (2017) employed advanced CCR and context-dependent (CD) models to rank the efficiency of 35 major global cities. Similarly, Yan et al. (2018) used CCR and BCC models to assess the sustainable development performance of 287 cities in China. The prevailing urban operational efficiency indicator system, utilizing the DEA method, especially within the Chinese context, exposes significant deficiencies. This study proactively closes this gap by introducing a comprehensive evaluation framework that systematically incorporates urban governance, ICT, and sustainability efficiency. Surpassing the constraints of prior models that predominantly focused on individual dimensions, the research propounds a more holistic perspective on urban operations, thereby enriching the understanding of multifaceted efficiency dynamics.

The groundbreaking introduction of the network SBM model in this study facilitates the concurrent assessment of urban governance and ICT efficiency, offering a nuanced comprehension of their intricate interplay and collective impact on urban sustainability. This addresses a conspicuous gap in existing literature where studies often employed traditional DEA models, neglecting the complex relationships between governance, ICT, and sustainability. The incorporation of the network SBM model presents a methodological advancement that significantly refines the precision of efficiency evaluations. The study addresses the research gap by introducing a scoring system using the network SBM of the DEA model. The aim is to identify inefficient DMUs and establish a new urban operational indicator framework. This framework integrates basic indicators of the triple bottom line (economic, social, and environmental sustainability) with governance and ICT indicators to comprehensively address inefficiency (Chang et al. 2013).

This study makes several notable contributions to the field: (1) Filling a gap in China's urban efficiency indicator system, this study incorporates urban governance, ICT, and sustainability in the DEA-based evaluation framework. (2) The network SBM model enables simultaneous assessment of urban governance and ICT efficiency, providing a precise evaluation of input and output efficiency. (3) Examining 38 major cities in China, this study scrutinized the shifts in relative rankings concerning urban governance, ICT, and sustainability efficiency over five years after the urbanization plan, thereby offering valuable insights into the efficacy of urban reforms. (4) Empirical results from this study provide evidence of differences in urban comprehensive operation, governance, ICT, and sustainability efficiency in coastal and inland areas of China, and shed light on the causes of these disparities.

Literature review

Urban governance. The inception of Local Agenda 21 was a turning point in the development of urban systems and policies, with the aim of promoting sustainable changes through innovative approaches (Raven et al. 2019). The effective planning of urban development by governments is crucial in achieving sustainable development, as policies in areas such as economic development, social welfare, and environmental protection all impact urban sustainability. However, factors such as the centralization of power, political risk, and corruption can impede a city's ability to implement sustainable development policies (Neirotti et al. 2014). In China, the top-down governance system, with its centralized administrative power, results in cities relying heavily on the leadership of the national government and the support of local governments (Raven et al. 2019). Adequate access to public funds can facilitate the implementation of plans. China's transition from a regionally decentralized authoritarian (RDA) regime, characterized by political centralization and economic regional decentralization, to a more decentralized system, has allowed local governments to impact regional economic development, environmental protection, and social stability through reforms and policies, under the supervision of the central government (Xu 2011). Urban development strategies in Chinese cities may vary, but all must align with the central government's requirements.

As the second-largest economy globally, the Chinese government is pursuing the development of smart cities, which can be achieved through the integration of information and communication technology (ICT) (Chourabi et al. 2012). In 2012, the government first proposed the construction of smart cities, and by 2019, it had invested in over 700 projects in more than 500 cities, with 290 smart cities built and evaluated annually (Zhang et al. 2021; Zhu et al. 2019). The central government has invested significant funds in many cities, requested local governments to establish ICT infrastructure, and announced policies focused on environmental protection and ICT (Dameri et al. 2019) to bridge the gaps between different cities.

The literature has established the importance of governance in promoting sustainability. Research by Feng et al. (Feng et al. 2022) indicated a positive relationship between government spending and green economic performance, while Bulkeley and Betsill (Bulkeley and Betsill 2005) illustrated how land use and transportation planning in the UK helped mitigate climate change and reduce energy consumption and waste. Owens and Cowell (Owens and Cowell 2011) suggested the need for changes in traffic road planning and car control to reduce greenhouse gas emissions in the transportation sector.

The chosen variables associated with government efficiency, derived from extant research, encompass a spectrum of dimensions. These comprise general government public expenditures (Fan et al. 2021; Xiao et al. 2021)alongside specific categories of public spending. The delineated areas encompass public finance expenditures related to science and technology, financial allocations for education, disbursements for health-related initiatives, investments in infrastructure, and the quantification of municipal expenditures on a per capita basis (Kairui 2018; Ouertani et al. 2018). In this study, to assess the effectiveness of governance, fiscal revenues, expenditures, employment, and investment in science and technology were adopted as representative indicators, drawing on prior research and empirical evidence.

Urban ICT. Keidanren (2016) posits that the stages of social development span from the hunting society to the agricultural society, industrial society, information society, and finally, the super-intelligent society. The shift from Industry 3.0 to Industry 4.0 marks the transition from a machine-led manufacturing approach to a digital-led approach, driven by the emergence of technologies such as the Internet of Things (IoT) and Machine-to-Machine (M2M) communication (Oztemel and Gursev 2020). To achieve sustainable urban development, a city must pursue smart urban development and informatization (Yigitcanlar et al. 2019). Information and Communication Technology (ICT) has a vital role in transforming a city's economy, society, and spaces (Hollands 2008) and optimizing urban governance for sustainable development (Wang and Zhou 2022; Yao et al. 2020).

To improve a city's informatization level, the construction of ICT infrastructure is crucial, as well as the development and utilization of information resources. Informatization has the potential to accelerate the growth of information industries, create employment opportunities, and attract high-tech talent (Harrison et al. 2010). Furthermore, ICT can enhance city management systems, improve the quality of life for urban residents, and optimize service infrastructures such as air pollution monitoring and sewage treatment for environmental governance.

In the realm of current research, variables utilized for gauging ICT or smart cities encompass a diverse set of metrics. These include the count of fixed telephone users, mobile users, indicators for internet accessibility, the prevalence of broadband users, the employed population, the number of information practitioners, the level of broadband network construction, the coverage rate of optical fiber access, per capita postal service volume, business volume of post and telecommunication services and the real GDP per capita within the information industry (ITU 2003; Kairui 2018; Wang and Feng 2015). This study assesses urban ICT efficiency based on the utilization and application of the information industry, the extent of ICT infrastructure construction, and revenue from Telecommunication Services.

Urban sustainability. The Brundtland Report of 1987 emphasized the need for cities to have plans for sustainable development, which has since been widely recognized globally (Bulkeley and Betsill 2005). For sustainable growth, cities must make efficient use of their resources and prioritize practicality (Walter et al. 1992).

China underwent reforms and opened up in 1978, resulting in rapid economic growth but also environmental degradation and increased social pressure (Chen et al. 2016). These issues, commonly referred to as "big city disease," pose a threat to the development of Chinese cities. In response, the Chinese government made sustainable development a basic international strategy in 1995, seeking to balance economic growth with social and environmental considerations (Lu et al. 2019).

To address the negative impacts of economic growth on cities, China introduced the "National New-Type Urbanization Plan (2014–2020)" in 2014. The plan aimed to promote sustainable cities by setting objectives for resources, environment, and infrastructure and reducing regional development disparities through spatial distribution and scaling (Chen et al. 2016; Wang et al. 2015).

The concept of sustainable development has three main objectives: economic development, environmental sustainability, and social inclusion (Sachs 2012). This aligns with the idea of the triple bottom line (TBL), first introduced by Elkington in 1994, which advocates for companies to balance profitability, social responsibility, and environmental responsibility for sustainability (Elkington 2018). Over time, the TBL has been interpreted in various ways, such as social, environmental, and economic performance, sustainable development, sustainable environment, sustainable communities, and impact on society, the environment, and economic sustainability (Vanclay 2004).

The TBL is a crucial aspect of urban sustainability and is widely used as a guiding principle in evaluating sustainability performance by integrating social, economic, and environmental variables (Chen and Zhang 2020). Governments worldwide use the TBL as part of their comprehensive assessments of their economy, environment, and society, which form the key conceptual requirements of the City Sustainability Index (CSI) (Mori and Christodoulou 2012). The TBL can be used to evaluate not only the overall sustainability of a city but also the sustainability of its urban communities (Berardi 2013).

