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Original Articles

A guiding index framework for examining urban carrying capacity

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ABSTRACT

Extant studies have presented various indexes for evaluating urban carrying capacity (UCC), but there is no consistent perspective on UCC. This paper presents a guiding index framework from a holistic perspective as a reference guidance for evaluating urban carrying capacity (UCC). The framework is developed based upon the theory of sustainable urban development by addressing the fundamental question of what carrying capacities are needed to enable sustainable urban development. The framework is composed of three-layer elements, namely, top-layer pillars, intermediate-layer carriers, and bottom-layer indexes. At top-layer, there are three pillars of UCC, namely, economic carrying capacity, social carrying capacity, and environmental carrying capacity. The intermediate-layer carriers are identified based upon production factors theory, Maslow's need-hierarchy theory, and environmental factors theory. The bottom-layer presents guiding indexes which are established through comprehensive literature review, references to criteria and expert validation. The three pillars of UCC carry on different functions. Economic capacity is to maintain economic growth, which is generated by utilising effectively economic carriers, such as natural materials, human resources, and capital resources. Socially, a city should have the capacity to meet human needs through providing effective social carriers, such as food, housing, transportation, education, and medical services. Environmentally, a city should be capable to provide quality environment including land, water, and atmosphere. Each carrier is underpinned by several measurable indexes to examine the level of urban carrying capacity. The guidance and rationale of how to apply the proposed UCC guiding index framework are provided across three pillars of urban carrying capacity.

1. Introduction

Pursuit for sustainable development is a global mission and it has become the theme of human development in the 21st century, which requests for a balance of mankind needs between present and future generations (Tran, 2016; Silvestre and Ţîrcă, 2019). The Covid-19 crisis has revealed the unsustainability of our development model, and highlighted how fragile and vulnerable our societies are when facing new global epidemiological challenges. Covid-19 impacts are just a foretaste of future disruption and much harsher crisis if we do not seriously address the issues challenging sustainable development. There is an urgent need to radically transform our development model towards sustainability. In line with this, the key agenda of sustainable development is widely appreciated as a synergetic process that strikes for a coordinated development among economic, social, and environmental dimensions in the long term (Hiremath et al., 2013; Kaur and Garg, 2019; Kissi et al., 2017; Munasinghe, 1993; Brundtland, 1985). In the context of an urban area, sustainable development relies on the adequate possession of various resources or carriers such as land resources, water resources, mineral resources, atmosphere environment, infrastructure, transportation, education, and health care (Phillis et al., 2017; Shen et al., 2018; Ren et al., 2018; Yang et al., 2017). These urban carriers must have certain capacity to support social and economic activities, and such capacity is often described as urban carrying capacity (UCC) (Shen et al., 2020). In fact, the level of UCC describes the potential of sustainable urban development. Sun et al., (2018) opined that the performance of UCC has become the barometer of sustainable urban development. Others also argued that UCC provides a guidance for city

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governors and urban planners to better understand and utilise urban resources in addressing the demands from the increasing urban population (for example, Liu et al., 2020; Wang et al., 2019; Pandit et al., 2017).

Nevertheless, various problems affecting urban carrying capacity have been widely reported in many cities around the world, typically such as water pollution and air pollution (Wei et al., 2016). Typical water pollution events reported include the seawater pollution in the Gulf of Mexico in 2010 caused by the spilled oil (Arora and Lodhia, 2017); the pollution of Zarjub and Goharrud rivers in Rasht City of Iran caused by the waste pollutants from industrial bases, hospitals, and poultry farms (Noorhosseini et al., 2017); the water pollution in Pra Basin of Ghana in the past 35–50 years caused by the heavy metal pollutants discharged by illegal mining activities (Duncan et al., 2018). There are also various urban problems reported from economic and social perspectives. For example, He et al (2017) reported the severe economic shrinkage in Daqing City in China, where economy has been fully relying on petroleum mining industry for past decades, the economy-decline in China's Pingxiang City where the economy has been fully relying on coal mining. Xie et al (2018) reported that the economic bankruptcy in Detroit of USA is largely due to the city's dependence upon single economic sector, namely, the car industry. Other typical reports on urban problems include the analysis by Zhao and Hu (2019) about the traffic congestion in Beijing; the investigation by Cheng and Yang (2010) about the homeless problem in Taiwan; the study by Chen et al. (2019) on high prices for affordable housing in Shanghai; and the study by Zacharias and Vakulabharanam (2011) on the polarised wealth distribution in New Delhi. All these reported urban problems reported indicate the vulnerability of sustainable urban development.

Whilst the causes for urban problems are in multiple categories, inadequate urban carrying capacity (UCC) is considered the main cause (Ren et al., 2019). In fact, it is widely appreciated globally that UCC is overloaded with the burdens they carry (Coaffee, 2010; Rao and Summers, 2016; Sarma et al., 2012). Wei et al. (2016) opined that the issue of overloaded UCC has become a widespread challenge for megacities worldwide particularly in the Global South, such as Brasilia in Brazil, Bombay in India, Beijing and Shanghai in China. The concern behind these problems is that the carriers which generate UCC are not properly examined and incorporated in urban development processes across urban planning, design, construction, and management (Farahani et al., 2019; (Ren et al., 2021)). Wei et al. (2015a) pointed out that city managers and planners often fail to undertake appropriate assessments upon the conditions of UCC, thus UCC carriers can not be properly utilised and their capacities are often overestimated and overloaded accordingly.

The above discussions demonstrate the importance of properly assessing UCC. For this, it is essential to employ a set of adequate indicators for conducting assessment. Although extant literature has presented various indicators for assessing UCC, it happens that these indicators are fragmented and even contradictory, thus their applications are limited. Zhang et al., (2018) commented that there are many cases where UCC has not been adequately assessed due to the lack of guidance on how to conduct the examination. In fact, only if proper examination indicators are used, UCC can be adequately examined, thus effective measures can be designed and implemented to ensure that UCC carriers are properly utilised without being overloaded. Accordingly, urban problems will be mitigated consequently. Therefore, this paper aims to develop a guiding index framework for helping to examine UCC.

2. Literature review

Extant studies have offered a number of index frameworks for examining urban carrying capacity (UCC). Table 1 presents several typical literature works in addressing UCC indexes.

It can be seen from Table 1 that the differences in developing the UCC indexes are significant between scholars. For example, some studies

Table 1
Typical literature in addressing UCC indexes.