This study assesses the sustainable development of 38 cities in China based on the TBL of sustainability. In earlier studies, indicators pertinent to urban sustainability were encompassed within a comprehensive set of metrics, spanning both economic and environmental dimensions. These indicators included CO2 emissions, concentrations of PM10, GDP as the anticipated output, the green rate of construction areas, per capita park green area, total energy consumption, water consumption, annual power consumption, unit employees, GDP, and the greening coverage of existing urban areas (Kairui 2018; Li et al. 2016, 2018; Shi et al. 2009). Additionally, various social indicators were considered, with social metrics encompassing the basic old-age insurance coverage ratio, unemployment insurance coverage ratio, and the insurance ratio of medical insurance for urban employees, while economic metrics included the urban unemployment rate (Li et al. 2018). The factors affecting sustainable development are defined as urban economy, social development, and environmental protection. The study evaluates the effectiveness of sustainable development using representative indicators such as per-capita GRP, employment rate, insurance coverage, and inhalable particle concentration.

Data envelopment analysis (DEA). DEA was first proposed by Charnes et al. (1978), which was also known as a CCR model, in which, the boundary of an efficiency frontier is constructed by linear programming. When compared with this frontier, the relative efficiency value between Decision Making Units (DMUs) can be identified. After 40 years of academic development, DEA has been applied to many studies. To solve the limitations of the CCR model, many different models have been derived from production possibility sets based on different assumptions, such as BCC, NIRS, FDH, etc. (Berardi 2013; Färe et al. 1985; Tulkens 1993). The traditional DEA treats DMU as a black box, which means that only a set of outputs appears after a set of inputs enters the DMU (Tone and Tsutsui 2014). The disadvantage is ignoring the internal structure or linking of the DMUs, causing the input and output to change proportionally (Tone and Tsutsui 2009).

Tone (2001) proposed a model based on the slacks-based measure, which is a non-radial method. Compared with CCR and BCC models, it can directly deal with excessive input and insufficient output. To make DEA modeling more flexible, Färe and Grosskopf (2000) proposed the use of a network model of "links" in the multi-stage input and output progress. In other words, network DEA uses the link variable to consider the internal structure of the DMU, which can further analyze the resource allocation of different stages and processes. Tone and Tsutsui (2009) proposed the network SBM Model based on SBM and network DEA, which can deal with any network structure in which divisions are connected and links are directed. Network SBM can evaluate comprehensive efficiency and increase the function of evaluating the efficiency of each department. They presented efficiency measuring cases of enterprises, hospitals, financial holding companies, etc. to prove the applicability and practicality of the model.

Recent studies have utilized various DEA models to evaluate urban efficiency. Santana et al. (Santana et al. 2014) used the output-oriented DEA-BCC model to compare the sustainable development of BRICS countries. Sueyoshi and Yuan (2015) evaluated the sustainability of economic development and air quality in China using DEA, while Yang et al. (2016) employed an extended urban metabolism framework and DEA model with negative output to evaluate the sustainability of 22 cities in Taiwan. He et al. (2016) used the DEA and ecological efficiency of Jiangsu Province to assess sustainability, while Feng et al. (2017) used DEA to assess the sustainable development efficiency of cities in coal-fired power plant regions. Yu and Zhang (2019) developed a non-convex meta frontier DEA model to measure the energy efficiency of cities in China, and Sun et al. (2020) used a common weight DEA to evaluate the sustainability performance of Southeast Asia. Additionally, Zhang et al. (2020) applied the SBM-DDF model to analyze the green innovation efficiency of Xi'an. Cui and Wang (2023) utilize a model based on the Super-SBM to assess the influence of China's green finance efficiency on the attainment of its multidimensional green finance objectives, while Miao and Zhou (2023) utilized the Stochastic Frontier Model approach to analyze the economic efficiency of Hohhot-Baotou-Ordos-Yulin urban agglomeration.

Methodology

Research framework. This study proposes a model based on the network SBM model of Kao (2014), which is used to evaluate the efficiency affecting urban governmental departments, information technology, and urban sustainability. The theoretical framework is divided into three stages: Governance, ICT, and Sustainability with 18 indicators. The overall framework is shown in Fig. 1.

The present study aims to evaluate the efficiency of urban sustainability by using a three-stage framework. In the first stage, fiscal revenue and employment are considered as inputs, while fiscal expenditures and capital expenditures for the information and communication technology (ICT) sector are considered as outputs. In the second stage, the input measures are the number of employees and the city's ICT infrastructure, which includes the number of users of telephones and Internet services. The output revenue generated in this stage is used as the economic input in the third stage, which focuses on the sustainability inputs of water supply, annual electricity consumption, and total gas supply. These inputs represent the resource and energy use of the city. In the sustainability stage, economic, social, and environmental performance indicators are used to measure the efficiency of the city's sustainability, as represented by the three aspects of the triple bottom line of sustainability. The economic indicators are

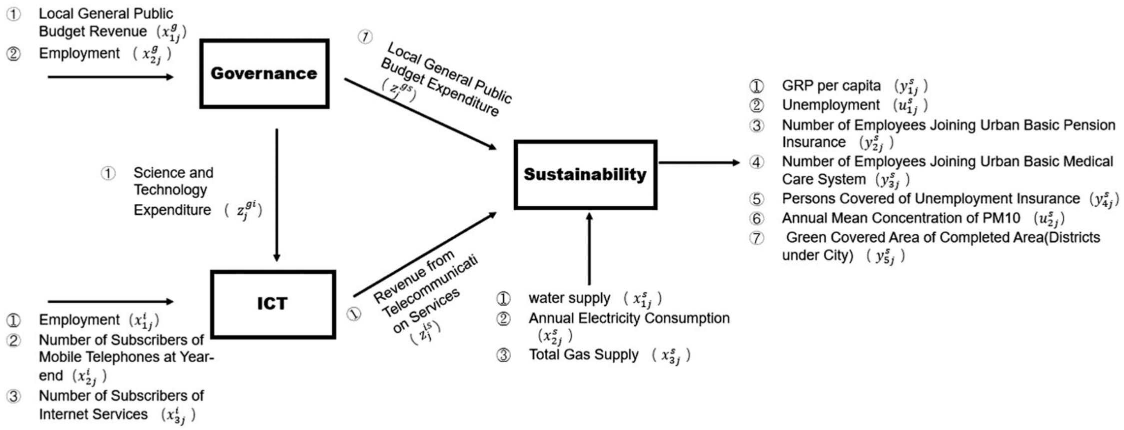

Fig. 1 The framework for measuring the comprehensive efficiency of major cities. This diagram illustrates the decomposition of major cities' comprehensive efficiency into three main components: Governance, ICT (Information and Communication Technology), and Sustainability.

gross regional product (GRP) and unemployment; the social indicators are three kinds of social insurance, while the environmental indicators are PM10 and green covered areas. It is important to note that the employment rate and PM10 are negative outputs.

To comprehensively analyze the indicators used to assess the basic characteristics of urban construction, Tables 1 and 2 were compiled, which include data collected for each indicator over a five-year period, amounting to 190 cases. The output indicator values, excluding negative indicators, have shown an upward trend in the selected urban areas. Typically, cities with higher indicator values, excluding negative indicators, are first-tier cities with strong overall economic development, such as Shanghai, Beijing, and Shenzhen. These cities have prioritized sustainable development, resulting in stable negative indicator values despite the urban expansion. Electricity consumption, which is influenced by factors such as overall economic development, key electricity-consuming industries, geography, and climate, exhibits the greatest variation among the indicators and can serve as an indirect measure of urban development. For example, Shanghai, as a leading commercial center, had the highest electricity consumption of 1568,5775GWh in 2019, while Suzhou ranked second with 1544,4800GWh due to its thriving industrial sector (NBS 2020).

Network performance evaluation model. This study evaluated 38 cities, which were used as the evaluation decision-making units (DMUs), then DMU (j = 1, 2, …, n). At the stage of governance efficiency, each DMU$_j$ has two input items $x_{r0}^g(r = 1, 2)$ and produces link activity Z_j^{gi} to the ICT efficiency stage and link activity Z_j^{gs} in the sustainability efficiency stage. At the stage of ICT efficiency, each DMU$_j$ has three input variables $x_{t0}^i(t = 1, 2$ produce a link activity Z_j^{is}. At the stage of sustainability efficiency, each DMU$_j$ has three input items $x_{p0}^s(p = 1, 2, 3)$ produce five output items $y_{qj}^s(q = 1, 2\ldots5)$ and two undesirable output items $u_{k0}^s(k = 1, 2)$. The comprehensive efficiency score (σ_0^*) of DMU$_0$ based on the network DEA-SBM model can be defined as:

subject to

$$x_{r0}^g = \sum_{j=1}^{n} x_{rj}^g\lambda_j^g + xs^g \quad (1.1)$$

$$Z_0^{gi} = \sum_{j=1}^{n} Z_j^{gi}\lambda_j^g - sz^g \quad (1.2)$$

$$\sum_{j=1}^{n} Z_j^{gi}\lambda_j^g = \sum_{j=1}^{n} Z_j^{gi}\lambda_j^i \quad (1.3)$$

$$Z_0^{gi} = \sum_{j=1}^{n} Z_j^{gi}\lambda_j^o - sz^i \quad (1.4)$$

$$Z_0^{gs} = \sum_{j=1}^{n} Z_j^{gs}\lambda_j^g - ez^g \quad (1.5)$$

$$\sum_{j=1}^{n} Z_j^{gs}\lambda_j^g = \sum_{j=1}^{n} Z_j^{gs}\lambda_j^s \quad (1.6)$$

$$Z_0^{gs} = \sum_{j=1}^{n} Z_j^{gs}\lambda_j^s - ez^s \quad (1.7)$$

$$x_{t0}^i = \sum_{j=1}^{n} x_j^i\lambda_j^i + xs^i \quad (1.8)$$

$$Z_0^{is} = \sum_{j=1}^{n} Z_j^{is}\lambda_j^i - sz^i \quad (1.9)$$

$$\sum_{j=1}^{n} Z_j^{is}\lambda_j^i = \sum_{j=1}^{n} Z_j^{is}\lambda_j^s \quad (1.10)$$

$$Z_0^{is} = \sum_{j=1}^{n} Z_j^{is}\lambda_j^s - sz^s \quad (1.11)$$

$$x_{p0}^s = \sum_{j=1}^{n} x_j^s\lambda_j^s + xs^s \quad (1.12)$$

$$y_{q0}^s = \sum_{j=1}^{n} y_{qj}^s\lambda_j^s - s_q^s \quad (1.13)$$

$$\text{Min}\sigma_0^* = \frac{w_g\left[1-\frac{1}{2}\left(\sum_{r=1}^{2}\frac{xs^g}{x_{r0}^g}\right)\right]+w_i\left[1-\frac{1}{3}\left(\sum_{t=1}^{3}\frac{xs^i}{x_{t0}^i}\right)\right]+w_s\left[1-\frac{1}{5}\left(\sum_{p=1}^{3}\frac{xs^s}{x_{p0}^s}+\sum_{k=1}^{2}\frac{b_k^s}{u_{k0}^s}\right)\right]}{w_g\left[1+\frac{1}{2}\left(\frac{sz^g}{Z_0^{gi}}+\frac{ez^g}{Z_0^{gs}}\right)\right]+w_i\left[1+\left(\frac{ez^i}{Z_0^{is}}\right)\right]+w_s\left[1+\frac{1}{5}\left(\sum_{q=1}^{5}\frac{s_q^s}{y_{q0}^s}\right)\right]} \quad (1)$$

Table 1 Symbols and definitions of the indicators.

Stage		Indicator	Symbol	Definition
Governance	Input	Local General Public Budget Revenue (100 million CNY)	x^g_{1j}	The income obtained by the local government's financial participation in the distribution of social products, including various tax and non-tax revenues.
		Employment (10,000 person)	x^g_{2j}	Including Public Management, Social Security and Social Organization.
	Link 1–2	Expenditure for Science and Technology (100 million CNY)	z^{gi}_j	Including research and development expenditures.
	Link 1–3	Local General Public Budget Expenditure (100 million CNY)	z^{gs}_j	The local government allocates the funds raised to meet the needs of economic construction and various projects.
ICT	Input	Employment (10,000 person)	x^i_{1j}	Including Information Transmission, Computer Services and Software.
		Number of Subscribers of Mobile Telephones at Year-end (10,000 households)	x^i_{2j}	Refers to all kinds of telephone users who have gone through the account opening registration procedures in the business of telecommunications operation enterprises.
		Number of Subscribers of Internet Services (10,000 households)	x^i_{3j}	Refers to the number of Chinese residents aged 6 and above who have used the Internet in the past six months.
	Link 2-3	Revenue from Telecommunication Services (100 million CNY)	z^{is}_j	Refers to the total number of various types of telecommunication services provided by telecommunication companies in currency.
Sustainability	Input	water supply (10,000 tons)	x^s_{1j}	Refers to the total amount of water, provided by various water sources to water users, including water loss.
		Annual Electricity Consumption (10,000 kwh)	x^s_{2j}	Including electricity consumption for industry, agriculture, residents, and public facilities.
		Total Gas Supply (10,000 tons)	x^s_{3j}	Refers to the amount of gas supplied to users by gas companies throughout the year. Including sales volume and loss volume.
	Output	GRP per capita (CNY)	y^s_{1j}	Gross Regional Product (Current Prices).
		Unemployment %	u^s_{1j}	The ratio of urban registered unemployed persons to the sum of urban units employed persons, out-of-work employees, self-employed, urban private enterprises and urban registered unemployed persons.
		Number of Employees Joining Urban Basic Pension Insurance (10,000 person)	y^s_{2j}	Refers to the number of employees who participated in the basic endowment insurance for urban employees in accordance with the policy at the end of the reporting period and have established payment record files in social security agencies.
		Number of Employees Joining Urban Basic Medical Care System (10,000 person)	y^s_{3j}	Refers to the total number of employees who participated in basic medical insurance for employees at the end of the reporting period in accordance with relevant state regulations.
		Persons Covered by Unemployment Insurance (10,000 person)	y^s_{4j}	Refers to the number of employees including urban enterprises and public institutions who have participated in unemployment insurance in accordance with national laws or required by local governments at the end of the reporting period.
		Annual Mean Concentration of PM10 (ug/m^3)	u^s_{2j}	The content of particulate matter is less than 10 microns in diameter per square.
		Green Covered Area of Completed Area (Districts under City) %	y^s_{5j}	Green Covered Area as % of Completed Area.

Source: National Bureau of Statistics of China (NBS).

$$u^s_0 = \sum_{j=1}^{n} u^s_j \lambda^s_j + b^s \tag{1.14}$$

$$\sum_{j=1}^{n} \lambda^g_j = 1 \tag{1.15}$$

$$\sum_{j=1}^{n} \lambda^i_j = 1 \tag{1.16}$$

$$\sum_{j=1}^{n} \lambda^s_j = 1 \tag{1.17}$$

$$xs^g, sz^g, sz^i, ez^g, ez^s, xs^i, sz^i, sz^s, xs^s, s^s_q, b^s, \lambda^g, \lambda^i, \lambda^s \geq 0$$

The λ^g_j (j = 1, 2, …, n), λ^i_j (j = 1, 2, …, n) and λ^s_j (j = 1, 2, …, n) are the intensity variables of the jth city in constructing the Governance, ICT, and sustainability efficiency frontiers. The weights of the three efficiency stages respectively denoted by w_g, $w_i$and w_s, represent the relative significance and contribution. In this study, they satisfy $w_g + w_o + w_i = 1$. The $xs^g, xs^i, and\ xs^s$ represent the excess input in the efficiency stages of governance, ICT, and sustainability. The $sz^g ez^g ez^i$ respectively denotes the shortage of the link activity in the governance and ICT efficiency stage, s^s_q denotes the shortage of the qth output in sustainability efficiency, and b^s denotes the excess of the undesirable output in the sustainability efficiency stage.

The calculation of governance efficiency is subject to Eqs. (1.1)–(1.7); The calculation of ICT efficiency is subject to Eqs. (1.8)–(1.11); The calculation of Sustainable efficiency is subject to Eqs. (1.12)–(1.14). Adding Eqs. (1.15)–(1.17) allow the returns to scale to be variable.