Researcher	Research method	UCC carriers addressed	UCC Indexes proposed
Ren et al. (2016)	Metabolic theory	Water resources	Water supply; water demand; water consumption; water exploitation; water utilisation
Yang et al. (2019)	Delphi method	Water resources	Water availability; Water demand; Water consumption; Wastewater treatment; Water supply
Lu et al. (2017)	Literature review	Water resources	Surface water; Water consumption; household water; water supply
Jia et al. (2018)	Delphi method	Water resources	Water resources; Water exploitation; Water vulnerability
Wang, Zhou and Engel, (2018b)	Literature review	Water environment	Industry; Water resources; Agriculture; Water ecology; Population; Water pollution
Zhang et al. (2019a)	Nature-based solutions concept	Land resources	Land productivity; Living standard; Ecological condition
Zhang et al. (2019b)	Sustainable development theory	Water resources	Water quantity; Water consumption; Wastewater treatment
Wang et al. (2016)	Literature review	Mineral resources	Economy scale; Sulfur dioxide; Mineral resources potential; Smoke dust; Wastewater discharge
Shen et al. (2022)	Literature review	Atmospheric environment	$PM_{2.5}$ concentration; NO_2 concentration; PM_{10} concentration; CO concentration; SO_2 concentration; O_3 concentration
Peng et al. (2016)	Coupling concept between human and nature	Ecological resources	Ecological vigor; Social development ability; Ecological environment
Wang et al. (2018a)	Sustainable development theory	Ecological environment	Social development; Environmental quality; Economic development; Ecological quality
Ma et al. (2017)	Ecological resilience	Marine ecosystems	Human activities; Ecological resilience; Social development; Economic development
Wei et al. (2015b)	Literature review	Urban resources and environment	Environmental impacts; Public perception; Natural resources; Institution setting; Infrastructure services; Society supporting
Wei et al. (2016)	Sustainable development theory	Urban resources and environment	Urban employment; Water supply; Wastewater treatment; Transport; Fiscal income; Water consumption; Solid-waste treatment; GDP; Construction land; Infrastructure
Wang et al. (2017)	Literature review	Urban resources and environment	Mineral resources; Land resources; Water resources; Environment protection
Zhang et al. (2018)	Sustainable development theory	Urban resources and environment	Ecological environment; Transportation; Factor market; Industrial economy
Zhang et al. (2018)			Water resources; Land resources; Solid waste

(continued on next page)

Table 1 (*continued*)

Researcher	Research method	UCC carriers addressed	UCC Indexes proposed
	Ecological civilisation theory	Urban resources and environment	treatment; Energy resources
Sun et al. (2018)	Literature review	Urban resources and environment	Industrial economy; Factor market; Ecological environment; Transport infrastructure
Oh et al. (2005)	Literature review	Urban resources and environment	Environment and ecology; Urban facilities; Public perception; Institutional setting
Liu (2012)	Literature review	Urban resources and environment	Land resources; Water resources; Transportation; Environment
Tehrani and Makhdoum (2013)	Literature review	Urban resources and environment	Natural state; Population resources; Energy resources; Water resources; Atmospheric environment; Transportation; Waste treatment; Land utilisation

focus upon the carriers of water and land resources (see for example, Yang et al., 2019; Jia et al., 2018). Some others introduced the assessment indicators from integrated perspectives (such as Tehrani and Makhdoum, 2013, Zhang et al., 2018). The differences of these UCC indexes present the inconsistence of the understanding upon the implication of UCC, which consequently limits their applications. The reason behind the inconsistence is that there is no consent upon what principle underpins the development of UCC indexes (Mahmoudi et al., 2019; (Meng et al., 2020)). In fact, even in referring to each index listed in Table 1, there is little argument upon the rationale behind the selection of the index. Consequently, the dimensions of indexes proposed for measuring UCC in previous studies are fragmental and non-comprehensive. Furthermore, some UCC carriers have been studied extensively, such as land, water resources and atmosphere environment, whereas other carriers, for example, public service, education services, human resources and medical services, have been given little attention. As a result, the methodologies adopted in developing UCC indexes are various between different studies.

The above discussions demonstrate that there is a lack of methodology agreeable among different studies to define what dimensions of carries and indexes should be built in order to help properly understand UCC (Singh et al., 2009). To mitigate this inherent limitation in extant literature, this study aims to develop a guiding index framework for examining urban carrying capacity (UCC) based upon the principle of sustainable urban development which is commonly agreed. The framework will present UCC carriers and indexes from a holistic perspective to ensure that no essential dimensions of UCC would be overlooked.

3. Methodology

In order to achieve the overarching research aim, three research tasks are designed in this study, and the methodological research roadmap is illustrated in Fig. 1.

Firstly, according to the research roadmap in Fig. 1, the principle of sustainable development theory will be applied to define three pillars of urban carrying capacity, namely, economic carrying capacity, social carrying capacity, and environmental carrying capacity. Sustainable urban development theory requests that the needed carrying capacities must be the concerted provision across these three pillars.

The second research task is to identify intermediate-layer UCC carriers under each of the three UCC pillars. In referring to economic UCC pillar, relevant carriers will be investigated by applying ***production factors theory*** which suggests that economic growth is driven collectively by a wide spectrum of economic factors (Smith, 1937; Marshall, 1920; Xu, 2010). In considering social UCC pillar, relevant carriers will be investigated by employing ***Maslow's need-hierarchy theory*** (Maslow, 1943; Wahba and Bridwell, 1976). The need-hierarchy theory advocates attaching importance to various human needs, synthesising these needs, and meeting these needs in referring to a needs-hierarchy model. For investigating the carriers under environmental UCC pillar, ***environmental factors theory*** will be applied, which argues that human survival and development are subject to the condition of various environmental factors (Kowalska et al., 2015).

Thirdly, as shown in Fig. 1, the indexes in bottom-layer are for examining UCC performance. These indexes will be studied through reviewing comprehensive relevant literature review and selection criteria, and conducting expert verification. Extant studies have presented various UCC indexes and measurements from various urban perspectives, which provide valuable references for establishing the bottom-layer indexes in this study. Comprehensive literature review will

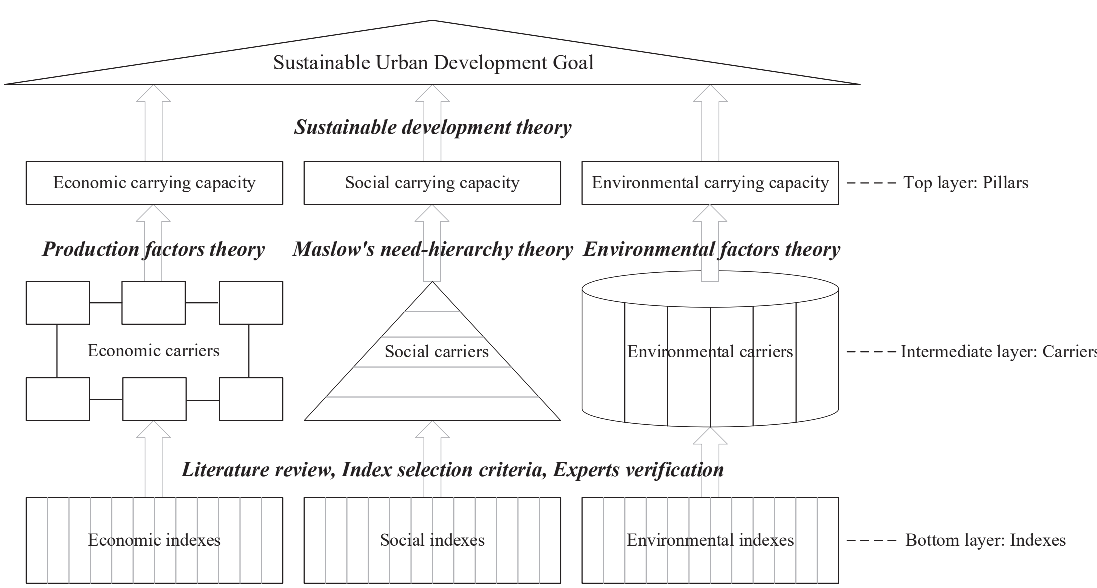

Fig. 1. Methodological research roadmap.