Decompose DMU$_0$ into governance efficiency score (σ^{g*}_0), ICT efficiency score (σ^{i*}_0) and sustainability efficiency score (σ^{s*}_0) using the optimal results ($xs^{g*}, sz^{g*}, sz^{i*}, ez^{g*}, ez^{s*}, xs^{i*}, sz^{i*}, sz^{s*}, xs^{s*},$

Table 2 Descriptive statistics of the indicators.

Indicator	Units	Number	Minimum	Maximum	Mean	Std. deviation.
x_{1j}^{g}	100 million CNY	190	100.7599	7165.0984	1195.5623	1320.2298
x_{2j}^{g}	10,000 persons	190	3.4419	50.2400	12.0166	8.4295
z_{j}^{gi}	100 million CNY	190	5.1647	554.9817	71.2066	102.2994
z_{j}^{gs}	100 million CNY	190	424.1331	8351.5363	1579.7109	1603.5313
x_{1j}^{i}	10,000 persons	190	0.4930	84.4109	8.1363	13.6860
x_{2j}^{i}	10,000 households	190	535	4052	1471.3300	853.9530
x_{3j}^{i}	10,000 households	190	100	1372	346.2300	191.1870
z_{j}^{is}	100 million CNY	190	55.9827	619.6743	162.4095	127.9770
x_{1j}^{s}	10,000 tons	190	7733	252377	68643.1100	54138.0960
x_{2j}^{s}	10,000 kwh	190	1057122	15685775	5116769.0700	3272583.3110
x_{3j}^{s}	10,000 tons	190	4673	1923347	180311.6500	298448.8030
y_{1j}^{s}	CNY	190	49066	203489	105358.2900	33212.6870
u_{1j}^{s}	%	190	1.2000	4.1000	2.5886	0.7189
y_{2j}^{s}	10,000 persons	190	72.3326	1651.6233	432.9510	351.6581
y_{3j}^{s}	10,000 persons	190	25.7400	1682.5174	396.9232	353.9767
y_{4j}^{s}	10,000 persons	190	49.3053	1294.7809	271.1881	267.1967
u_{2j}^{s}	ug/m3	190	42	167	74.2510	25.6054
y_{5j}^{s}	%	190	32.8100	53.5900	41.4427	3.0539

Source: Author calculations.

$s_q^{s*}, b^{s*}, \lambda^{g*}, \lambda^{i*}, \lambda^{s*}$) in Eq. (1) as follows:

$$\text{Minimize } \sigma_0^{g*} = \frac{1 - \frac{1}{2}\left(\sum_{r=1}^{2} \frac{xs^g}{x_{r0}^g}\right)}{1 + \frac{1}{2}\left(\frac{sz^g}{Z_0^{gi}} + \frac{ez^g}{Z_0^{gs}}\right)} \quad (2)$$

$$\text{Minimize } \sigma_0^{i*} = \frac{1 - \frac{1}{3}\left(\sum_{t=1}^{3} \frac{xs^i}{x_{t0}^i}\right)}{1 + \left(\frac{ez^i}{Z_0^{is}}\right)} \quad (3)$$

$$\text{Minimize } \sigma_0^{s*} = \frac{1 - \frac{1}{5}\left(\sum_{p=1}^{3} \frac{xs^s}{x_{p0}^s} + \sum_{k=1}^{2} \frac{b_k^s}{u_{k0}^s}\right)}{1 + \frac{1}{5}\left(\sum_{q=1}^{5} \frac{s_q^s}{y_{q0}^s}\right)} \quad (4)$$

Sources of samples. Golany and Roll (1989) suggested that when using the Data Envelopment Analysis (DEA) model, the number of observations should not be less than twice the sum of inputs and outputs. Based on this recommendation, the sample selection in this study consists of the top 38 cities in the 2020 urban business charm ranking, released by New First-tier Cities Research, which includes 4 first-tier cities, 15 new first-tier cities, and 19 second-tier cities. The observation period for this study ranges from 2015 to 2019. The data used in this study are derived from various official sources, including the China City Statistical Yearbook (2016–2020), China Statistical Yearbook (2016–2020), the Yearbook of China Communication (2016–2020), and statistical yearbooks of each province and city.

In 2014, the State Council of the People's Republic of China defined major cities as those with a population of over 1 million (The State Council 2020). The largest city in terms of population among the selected cities was Chongqing with 34.16 million people, while the smallest was Dongguan with 2.51 million people in 2019. The total population of the 38 selected cities is approximately 313.28 million, accounting for approximately 22% of the national population. These cities possess favorable economic conditions and infrastructure, which attract large numbers of migrant workers. As highly populated areas, they are confronted with various challenges such as social contradictions, environmental pollution, and traffic congestion. However, the selected cities are widely dispersed across China, which results in significant variations in geographical environments and natural resources, economic structures, and population densities. Therefore, the efficiency of urban sustainability is influenced by a range of factors that vary across the selected cities.

Empirical results

Efficiency value analysis. The study employed the network SBM model to analyze the overall efficiency of 38 cities in China from 2015 to 2019. Figure 2 presents a visual representation of this analysis, providing a comprehensive perspective on performance across various spatial DMUs or over time. The illustration comprises five maps, each corresponding to a specific year. Serial numbers are assigned to the positions of 38 cities on each map, and blue indicators signify the overall efficiency of each city. The diverse shades of color convey distinct levels of overall efficiency, with dark blue indicating high efficiency and light blue indicating low efficiency. Positioned on the right side of each map is a color legend elucidating the relationship between different color shades and their corresponding levels of overall efficiency. Across all five maps, a discernible gradient is observed from light blue to dark blue, particularly from inland to coastal areas, indicating a notable difference in efficiency between coastal and inland cities.

The meticulous presentation of detailed efficiency values for each Decision Making Unit (DMU) in Table 3 offers a nuanced perspective on the comprehensive operational efficiency and specific stage efficiencies (governance, ICT, and sustainability) across 38 Chinese cities from 2015 to 2019. In this table, a score of 1 signifies optimal comprehensive efficiency or stage efficiency in the cities. Notably, the most substantial enhancement in urban efficiency occurred in the sustainability stage, with the number of effective cities rising from 25 in 2015 to 29 in 2019. On average, coastal cities surpass their inland counterparts in overall efficiency, reflected in their higher scores.

As indicated by Table 3, specific cities have consistently held a relative ranking within the lower 15% over the last five years, like Wuhan, Tianjin, and Shijiazhuang. Conversely, certain cities have demonstrated considerable enhancements in their relative rankings during this five-year period, exemplified by Harbin's ascent