first lead to the formulation of a set of candidate UCC indexes, which will be filtered by applying certain criteria. The filtering criteria should be defined to ensure that the indexes can properly represent and measure the performance of intermediate-layer UCC carriers. In this regard, Hák et al. (2016) developed a set of criteria for selecting indexes to measure the performance of sustainable urban development, including feasibility, rationality, data availability, number limitation, completeness, representativeness, relevance, measurability, and communicability. These criteria are considered appropriate to examine the candidate UCC indexes in this study. Following the filtering process, the index framework will further be verified by a number of experts who are rooted in the research domain of sustainable urban development, thus the scientific creditability can be guaranteed. The above research procedures will lead to the finalisation of the UCC guiding index framework.

4. Three urban carrying capacity pillars

As argued above, urban carrying capacity (UCC) composes of three pillars, namely, economic carrying capacity, social carrying capacity, and environmental carrying capacity. The composition of the three pillars is line with sustainable urban development theory, as delineated in Fig. 2.

Among the three pillars, urban economic carrying capacity is to ensure sustainable economic growth in an urban area, which is considered as the basic condition for enabling sustainable urban development (Sarma et al., 2012; Ali-Toudert and Ji, 2017).

Social carrying capacity is to meet human needs. Various social problems will be triggered if social carrying capacity cannot satisfy human needs, such as traffic congestion (Zhao and Hu, 2019), housing shortage (AKAABRE et al., 2018; Huang, Shen and Zheng, 2015), and polarised wealth distribution (Zacharias and Vakulabharanam, 2011).

Environmental carrying capacity provides natural support for human to survive and reproduce. Various urban environmental problems will occur if environmental carriers can not generate proper capacities, such as deteriorated air pollution (Xia et al., 2014), degraded water quality (Seilheimer et al., 2007), decreased biodiversity (Mckinney, 2008), and habitat loss (Kjølle et al., 2012).

It is important to appreciate that all the three pillars of capacities are essential for enabling sustainable urban development. They are equally important, and none of them should be overlooked. Therefore, the establishment of the carriers and indexes for examining UCC must be in line with these three UCC pillars.

5. Carriers for providing urban carrying capacity

According to the discussions in the previous Section, the carriers for providing urban carrying capacity are across three UCC pillars.

5.1. Urban economic carriers

Urban economic carriers are in the form of various types of resources such as natural resources, human and capital resources (Ren et al., 2016; Wang et al., 2016; Bogataj et al., 2019; Kurronen, 2018). They provide carrying capacities to enable that a city can promote its economic growth sustainably (Wang et al., 2020). As economic performance is contributed by various production factors, the theory of production factors is commonly adopted in examining economic factors (Marshall, 1920; Smith, 1937; Krugman, 1991; Xu, 2009; Liu et al., 2019). According to the theory, production factors include six categories, namely, natural-resources, human-resources, capital-resources, sci-tech, management, and urban-location.

Each category of production factors is composed of specific carriers. For example, natural resources typically include land, water, biological resources, energy, mineral resources, and tourism resources (Jowsey, 2007). The carriers contributing to sci-tech factor include research, technology, and information (Fine, 2000; Pipirigeanu et al., 2014). Other researchers have also examined the carriers supporting the production factors of human-resources (Schultz, 1981; Razin and Sadka, 1995; Simon, 2019), capital-resources (Boero et al., 2019), management (Drucker, 1985; Schumpeter, 2008; Oleinik, 2018), and location-resources (Krugman, 1991; MacPherson, 1992).

The above discussions lead to the establishment of a portray of urban economic-carriers network (see Fig. 3). These carriers work collectively to generate the economic carrying capacity needed in order to implement urban economic activities in a sustainable way.

5.2. Urban social carriers

Urban social carriers generate carrying capacity to meet urban residents' needs and enable sustainable social development. According to the widely-appreciated Maslow's needs-hierarchy theory (Maslow, 1943), human needs lie in five-hierarchy levels, namely, physiological needs, safety needs, love and belonging needs, esteem needs, and self-actualisation needs. The needs-hierarchy theory suggests that each level of urban residents' needs should be met by the provision of various social carriers. For example, physiological needs can be met by the provision of the food, shelter, transportation, public facilities, and education. Safety needs are met with the provision of personal protection,

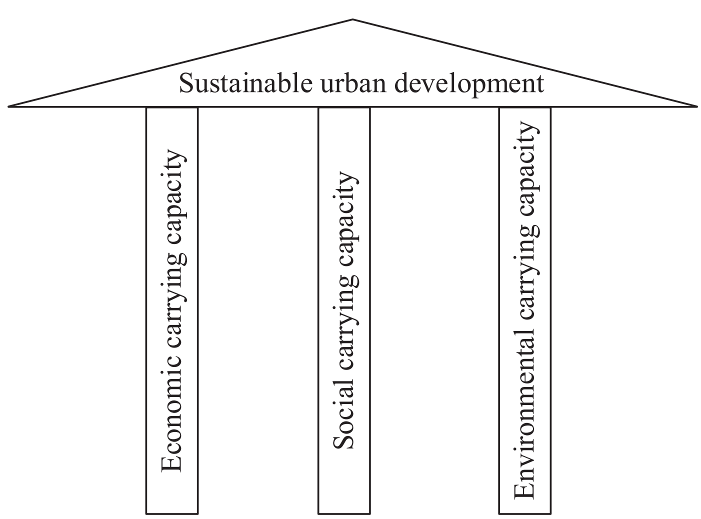

Fig. 2. Three pillars of urban carrying capacity.

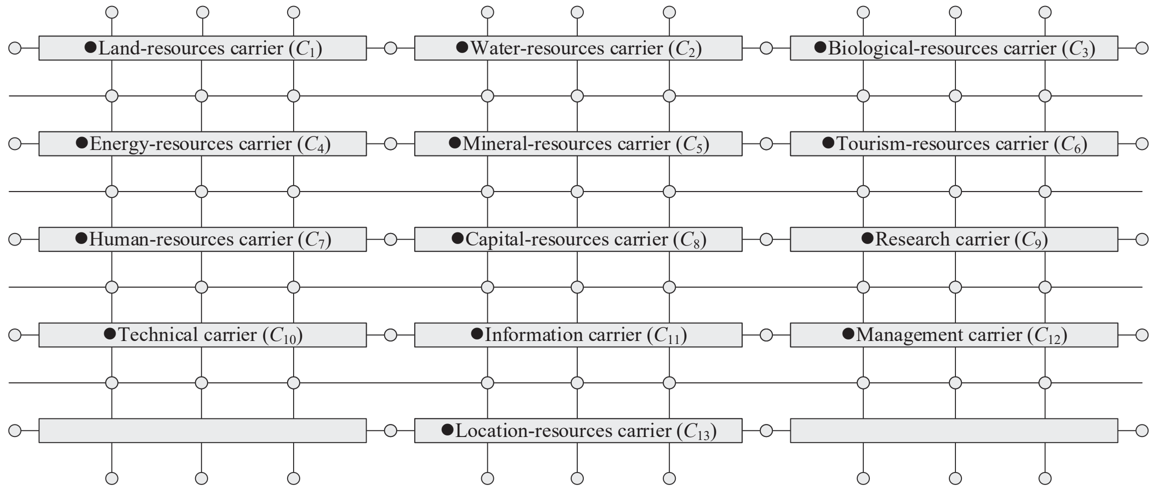

Fig. 3. Economic carriers for providing urban economic carrying capacity.

security regulation, disaster prevention, health protection, and employment. Love and belonging are met with various social-relationship. Esteem can be obtained by achieving success and prestige. And self-actualisation can be met by the provision of social-morality (Maslow, 1943; Broom, 2006; Freitas and Leonard, 2011; Perlman, 2017).

Based upon above discussion, urban social carriers can be elucidated as a pyramid structure in corresponding to Maslow's needs-hierarchy (see Fig. 4). The effective provision of these carriers in the pyramid structure can meet the five-hierarchy levels of human needs.

5.3. Urban environmental carriers

Urban environmental carriers mainly refer to land, water, and atmosphere environment that supporting urban living and working environment (Lu et al., 2017). Urban environmental carriers should be endowed with the carrying capacities to provide sufficient and quality natural environment for urban inhabitants to survive and develop. In this regard, Kowalska et al. (2015) introduced environmental factors theory, suggesting that the survival and reproduction of living organisms or biological group including human being, rely on various natural-environmental carriers, including green lands, quality soil, quality water, quality air, light environment, acoustic environment, and temperature environment. It is widely appreciated that environmental carriers form jointly a barrel structure to generate urban environmental carrying capacities (Drucker, 2012; Kowalska et al., 2015; Costanza, 1992), see Fig. 5. Each plank in the barrel can be seen as an environmental carrier. The barrel structure spells that proper urban environmental carrying capacity can only be generated by the synergetic and concerted provision of all individual plank carriers.

6. Development of guiding index framework for examining urban carrying capacity

The examination on urban carrying capacity is virtually the assessment on the performance of the urban carriers across economic, social and environmental pillars, which have been presented in Figs. 3–5 respectively. However, specific indexes are needed to measure the performance of these carriers, and this section discusses how these indexes should be developed rationally.

There are two processes to develop the indexes for measuring carrier performance: 1) To identify candidate indexes via comprehensive literature review; 2) to formulate and finalise effective indexes through filtering the candidate indexes according to index selection criteria and experts verification.

According to Figs. 3–5, there are 35 carriers in total across economic, social and environmental UCC pillars. The volume of the research contents about the index development for all 35 carriers would be too large to be included in the paper. Instead, this paper only shows the process in developing the indexes for a sample carrier, namely, public facilities

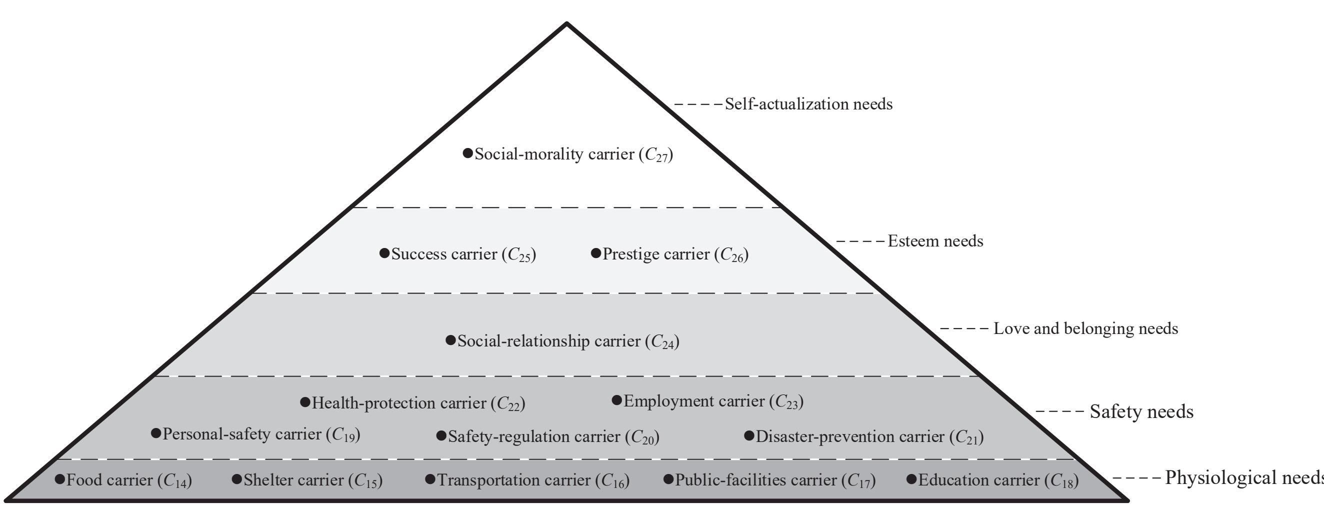

Fig. 4. A pyramid structure of social carriers for generating urban social carrying capacity.