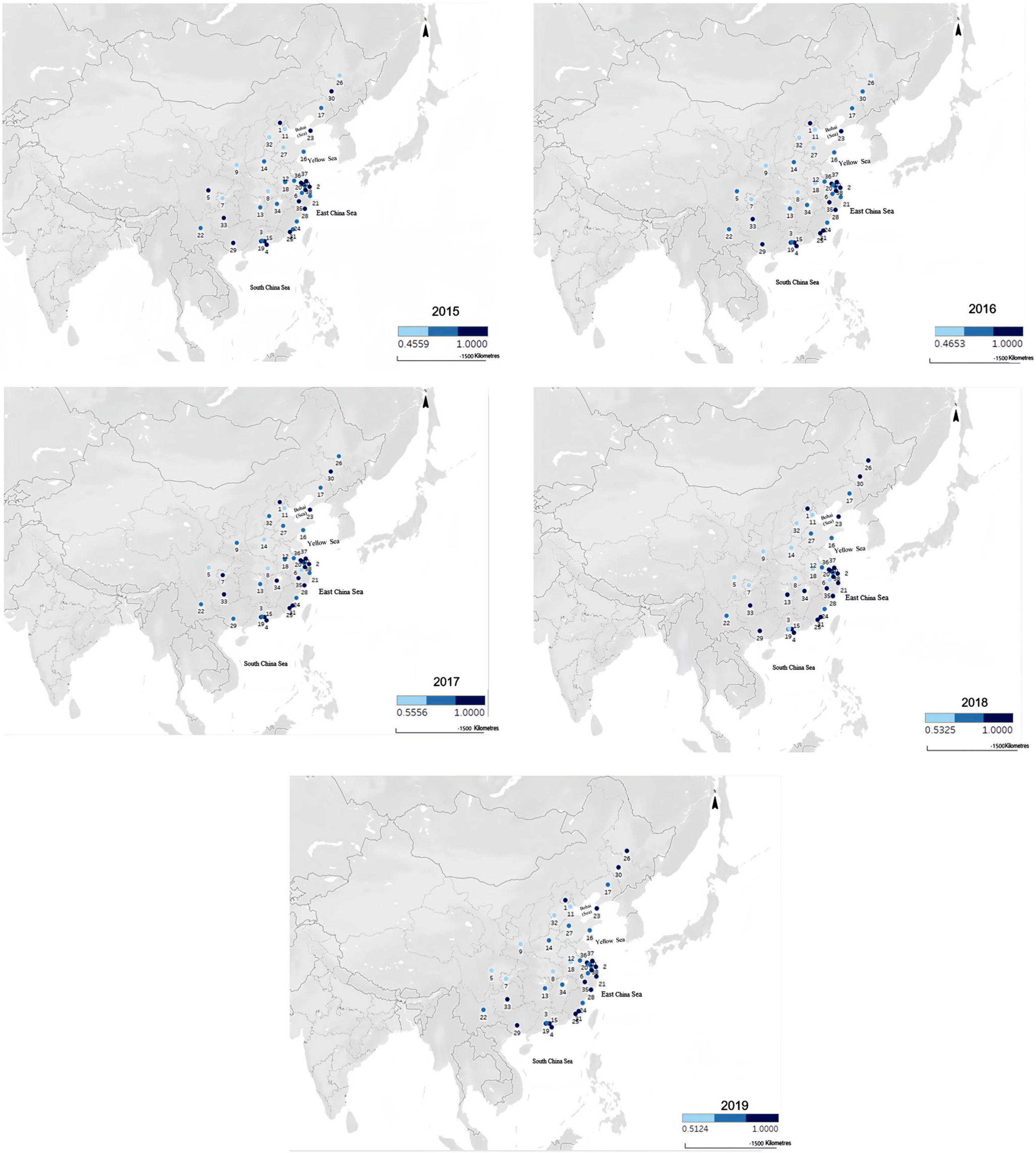

Fig. 2 Spatial distribution of comprehensive efficiency in 38 cities during 2015–2019. This figure demonstrates the spatial distribution and efficiency scores of 38 cities, using a color gradient to signify varying levels of comprehensive efficiency, and reveals that coastal cities consistently outperform inland cities from 2015 to 2019.

from the 33rd position in 2015 to the 16th in 2019. Nevertheless, contrasting trends are observable as well, with cities like Shenzhen experiencing a decline, transitioning from the top position in 2015 to the 18th in 2019.

Changzhou and Jiaxing consistently emerge as benchmark cities in the annual comparative analysis of comprehensive efficiency from 2015 to 2019, showcasing an exceptional ability to optimally allocate and utilize resources. The governments of Changzhou and Jiaxing strategically leverage their geographical advantages to foster the development of characteristic industries. Furthermore, they prioritize the judicious use of financial funds to support coordinated urban resource management and environmental development. For instance, Changzhou strategically shifted its economic structure from a reliance on the secondary industry to a focus on the tertiary industry in 2015, concurrently committing to the ambitious goal of building an

Table 3 Overall and divisional efficiencies for cities in China.

	2015					2016					2017					2018					2019				
DMU	Overall	Rank	Governance	ICT	Sustainability	Overall	Rank	Governance	ICT	Sustainability	Overall	Rank	Governance	ICT	Sustainability	Overall	Rank	Governance	ICT	Sustainability	Overall	Rank	Governance	ICT	Sustainability
1. Beijing[a]	0.99993	9	0.99996	0.99985	1	0.99995	7	0.9999	0.99995	1	0.99994	6	1	0.99981	1	0.99991	9	0.99991	0.99982	1	0.99993	8	0.99993	0.99987	1
2. Shanghai[a]	0.99999	8	0.99998	1	1	0.99997	6	0.99993	0.99999	1	1	1	1	1	1	0.99999	8	0.99996	1	1	0.99998	7	0.99994	1	1
3. Guangzhou[a]	0.76918	27	0.57774	0.7298	1	0.7305	23	0.41994	0.77156	1	0.7949	25	0.62943	0.75527	1	0.67029	31	0.25407	0.86632	0.88137	0.74034	27	0.39729	0.82402	0.99968
4. Shenzhen[a]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.85689	20	0.62797	0.94269	1	0.85439	18	0.61261	0.95055	1
5. Chengdu[a]	0.94793	10	0.99802	0.84595	0.99981	0.64701	30	0.20667	0.73435	1	0.65304	35	0.30084	0.65826	1	0.63613	32	0.21623	0.69216	1	0.61833	33	0.21197	0.64303	1
6. Hangzhou[a]	0.67772	31	0.42097	0.6122	1	0.65932	29	0.34491	0.63304	1	0.68148	34	0.41767	0.62676	1	0.67963	30	0.41622	0.62267	1	0.70301	30	0.37715	0.73188	1
7. Chongqing[a]	0.56534	34	0.33891	0.72103	0.61452	0.47483	37	0.26182	0.50121	0.61929	0.99634	7	0.99403	0.99886	0.99613	0.53251	38	0.43067	0.70696	0.48553	0.54135	36	0.35221	0.64944	0.59777
8. Wuhan[a]	0.45585	38	0.33444	0.43447	0.5756	0.46527	38	0.33418	0.4238	0.61252	0.55979	37	0.48688	0.53138	0.64982	0.60781	33	0.43373	0.65394	0.72411	0.59301	34	0.36351	0.69866	0.70615
9. Xi'an[a]	0.51925	35	0.33104	0.61654	0.59534	0.49438	35	0.31272	0.57655	0.57677	0.71225	31	0.4399	0.69684	1	0.54941	36	0.33685	0.676	0.6337	0.5685	35	0.38167	0.72722	0.59218
10. Suzhou[a]	0.78937	24	0.58654	0.78158	1	0.81095	16	0.69051	0.74235	1	0.78349	28	0.64651	0.70398	1	0.80259	23	0.5844	0.82338	1	0.75842	23	0.4605	0.81475	1
11. Tianjin[a]	0.50066	37	0.53036	0.36247	0.60344	0.52444	34	0.57232	0.40069	0.59167	0.59732	36	0.70457	0.48567	0.60108	0.57099	34	0.42621	0.65624	0.62248	0.53854	37	0.38554	0.51013	0.70469
12. Nanjing	0.71899	28	0.44751	0.71028	0.99909	0.69622	25	0.39259	0.69651	0.99952	0.73166	30	0.39502	0.79994	1	0.72873	28	0.45976	0.72643	1	0.70347	29	0.36187	0.74856	1
13. Changsha	0.7779	25	0.5803	0.75341	1	0.80586	17	0.56524	0.85233	1	0.84049	19	0.64624	0.87523	1	0.87177	17	0.64679	0.96853	1	0.67526	31	0.69113	0.63528	0.69556
14. Zhengzhou[a]	0.79012	23	0.71333	0.65702	1	0.74727	22	0.47566	0.76615	1	0.5556	38	0.51436	0.4964	0.63467	0.55093	35	0.40218	0.59609	0.6304	0.74226	26	0.3849	0.84188	1
15. Dongguan	0.86848	16	0.76105	0.8444	1	0.95287	9	1	0.8586	1	0.9603	9	1	0.88089	1	0.95928	11	1	0.87785	1	0.91475	12	1	0.74425	1
16. Qingdao	0.80181	21	0.58461	0.82081	1	0.72981	24	0.51809	0.67135	1	0.79478	26	0.57444	0.8099	1	0.83569	21	0.62961	0.87745	1	0.78764	21	0.58159	0.78132	1
17. Shenyang	0.7698	26	0.542	0.76753	0.99985	0.66773	27	0.55185	0.72094	0.72065	0.79586	24	0.67238	0.71521	1	0.79762	25	0.61803	0.77483	1	0.76857	22	0.63333	0.67238	1
18. Hefei	0.80731	19	0.57301	0.84996	0.99889	0.5835	33	0.56161	0.63826	0.55368	0.78794	27	0.54063	0.82363	0.99949	0.68467	29	0.56993	0.79706	0.68686	0.63078	32	0.58637	0.67583	0.63016
19. Foshan	1	1	1	1	1	0.87989	14	0.83982	0.81025	0.98912	0.8867	15	0.98913	0.88896	0.79464	0.82497	22	0.83923	0.88033	0.76271	0.88327	14	0.87638	0.79909	0.9738
20. Wuxi	0.82673	17	0.64579	0.8344	1	0.78992	20	0.58201	0.78776	1	0.91358	13	0.74073	1	1	0.86818	18	0.70821	0.89632	1	0.83518	19	0.62826	0.87727	1
21. Ningbo	0.80596	20	0.55657	0.86132	1	0.80338	18	0.58995	0.82019	1	0.81763	21	0.76303	0.78058	0.90566	0.89113	15	0.78291	0.89046	1	0.85535	17	0.67288	0.89315	1
22. Kunming	0.70033	30	0.76346	0.70059	0.64351	0.66201	28	0.60662	0.72576	0.65442	0.74992	29	0.69475	0.79515	0.75793	0.80129	24	0.61599	0.78787	1	0.74941	25	0.61253	0.6357	1
23. Dalian	0.89359	15	0.68076	1	1	0.87831	15	0.6461	0.98883	1	0.88354	17	0.67531	0.97532	1	0.95207	12	1	0.85621	1	0.87279	15	0.70777	0.91061	1
24. Fuzhou	0.79443	22	0.63804	0.74525	1	0.79033	19	0.56314	0.80786	1	0.83127	20	0.59504	0.89878	1	0.75432	27	0.50951	0.75345	1	0.75517	24	0.51585	0.74967	1
25. Xiamen	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.9593	9	1	0.8779	1
26. Harbin[a]	0.56704	33	0.52215	0.62012	0.56046	0.60908	31	0.5011	0.7476	0.58496	0.81397	23	0.49618	0.94571	1	0.89479	14	0.68437	1	1	0.86475	16	0.59426	1	1
27. Jinan	0.62339	32	0.45999	0.64996	0.75465	0.60869	32	0.43828	0.71895	0.663	0.70846	32	0.4383	0.68708	1	0.76066	26	0.46125	0.82072	1	0.71999	28	0.43323	0.72672	1
28. Wenzhou	0.91547	12	1	0.74641	1	0.93842	11	1	0.81527	1	0.95891	10	0.99992	0.8768	1	0.93816	13	1	0.81449	1	0.93431	11	1	0.80294	1
29. Nanning	1	1	1	1	1	1	1	1	1	1	0.81751	22	0.64489	0.80764	1	1	1	1	1	1	1	1	1	1	1
30. Changchun	1	1	1	1	1	0.78713	21	1	0.82812	0.58192	0.87386	18	0.65536	0.96622	1	1	1	1	1	1	1	1	1	1	1
31. Quanzhou	0.81323	18	0.65598	0.7837	1	0.88355	13	0.65066	1	1	0.90391	14	0.71174	1	1	0.85813	19	0.63983	0.93456	1	0.95065	10	0.90447	0.94747	1
32. Shijiazhuang[a]	0.51758	36	0.49006	0.81696	0.33736	0.49374	36	0.47476	0.68904	0.36812	0.70463	33	0.43232	0.68479	0.99613	0.54037	37	0.43362	0.72906	0.47349	0.51244	38	0.43688	0.67578	0.44743
33. Guiyang	0.94025	11	1	0.82076	1	0.95443	8	1	0.86329	1	0.92272	12	1	0.76816	1	0.96264	10	1	0.88793	1	0.91001	13	0.79877	0.93127	1
34. Nanchang	0.71716	29	0.94432	0.83049	0.48956	0.68578	26	0.87477	0.84553	0.45	0.97931	8	1	0.93792	1	0.8803	16	0.74817	0.89274	1	0.82322	20	0.59908	0.87057	1
35. Jinhua	0.89843	13	0.6953	1	1	0.94179	10	0.82538	1	1	0.93757	11	0.8842	0.92852	1	1	1	1	1	1	1	1	1	1	1
36. Changzhou	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
37. Nantong	0.8954	14	0.79795	0.88824	1	0.90186	12	0.78915	0.91643	1	0.88486	16	0.73315	0.92145	1	1	1	1	1	1	1	1	1	1	1
38. Jiaxing	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