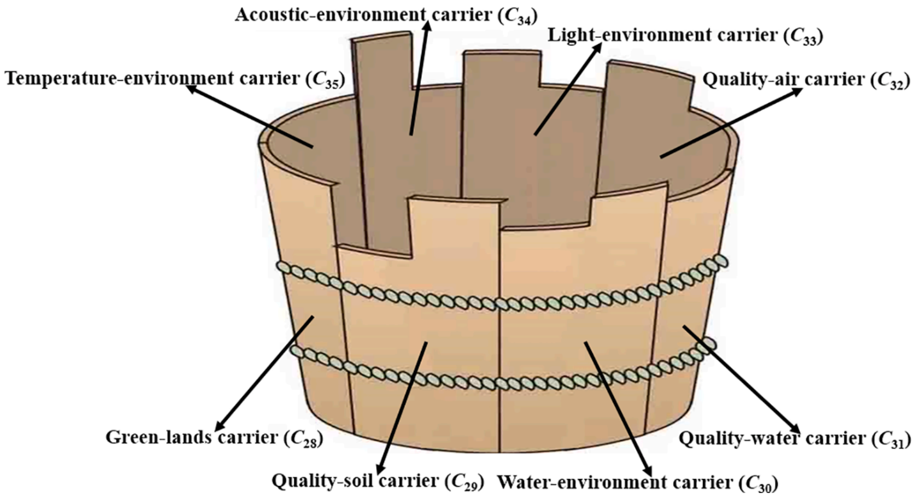

Fig. 5. Environmental carriers for generating urban environmental carrying capacity.

(Carrier C_{17}).

The identification of the candidate indexes for examining the performance of carrier C_{17} are through comprehensive literature review. The retrieval of the relevant literature is based upon three principles: a) Literature should be relevant to carrying capacity of urban public facilities; b) literature should be published on international journals with high impact factors; and c) literature should be published within the recent five years (2015–2020). Accordingly, a list of effective literature has been retrieved, which present various indexes for examining the capacity of public-facilities (Carrier C_{17}), as shown in Table 2.

Secondly, these candidate indexes in Table 2 are filtered by applying the index selection criteria including feasibility, rationality, data availability, number limitation, completeness, representativeness, relevance, measurability, and communicability, as stated in the Methodology Section. Accordingly, seven effective indexes for examining the carrying capacity performance of the carrier *public-facilities* (C_{17}) are filtered out, including water supply, electricity supply, gas supply, heating supply, sewage treatment, solid-waste disposal, and drainage. The proper delivery of public facilities across these seven aspects is considered essential for meeting the basic needs of urban residents and supporting urban social activities (Wang et al., 2020; World Bank, 1994).

The identification of the examination indexes for other UCC carriers described in Figs. 3–5 follows the same research processes as that applied for the Carrier C_{17}. As a result, a comprehensive index framework can be obtained. To further enhance the scientific creditability of the obtained index framework, four experts rooted in the domain of urban sustainability are invited from global research communities to verify the framework during September to October 2021. The profiles of the invited experts are shown in Table 3).

Revisions and modification are conducted accordingly by taking the comments and advices received from the experts. Consequently, the finalised UCC guiding indexes are formulated, as shown in Table 4. This framework is referred as a guidance to assist in setting indexes for examining urban carrying capacity.

The index framework presented in Table 4 is comprehensive and endowed with the guiding function for examining urban carrying capacity. It serves as a “dictionary” to integrate the carriers across natural supporting resources (such as water, air) and socioeconomic functions (such as public services, transportation). In practical application of the framework, the UCC status of a concerned city can be examined in a holistic and integrated manner, whilst each specific UCC carrier can also be examined and investigated separately. In examining the UCC status, each UCC index should be converted/represented by a measurable indicator.

It is important to note that, for targeting at different evaluation aim, standing at different time point and setting in different scenario, the measurable indicator representing each index will be selected differently. And the indicator weightings will also be set differently.

For example, if the evaluation scenario is set to investigate the scale status of the Carrier C_{17} (Public facilities) across various large cities, the seven indexes of Carrier C_{17} (namely, water supply, electricity supply,

Table 2
Typical literature presenting the indexes for examining the capacity of public-facilities (C_{17}).

Researcher	Assessment indexes presented for public-facilities carrier C_{17}
Yuan and Sun (2018)	Per-capita water supply; The ratio of sewage treatment; The garbage harmless disposal
Jia et al. (2018)	Wastewater treatment concentration; Water supply per capita
Wang et al. (2018a)	Water coverage rate; Recycling rate of waste water
Sun et al. (2018)	Per-capita water supply; The ratio of sewage treatment; Ratio of garbage harmless disposal
Mo et al. (2018)	Per capita water resources; Sewage treatment rate; Harmless disposal of solid waste
Zhang et al. (2018)	Per-capita water supply; The ratio of sewage treatment; Ratio of garbage harmless disposal
Wei et al. (2016)	Per capita water supply; Per capita gas supply; Per capita electricity supply; Living garbage treatment rate; The ratio of sewage treatment; The treatment ratio of solid waste; Density of drainage pipe; Water access rate; Gas access rate
Wei et al. (2015c)	Per capita water resources; The recycling rate of waste water; Urban gas connection rate; Harmless disposal of domestic garbage
Wang et al. (2020)	Water supply; Gas supply; Electricity supply; Heat supply; Transportation; Telecommunication; Education; Medical service; Drainage; Sewerage; Garbage disposal
Zhang et al. (2019d)	Area of land used for urban construction; Total water resources; Area of urban green space; Area of paved roads; Length of sewage pipes; Total gas supply

Table 3
Profile of the four invited experts for discussing the creditability of index framework.

Expert code	Institute	Expertise
Expert-A	Zhejiang University, China	Sustainable urban–rural development
Expert-B	University of Hong Kong, Hong Kong SAR, China	Sustainable neighbourhood planning
Expert-C	University of Manchester, United Kingdom	Sustainable urbanisation
Expert-D	University of Wisconsin–Madison, United States	Sustainable urban design and urbanism

Table 4
A guiding index framework for examining urban carrying capacity.

Top-layer pillars	Intermediate-layer carriers	Bottom-layer indexes
Economic (P_E)	Land resources (C_1)	Cultivated land resource (X_1); Grass land resource (X_2); Wood land (X_3) resource; Water conservancy land resource (X_4); Urban construction land resource (X_5)
	Water resources (C_2)	Ocean water resource (X_6); River water resource (X_7); Lake water resource (X_8); Marsh wetland resource (X_9); Artificial wetland resource (X_{10}); Ground water resource (X_{11}); Rainfall resource (X_{12})
	Biological resources (C_3)	Animal resources (X_{13}); Plant resources (X_{14})
	Energy resources (C_4)	Coal (X_{15}); Petroleum (X_{16}) ; Natural gas (X_{17}) ; Solar energy (X_{18}) ; Wind energy (X_{19}) ; Hydraulic energy (X_{20}) ; Tidal energy (X_{21}) ; Geothermal energy (X_{22}); Biomass energy (X_{23}); Hydrogen energy (X_{24}) ; Nuclear energy (X_{25})
	Mineral resources (C_5)	Ferrous metals (X_{26}); Nonferrous minerals (X_{27}); Rare metals (X_{28}); Noble metals (X_{29})
	Tourism resources (C_6)	Geomorphologic forms (X_{30}); Climatic resources (X_{31}); Historical events (X_{32}); Cultural resources (X_{33})
	Human resources (C_7)	Total population (X_{34}); Population density (X_{35}); Unskilled labor forces (X_{36}); Degree-and-above holders (X_{37}) ; Technicians (X_{38}); Age structure (X_{39}); Gender structure (X_{40}); Family structure (X_{41}); Population inflow (X_{42}); Population outflow (X_{43})
	Capital resources (C_8)	Bank savings (X_{44}); City debt (X_{45}); Tax revenue (X_{46}); Public-consuming capability (X_{47}); Domestic investment (X_{48}); Foreign investment (X_{49}); Fixed assets (X_{50}); Commercial fund (X_{51}); (X_{52}); Private investment (X_{53}); Government appropriation (X_{54})
	Research capability (C_9)	Natural science research (X_{55}); Social science research (X_{56})
	Technology capability (C_{10})	Innovation capability (X_{57}); Transfer capability (X_{58});
	Information capability (C_{11})	Information generation (X_{59}); Information collection (X_{60}); Information processing (X_{61}); Information storage (X_{62}); Information application (X_{63})
	Management (C_{12})	Policy regulation (X_{64}); Business norms (X_{65}); Competition intensity (X_{66}); Entrepreneurship (X_{67})
	Location resources (C_{13})	Traffic location (X_{68}); Commercial location (X_{69}); Political status (X_{70}); Religious location (X_{71})
Social (P_S)	Food (C_{14})	Grain (X_{72}); Vegetables (X_{73}); Meat (X_{74}); Aquatic foods (X_{75}); Eggs (X_{76}); Dairy (X_{77}); Oils and fats (X_{78}); Seasoning (X_{79}); Drink (X_{80}); Candy (X_{81}); Food supervision (X_{82}); Food security (X_{83})
	Shelter (C_{15})	Commercial residence (X_{84}); Public housing (X_{85}); Affordable housing (X_{86})
	Transportation (C_{16})	Air transportation (X_{87}); Water transportation (X_{88}); Railway transportation (X_{89}); Road transportation (X_{90}); Buses (X_{91}); Subways and light rails (X_{92}); Taxis (X_{93}); Private cars (X_{94})
	Public facilities (C_{17})	Water supply (X_{95}); Electricity supply (X_{96}); Gas supply (X_{97}); Heating supply (X_{98}); Sewage treatment (X_{99}); Solid-waste disposal (X_{100}); Drainage (X_{101})
	Education (C_{18})	

Table 4 (*continued*)

Top-layer pillars	Intermediate-layer carriers	Bottom-layer indexes
		Educational institutions (X_{102}); Educational facilities (X_{103}); Teacher resources (X_{104})
	Personal safety (C_{19})	Pension security (X_{105}); Widowed security (X_{106}); Maternity security (X_{107}); Orphaned security (X_{108}); Disability security (X_{109}); Unemployment security (X_{110}); Veterans security (X_{111}); Family security (X_{112}); Immune security (X_{113})
	Safety regulation (C_{20})	Legal regulations (X_{114}); Government regulations (X_{115}); Department regulations (X_{116}); Local regulations (X_{117})
	Disaster prevention (C_{21})	Prevention officers (X_{118}); Prevention facilities (X_{119}); Disaster warning (X_{120}); Disaster emergency (X_{121}); Disaster aftermath (X_{122})
	Health protection (C_{22})	Hospitals (X_{123}); Medical facilities (X_{124}); Medical instruments (X_{125}); Medicines (X_{126}); Physicians (X_{127})
	Employment (C_{23})	Employment channels (X_{128}); Job opportunities (X_{129}); Employment skills (X_{130}); Employment happiness (X_{131})
	Social relationship (C_{24})	Holiday (X_{132}); Family communication (X_{133}); Love (X_{134}); Hometown circle (X_{135}); Classmate circle (X_{136}); Colleague circle (X_{137}); Interest circle (X_{138}); Recreational sports (X_{139}); Communication medium (X_{140})
	Success (C_{25})	Achievement level (X_{141}); Esteem level (X_{142})
	Prestige (C_{26})	Attention (X_{143}); Appreciation (X_{144}); Admiration (X_{145})
	Social morality (C_{27})	Freedom (X_{146}); Experiences (X_{147}); Lessons (X_{148}); Teach (X_{149}); Care (X_{150})
Environmental (P_{En})	Green lands (C_{28})	Natural-reserve areas (X_{151}); Recreational parks (X_{152}); Botanical gardens (X_{153});; Green belt (X_{154}); Green living areas (X_{155})
	Quality soil (C_{29})	Cadmium content (X_{156}); Mercury content (X_{157}); Arsenic content (X_{158}); Copper content (X_{159}); Lead content (X_{160}); Chromium content (X_{161}); Zinc content (X_{162}); Nickel content (X_{163}); PH value (X_{164})
	Water environment (C_{30})	Coastal-water environment (X_{165}); River-water environment (X_{166}); Lake-water environment (X_{167}); Wetland-water environment (X_{168}); Underground water (X_{169}); Rainfall-water environment (X_{170})
	Quality water (C_{31})	DO concentration (X_{171}); COD_{Mn} concentration (X_{172}); BOD_5 concentration (X_{173}); COD_{Cr} concentration (X_{174}); NH_3-N concentration (X_{175}); TN concentration (X_{176}); TP concentration (X_{177})
	Quality air (C_{32})	SO_2 concentration (X_{178}); NO_2 concentration (X_{179}); PM_{10} concentration (X_{180}); CO concentration (X_{181}); O_3 concentration (X_{182}); $PM_{2.5}$ concentration (X_{183})
	Light environment (C_{33})	Improper light design (X_{184}); Reflective building materials (X_{185}); Poor lightproof facility (X_{186}); Poor lightproof management (X_{187})
	Acoustic environment (C_{34})	Poor noise-prevention facility (X_{188}); Poor noise management (X_{189})
	Temperature environment (C_{35})	Building density (X_{190}); Poor building greening (X_{191}); Road density (X_{192}); Poor green-road belt (X_{193}); Non-endothermic building materials (X_{194});

(*continued on next page*)

Table 4 (*continued*)

Top-layer pillars	Intermediate-layer carriers	Bottom-layer indexes
		Non-endothermic road materials (X_{195}); Number of conditioning facilities (X_{196})

gas supply, heating supply, sewage treatment, solid-waste disposal, and drainage) need to be converted into seven measurable indicators: *Quantity of water production, household electricity consumption, quantity of natural gas storage, total quantity of heating supply, quantity of total sewage treatment, volume of domestic garbage harmless treatment*. However, if the examination scenario is set to investigate the per capita status of the Carrier C_{17}, then similarly the carrier's seven indexes should be converted into per-capita based measurable indicators. Following the conversion from index to measurable indicator, indicator data can be collected from the channels such as official statistics and remote sensing, and processed or standardised, followed by setting indicator weightings. Consequently, the status performance of Carrier C_{17} in concerned cities will be captured and understood.