[a]Denote cities with a permanent population exceeding 10 million at the end of 2019.

eco-friendly city. Jiaxing, on the other hand, has been consistently enhancing its Information and Communication Technology (ICT) infrastructure, integrating Internet elements into the urban landscape and gaining international recognition by hosting the World Internet Conference since 2014.

Beijing and Shanghai, as the largest cities in China, exhibit efficiency values close to 1, indicating highly effective overall operating efficiency, with minor adjustments in resource input required. Examining governance efficiency, Beijing and Shanghai consistently exhibit excellence, while some cities like Guangzhou and Dongguan display fluctuations in this dimension, contributing to overall disparities. In the field of ICT efficiency, Shenzhen and Beijing are consistent leaders, although certain inland cities like Changchun and Jiaxing demonstrate competitive ICT efficiencies. Generally, coastal cities tend to exhibit superior ICT efficiencies, influencing their overall standings. Sustainability efficiency reveals variations among cities, with Dongguan and Changzhou consistently attaining top scores, while inland cities such as Shijiazhuang face sustainability challenges, evident in their lower scores.

Slack analysis for improvements. To further analyze the efficiency of cities and provide improvement suggestions, this study gives suggestions for improvement to inefficient cities, this study analyzed the slack in input and output usage of each city in 2019 to obtain the potential improvement averages. Table 4 shows the results obtained by dividing the slack by the original values of the input, output, and intermediate products of each city. The values in the table represent the input proportion that should be reduced and the output proportion that should be increased. Take Shijiazhuang with the lowest score for overall efficiency as an example, the part of its input $x^g_{1j}, x^g_{2j}, x^i_{1j}, x^i_{2j}, x^i_{3j}, x^s_{1j}, x^s_{2j}, x^s_{3j}$ should be reduced, respectively, 31.96%, 32.88%, 68.1%, 50.38%, 50.46%, 11.46%, 24.46%, 66.84%.The part of its output $y^s_{1j}, y^s_{2j}, y^s_{3j}, y^s_{4j}, y^s_{5j}$ should be increased, respectively, 100.98%, 0, 18.18%, 55.92%, 0. The part of its undesirable output u^s_{1j}, u^s_{2j} should be reduced, respectively, by 41.8% and 53.39%.

Regarding urban governance, some essential inputs cannot be omitted, such as government revenue (x^g_{1j}) and ICT infrastructure (x^i_{2j}, x^i_{3j}). A larger input value indicates that the city has invested more resources in the construction of infrastructure. However, some inputs, such as the number of public management staff (x^g_{2j}), can be appropriately reduced. In the sustainability stage, to reduce the water and electricity consumption of urban residents (x^s_{1j}, x^s_{2j}), the government should advocate resource conservation for urban residents, promote the use of clean energy, and gradually reduce the use of gas. Therefore, in order to improve the overall operation governance efficiency of the city, it is necessary to increase GRP(y^s_{1j}), improve the coverage of social welfare insurance ($y^s_{2j}, y^s_{3j}, y^s_{4j}$) and urban greening coverage output (y^s_{5j}), while reducing the negative output of the employment rate and inhalable particles(u^s_{1j}, u^s_{2j}).

The effect of region on efficiencies. In the context of China's reform and opening up, the growth of urban conglomerates in the Yangtze River Delta and Pearl River Delta regions has driven the development of nearby cities, resulting in a geographical disparity between coastal and inland regions. To investigate the potential difference in comprehensive efficiency between these two regions, this study proposes the following research hypotheses: From 2014 to 2019, there was no difference between coastal and inland cities in comprehensive operation efficiency (H_a), governance efficiency (H_b), ICT efficiency (H_c) or sustainability efficiency (H_d). The Kruskal–Wallis test was employed to evaluate the significance level of 5% to compare the efficiency scores of comprehensive operation, governance, ICT, and sustainability based on the geographical location of the cities (coastal or inland).