7. Application of the guiding index framework

This Section presents a demonstration for discussing the reasoning of applying the guiding index framework introduced in previous Section. The discussion will be conducted by addressing the following three components:

1) How to guide for examining urban economic carrying capacity?

The UCC guiding index framework in Table 3 has 13 economic carriers for providing urban economic carrying capacity. The framework suggests that the carrying capacity performance of each economic carrier should be examined jointly by a number of individual indexes. The carrying capacity threshold of each economic carrier is determined by the inputs of its indexes. As the input of each index can be adjusted and changed in practice during a given period of time, the carrying capacity of the concerned carrier will form an interval with a minimum and maximum value during the given period. Fig. 6 elucidates a carrying capacity interval spider for all 13 economic carriers.

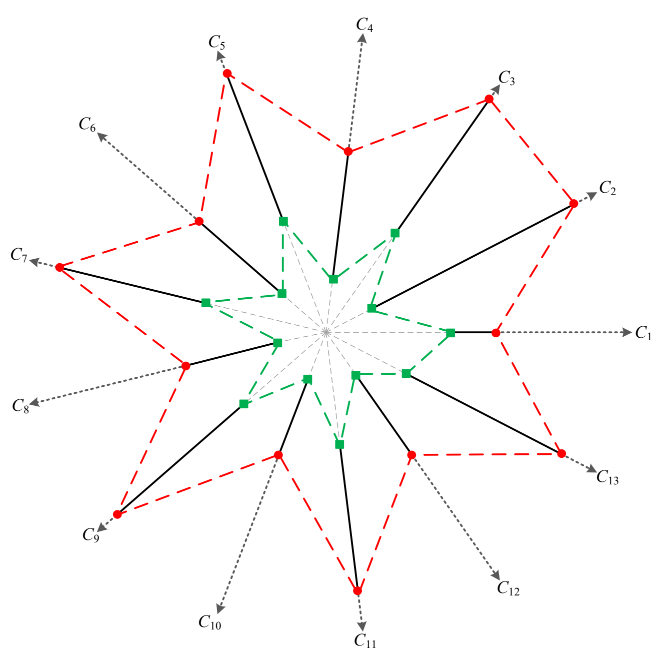

Fig. 6. Carrying capacity interval for urban economic carriers.

Taking the carrier "land resources (C_1)" as an example, there are five guiding indexes for examining its carrying capacity performance, as stated in Table 3, including cultivated land resource (X_1), grass land resource (X_2), wood land resource (X_3), water conservancy land resource (X_4), and urban construction land resource (X_5). In other words, the carrying capacity performance of "land resources (C_1)" must be examined jointly from these five perspectives. It can be seen that the carrying capacity of land resources (C_1) is changeable as the contribution of each of these five indexes is changeable. For example, the index X_1 (cultivated land resource) has been changing in the contemporary urbanisation process in many Chinese cities. According to the study by Sun et al. (2017), the volume of cultivated lands in Beijing have been reduced from 5.5 million hectares in 1995 to 1.5 million hectares in 2017. Consequently, the carrying capacity of land resources in Beijing has changed significantly for the period 1995–2017. On the other hand, the utilisation efficiency of the cultivation land has been improving. According to Jiang et al. (2017), the productivity of unit cultivation land has been improving significantly during the urbanisation process over last several decades in China. The dynamism nature of these assessment indexes suggest that the carrying capacity of land resources lies within an interval in a given period. This interval represents the resilience of land resources carrying capacity in responding to the external changes in order to sustain urban economic growth.

Similar analogy can be applied for analysing other urban economic carriers. The key point for applying the guiding index framework is that the individual indexes should be measured from a dynamistic perspective, and the assessment upon a carrier's carrying capacity should be associated to a specific time period. It is considered more important to understand how the capacity evolves than to capture a static capacity value.

2) How to guide for examining urban social carrying capacity?

There are 14 social carriers in UCC index framework, as listed in Table 3, which generate urban social carrying capacity. Previous study echoes that only if these social carriers are provided sufficiently, human social needs can be met sustainably (Wei et al 2015b; Wei et al. 2016). However, previous studies have been only focusing limited social carriers, such as transportation, public facilities, safety supporting, and employment. Other essential social carriers appear overlooked traditionally, such as the disaster prevention (C_{21}), health protection (C_{22}), social relationship (C_{24}), success perception (C_{25}), prestige (C_{26}), and social morality (C_{27}).

Table 3 shows that the carrying capacity performance of each social carrier is measured jointly by a few indexes. This is because the capacity of each social carrier is for meeting some specific needs of urban inhabitants. Furthermore, according to Maslow's need-hierarchy theory (Maslow, 1943), there is a pyramid-hierarchy needs for human beings, and each hierarchy need has a baseline to be met. This baseline requires a minimum provision from various social carriers (Silva-Laya et al., 2020; Vieira et al., 2018; Zhang et al., 2019d). Fig. 7 illustrates that each social carrier generates a minimum value of carrying capacity in order to meet the needs of urban inhabitants.

Taking the urban social carrier "shelter (C_{15})" as an example, the guiding index framework in Table 3 suggests that three guiding indexes are needed for measuring the carrier's carrying capacity performance, namely, commercial residence (X_{84}), public housing (X_{85}), and affordable housing (X_{86}). In other words, the carrying capacity performance of the carrier "shelter (C_{15})" must be examined jointly from these three perspectives. The proper provision of these three types of housing are able to meet the basic housing demand of urban inhabitants. Accordingly, the contribution from all the three indexes to "shelter (C_{15})" will form this carrier's carrying capacity value.

3) How to guide for examining urban environmental carrying capacity?

The UCC index framework in Table 3 presents 8 carriers for generating urban environmental carrying capacity. As echoed in previous

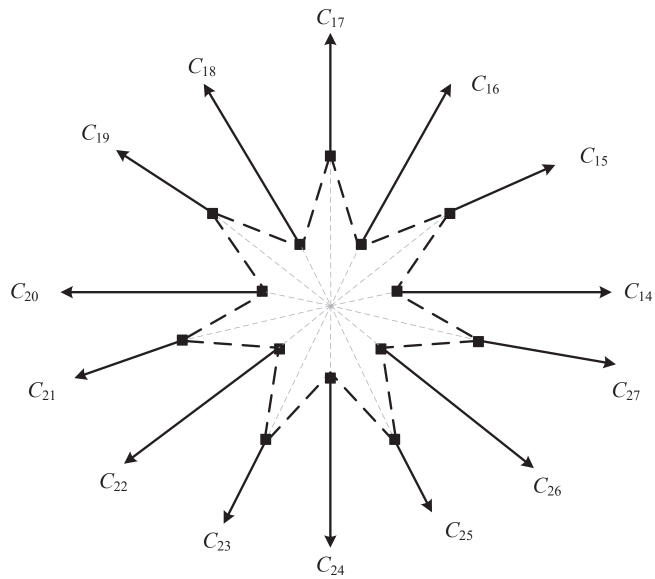

Fig. 7. Minimum value of carrying capacity between urban social carriers.