According to the geographical location, the 38 cities are divided into coastal and inland areas, including 17 coastal cities and 21 inland cities. The results of the Kruskal–Wallis test are shown in Table 5. It is evident that H_aH_d showed significant differences in 2015; $H_aH_bH_cH_d$ exhibited significant differences in 2016; $H_aH_bH_c$ revealed significant differences in 2017. However, in 2018, $H_aH_bH_cH_d$ did not show significant differences. Intriguingly, $H_aH_bH_c$ again revealed significant differences in 2019.The findings of the Kruskal–Wallis test revealed significant differences in the comprehensive efficiency rates of coastal and inland cities from 2015 to 2017, as indicated by the statistical results.

Figure 3 presents the 5-year average overall efficiency of coastal and inland cities. The data indicates that from 2015 to 2019, although the gap between inland and coastal cities displayed a decreasing trend in the initial four years, it expanded in the fifth year. Average overall efficiency scores for coastal cities consistently exceeded 0.8, while those for inland cities struggled to surpass the 0.8 threshold. Importantly, the efficiency gap between inland and coastal cities during the sustainability phase was significant in 2015–2016 but became non-significant from 2017 onwards.

In the governance dimension, the average efficiency scores for inland cities from 2015 to 2019 were 0.662, 0.597, 0.652, 0.628, and 0.593, compared to coastal cities, which scored 0.780, 0.753, 0.808, 0.781, and 0.771. Regarding the ICT dimension, the average efficiency scores for inland cities over the same period were 0.762, 0.739, 0.791, 0.822, and 0.787, while coastal cities scored 0.871, 0.873, 0.889, 0.891, and 0.872.

It is evident that there is a substantial efficiency gap between inland and coastal cities in both governance and ICT. In conclusion, the overarching efficiency disparity between these two categories of cities can be predominantly attributed to variations in governance and ICT.

The Chinese government has acknowledged the necessity for balanced development between coastal and inland regions, implementing various policies to address this imperative. The "Urbanization Plan" initiated in 2014 aimed to balance the development of national land space, resulting in a gradual and orderly transfer of industries from coastal and international areas to urban agglomerations in the central and western regions of China. Inland cities such as Chengdu and Chongqing, and the middle reaches of the Yangtze River, have leveraged this initiative to undertake the process of new industrialization and enhance their infrastructure. Furthermore, the "Vision and Actions on Jointly Building Silk Road Economic Belt and 21st-Century Maritime Silk Road" plan, launched in 2015, not only prioritizes economic and urban development but also highlights the pivotal role of digital infrastructure in enhancing interconnectivity. This strategic initiative has spurred economic advancement across 18 provinces in China, fostering connections among provinces, cities, and nations spanning Asia, Africa, and Europe. By successfully propelling economic development along the Belt and Road, the plan has broadened the global reach and accessibility of inland cities (Xie et al. 2023). Despite the active efforts of inland cities to narrow the development gap, the economic prowess and well-established infrastructure of coastal cities persist as noteworthy factors that cannot be overlooked. The optimal scenario envisions concurrent progress for both coastal and inland cities.

Conclusions and policy implications

This study presents a novel model for evaluating the overall operational efficiency of urban areas using network SBM

Table 4 Potential improvement for the 38 cities.

DMU	INPUT		Link		INPUT			Link	INPUT			OUTPUT						
	x^g_{1j}(%)	x^g_{2j}(%)	z^{gi}_j(%)	z^{gs}_j(%)	x^i_{1j}(%)	x^i_{2j}(%)	x^i_{3j}(%)	z^{is}_j(%)	x^s_{1j}(%)	x^s_{2j}(%)	x^s_{3j}(%)	y^s_{1j}(%)	u^s_{1j}(%)	y^s_{2j}(%)	y^s_{3j}(%)	y^s_{4j}(%)	u^s_{2j}(%)	y^s_{5j}(%)
Beijing	0	−0.03	0	0	−0.01	−0.01	0	0	0	0	0	0	0	0	0	0	0	0
Shanghai	0	0	−0.03	−67.26	−0.01	−0.01	−0.01	−0.06	0	0	0	0	0	0	0	0	0	0
Guangzhou	−19.91	−15.28	0	−0.01	−64.83	−71.32	−44.66	0	−0.06	−0.03	0	0	−0.04	0	0	0.02	−0.02	0
Shenzhen	−7.96	−1.93	0	−68.56	−50.78	−43.21	−22.22	0	0	0	0	0	0	0	0	0	0	0
Chengdu	−46.23	−25.16	0	−70.68	−90.25	−74.1	−72.06	0	0	0	0	0	0	0	0	0	0	0
Hangzhou	−44.44	−9.19	0	−66.93	−79.55	−53.59	−53.71	0	0	0	0	0	0	0	0	0	0	0
Chongqing	−37.53	−32.59	−35.1	−36.46	−33.84	−79.04	−81.47	13.61	0	−27.3	−34.88	102.72	0	0	44.61	59.99	−8.38	11.1
Wuhan	−60.12	−0.15	−41.11	−83.46	−74.15	−57.39	−59.4	43.72	−28.11	0	−59.3	0	0	0	0	39.04	−26.11	8.27
Xi'an	−35.74	−18.82	−7.57	−9.99	−74.71	−61.04	−49.75	66.25	−16.57	0	−60.13	28.42	−26.64	0	21.96	32.08	−45.41	10.67
Suzhou	−33.71	−3.34	0	−60.1	−58.43	−45.02	−58.4	0	0	0	0	0	0	0	0	0	0	0
Tianjin	−69.72	−28.26	−54.82	−71.28	−71.12	−61.39	−51.83	25.11	0	−29.82	−48.94	7.95	−20.16	0	0.78	23	−16.37	14.19
Nanjing	−50.29	0	0	−65.1	−87.14	−44.92	−59.38	0	0	0	0	0	0	0	0	0	0	0
Changsha	−42.11	−30.84	−25.65	−28.39	−3.18	−49.78	−39.7	158.39	−18.24	−5.1	−45.17	0	−1.95	0	23.99	62.62	−16.64	7.01
Zhengzhou	−31.62	0	0	−45.83	−78.51	−52.44	−53.58	0	0	0	0	0	0	0	0	0	0	0
Dongguan	−23.62	−27.53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Qingdao	−43.74	0	0	−55.35	−48.47	−45.75	−31.3	0	0	0	0	0	0	0	0	0	0	0
Shenyang	−44.33	−21.2	0	−3.27	−42.51	−45.29	−22.2	0	0	0	0	0	0	0	0	0	0	0
Hefei	−24.73	−40.1	−28.44	−77.54	−50.48	−35.73	−37.88	145.69	−44.71	−11.52	−76.77	0	−15.42	2.5	6.19	3.25	−28.57	0.68
Foshan	−31.21	−8.97	3.59	−71.38	0	−31.52	−5.57	0.47	−3.51	−0.78	−3.53	0	−1.91	1.42	0	1.42	−0.6	0
Wuxi	−24.55	0	0	−17.69	−62.79	−17.85	−30.88	0	0	0	0	0	0	0	0	0	0	0
Ningbo	−21.37	0	0	−53.54	−32.63	−31.51	−34	0	0	0	0	0	0	0	0	0	0	0
Kunming	−33.68	−39.18	0	2.25	−47.03	−39.97	−29.24	0	0	0	0	0	0	0	0	0	0	0
Dalian	−17.88	0	0	16.2	−73.22	−14.1	−0.34	0	0	0	0	0	0	0	0	0	0	0
Fuzhou	−33.12	−16.95	0	−31.06	−68.08	−30.09	−47.08	0	0	0	0	0	0	0	0	0	0	0
Xiamen	−18.5	−5.92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Harbin	0	0	0	0	−73.53	−37.97	−10.22	0	0	0	0	0	0	0	0	0	0	0
Jinan	−51.81	−2.84	0	−57.51	−80.05	−38.61	−51.38	0	0	0	0	0	0	0	0	0	0	0
Wenzhou	−29.19	−10.22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nanning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Changchun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quanzhou	0	−10.51	0	62.17	0	−8.25	−20.41	0	0	0	0	0	0	0	0	0	0	0
Shijiazhuang	−31.96	−32.88	−12.05	56.69	−68.1	−50.38	−50.46	23.73	−11.46	−24.46	−66.84	100.98	−41.8	0	18.18	55.92	−53.39	0
Guiyang	0	−13.75	0	−28.48	−49.85	−10.52	0	0	0	0	0	0	0	0	0	0	0	0
Nanchang	−17.06	−8.82	0	−37.51	−45.41	−30.61	−44.26	0	0	0	0	0	0	0	0	0	0	0
Jinhua	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Changzhou	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nantong	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jiaxing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	−24.3718	−10.6437	−5.2942	−25.528	−39.7016	−30.5634	−27.9313	12.5503	−3.2279	−2.6055	−10.41	6.3176	−2.84	0.1032	3.045	7.2984	−5.1445	1.3663

Table 5 The results of the Kruskal–Wallis test.

	2015		2016		2017		2018		2019	
Efficiency	**Z**	***p*-value**	**Z**	***p*-value**	**Z**	***p*-value**	**Z**	***p*-value**	**Z**	***p*-value**
Overall	−2.4514[a]	0.0142	−3.2440[a]	0.0012	−2.3926[a]	0.0167	−1.8642	0.0623	−2.43670[a]	0.014822
Governance	−1.8936	0.0583	−2.2165[a]	0.0267	−2.1284[a]	0.0333	−1.8349	0.0665	−2.12844[a]	0.033301
ICT	−2.0844[a]	0.0371	−2.4220[a]	0.0154	−2.0991[a]	0.0358	−1.5119	0.1306	−2.01101[a]	0.044325
Sustainability	−3.2440[a]	0.0012	−3.0972[a]	0.0020	−1.1596	0.24612	−1.3359	0.1816	−1.33578	0.181621

[a]Denote significance at the 5% levels.

methodologies. The model decomposes comprehensive efficiency into three key elements: governance, ICT, and sustainability. The model is applied to assess the efficiency of 38 significant cities in China using data collected from 2015 to 2019. The primary findings of this study are as follows:

1. A majority of the cities lacked efficiency in governance and ICT. The indicators of governance employment and mobile phone usage were particularly inefficient, indicating challenges with financial structure and over-employment in urban governments. Additionally, the government's investment in ICT infrastructure did not necessarily lead to efficient economic outcomes.
2. In the context of China's reform and opening up, the growth of urban conglomerates in the Yangtze River Delta and Pearl River Delta regions has led to a geographical disparity between coastal and inland areas. The Kruskal–Wallis test was used to compare efficiency scores, dividing 38 cities into coastal and inland. Results show significant differences in comprehensive efficiency from 2015 to 2017, with the gap narrowing initially but expanding in 2019. Coastal cities consistently outperformed inland cities, especially in governance and ICT.
3. The study discerned that the overall operational efficiency of 14 cities, each with an urban population surpassing 10 million, proved suboptimal in 2019, registering an average efficiency score of merely 0.7168. In stark contrast, 7 out of the 24 cities with a population below 10 million demonstrated superior overall operational efficiency, boasting an average score of 0.8637. The detailed breakdown of cities with a permanent population exceeding 10 million is presented in Table 3. This observation underscores that cities characterized by larger urban populations contend with heightened ecological and social pressures, rendering sustainable development more intricate and resulting in comparatively diminished overall efficiency.
4. To enhance the overall operational efficiency of cities, it is imperative to make strategic adjustments to the economic structure and foster the development of green industries. The application of Network SBM methodologies facilitates inefficient cities in identifying benchmark cities, learning from them, drawing inspiration, and subsequently refining urban planning strategies. Notably, among the 14 cities identified by the model construction with an overall efficiency score of 1, 11 display a predominant focus on developing the tertiary industry. This emphasis is substantiated by data from the yearbook, revealing that the proportion of the tertiary industry in these cities' regional GDP surpasses that of the primary and secondary industries. The cities exhibiting this focus include Qingdao, Kunming, Dalian, Harbin, Jinan, Wenzhou, Nanning, Changchun, Shijiazhuang, Jinhua, and Changzhou. A case in point is Qingdao, which illustrates a five-year period marked by rapid and effective industrial structure optimization. The proportional distribution of primary, secondary, and tertiary industries concerning Gross Regional Product (GRP) shifted from 3.9:43.3:52.8 in 2015 to a more harmonized 3.49:35.63:60.89 in 2019. Consequently, the overall efficiency, computed within the specified model architecture, progressed from 0.80181 in 2015 to a perfect score of 1 in 2019. The case study of Qingdao illustrates the positive impact of policies promoting the tertiary and green industries, indicating a symbiotic relationship between industrial structure optimization and increased overall efficiency. Therefore, cities facing inefficiencies can propel sustainable urban development through policies directed at fostering the development of tertiary and green industries.

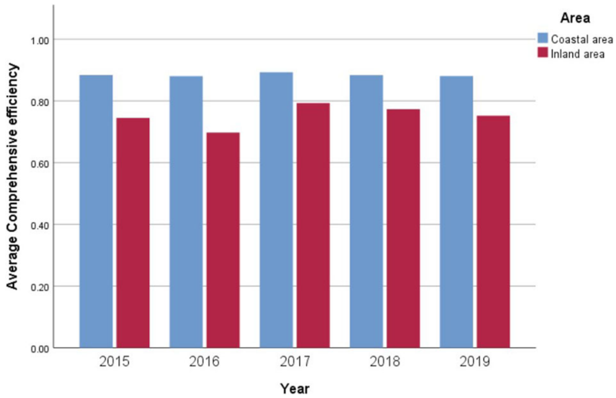

Fig. 3 Comprehensive efficiency of coastal and inland cities during 2015–2019. This bar graph compares the average comprehensive efficiency of coastal and inland areas from 2015 to 2019, clearly illustrating higher efficiency scores for coastal cities each year.

While it is acknowledged that other short-term and conventional policies may impact urban development efficiency, the commencement of the "National New-Type Urbanization Plan" in 2014 stands as a pivotal moment. This initiative sparked substantial reforms in city governance, economic restructuring, and a pronounced focus on environmental protection. A discernible outcome of these reforms is the notable progress in sustainability practices, evident in a substantial increase in the number of cities implementing efficient sustainability measures from 2015 to 2019. This dynamic reflects a pervasive upward trajectory in the sustainability efficiency of Chinese cities.

A geographical disparity between coastal and inland areas becomes evident, with coastal cities consistently outperforming their inland counterparts. The study nuances this gap, emphasizing its initial narrowing and subsequent expansion from 2015 to 2019. Despite earnest endeavors by the Chinese government to foster balanced development, coastal cities continue to wield significant economic strength. The imperative for both coastal and inland cities to progress collectively for optimal development is underscored. Key government initiatives, such as the

"Urbanization Plan" and the "Belt and Road" initiative, have contributed to shaping this landscape. However, challenges persist in achieving equilibrium in development.

The study identifies prevalent inefficiencies in governance and ICT, emphasizing challenges in financial structures and potential over-employment in urban government bodies. Consequently, the government is urged to address these challenges by streamlining bureaucracy, restructuring financial expenditures, and enhancing governance efficiency. Furthermore, local governments are urged not to overlook the potential of ICT and informatization. Increased investment in science and technology is essential to meet the smart city requirements mandated by the central government. To propel a smarter, low-carbon urban economy, local governments should focus on developing robust ICT infrastructure and seamlessly integrating ICT technology with traditional industries. Additionally, transforming the industrial structure and promoting green industries require concerted efforts to reduce the consumption of ecological resources, enforce strict controls on factory emissions of sewage and waste gas, and enhance social security, basic life services, air quality monitoring, green spaces, and residents' living environments.

In conclusion, achieving sustainable urban development demands coordinated efforts across various domains, including ICT, the economy, society, and the environment. While acknowledging the significant strides made by the Chinese government in promoting sustainable urbanization, the study emphasizes the need for ongoing efforts to mitigate the negative impacts of urban development and ensure the enduring sustainability of cities. Thus, governance, ICT, and sustainability emerge as pivotal facets in effectively addressing the multifaceted challenges inherent in urban development.

Data availability

The data for this study were sourced from the "China City Statistical Yearbook," available on the official website of the National Bureau of Statistics of China. The database can be accessed at: https://data.stats.gov.cn/easyquery.htm?cn=E0105. The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Received: 8 September 2023; Accepted: 28 March 2024;
Published online: 23 April 2024

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Competing interests

The authors declare no competing interests.

Ethical approval
This article does not contain any studies with human participants performed by any of the authors.

Informed consent
This article does not contain any studies with human participants performed by any of the authors.

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