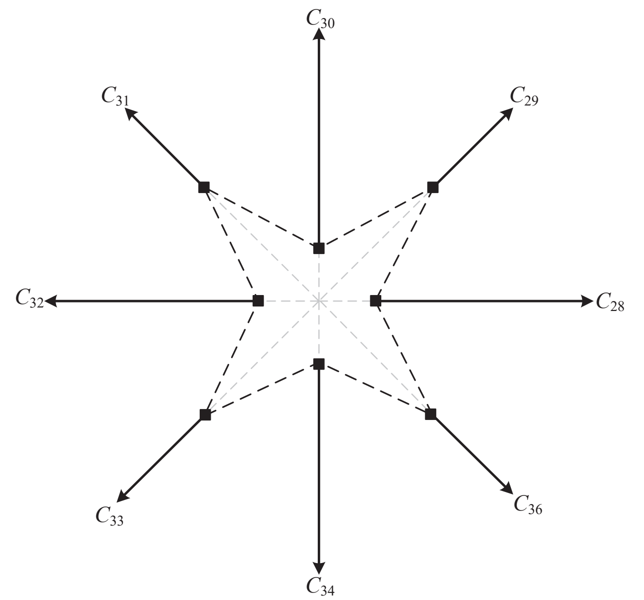

Fig. 8. Minimum carrying capacity value between urban environmental carriers.

studies, only if these environmental carriers are provided sufficiently and controlled properly, quality environment can be gained for sustainable urban development (Tehrani and Makhdoum, 2013; Zhang et al., 2018). The environmental carriers identified in previous studies focus on land environment, water environment, and atmospheric environment, but other essential urban environmental carriers were ignored, such as light environment (C_{33}), acoustic environment (C_{34}), and temperature environment (C_{35}).

According to the guiding index framework, the carrying capacity performance of each environmental carrier should be examined by using a number of indexes. The environmental carriers for supporting sustainable urban development can be divided into two groups. One group carriers refer to natural environment, such as green lands (C_{28}) and water environment (C_{30}), which should have minimum carrying capacity value. The other group concerns the quality of the environment, including quality soil (C_{29}), quality water (C_{31}), quality air (C_{32}), light environment (C_{33}), acoustic environment (C_{34}), and temperature environment (C_{35}). For these quality environmental carriers, their carrying capacity should also be defined by a minimum value. Fig. 8 elucidates that all the environmental carriers should have a minimum carrying capacity value.

Taking the carrier "green lands (C_{28})" as an example, the guiding index framework in Table 3 suggests that the carrier's carrying capacity should be examined by employing six indexes, including natural-reserve areas (X_{151}), recreational parks (X_{152}), botanical gardens (X_{153}), green belt (X_{154}), and green living areas (X_{155}). All individual indexes are important for ensuring that quality green lands environment is provided. Therefore, these indexes should assume a minimum value to support a proper carrying capacity value of "green lands".

Taking the carrier "quality air (C_{32})" for another example, according to the guiding index framework, its carrying capacity performance should be examined jointly by using six indexes, including SO_2 concentration (X_{178}), NO_2 concentration (X_{179}), PM_{10} concentration (X_{180}), CO concentration (X_{181}), O_3 concentration (X_{182}), and $PM_{2.5}$ concentration (X_{183}). Zhang et al. (2019c) adopted these six indexes in studying air quality in 13 cities in the Jing-Jin-Ji region of China. It was suggested that threshold should be applied to these indexes in order to gain a minimum carrying capacity of the carrier "quality air (C_{32})".

The above analysis provides an understanding upon how to examine urban carrying capacity across economic, social, and environmental carriers by adopting the introduced guiding index framework. From economic perspective, the carrying capacity of each carrier is specified with an interval, which spells the resilience of carrier's capacity. With this understanding, decision makers have flexibility in making decisions to control individual indexes under each carrier. Therefore, proper strategies can be designed and implemented to ensure the provision of proper level of carrying capacity which supports sustainable urban economic growth. From social and environmental perspectives, the guiding index framework suggests that a minimum capacity must be provided for each carrier. That way can ensure that social needs and environmental quality requested by urban residents can be met, which contributes accordingly to the sustainable urban development.

8. Conclusions and policy implications

To conclude, the overall advantage of the introduced guiding index framework is that the framework can assist in selecting proper indexes to assess urban carrying capacity which is generated from various urban carriers. The framework consists of three layers, including top-layer pillars, intermediate-layer carriers, and bottom-layer indexes. The development of each layer is based upon proper principles and theories, thus the creditability of the framework is ensured. The formation of three top-layer pillars is based upon sustainable development theory, which addresses the question of what carrying capacities are needed to support sustainable urban development. The intermediate-layer carriers are built based upon respectively the production factors theory (for urban economic carriers), Maslow's need-hierarchy theory (for urban social carriers), and environmental factors theory (for urban environmental carriers). The bottom-layer guiding indexes are established via comprehensive literature review, criteria reference and experts verification. The guiding index framework is appreciated systematic, proper, and effective. It is considered that the framework can guide city governors and professionals to examine UCC status in a given urban context.

This study focus on establishing a guiding UCC examination framework for indicator setting across different application scenarios, rather than presenting a set of indicators for specific application. The establishment of UCC indicators in a specific application will need to convert index into measurable indicators, to set weightings between indicators and to aggregate the evaluation value. The carriers and indexes built in the guiding index framework are systematic and comprehensive, which ensures that no urban carriers will be overlooked in examining urban carrying capacity (UCC). According to the framework, assessment upon the carrying capacity performance of individual carrier can also be conducted, thus those weak capacity carriers can be identified. The examination can alert city governors to pay more attention to those weak carriers that might be overlooked. In fact, as appreciated in previous studies, some essential carriers and indexes supporting sustainable urban development have been traditionally overlooked, for example, cultural location, entrepreneurship, information, science, technology, personal safety, health protection, light environment, and temperature environment, (Sun et al., 2018; Zhang et al., 2018), However, the mission of sustainable urban development would be sabotaged if the urban carrying capacities cannot be gained properly from urban carriers, and this issue has been overshadowed in the extant literature.

The guiding index framework introduced in this study provides a reference tool for examining upon urban carrying capacity (UCC), which works as a "dictionary" to help establish proper UCC evaluation indicators given its specific evaluation context. The application of the framework can help city decision makers understand what aspects should be addressed for examining the carrying capacity status of their cities and whether a specific urban carrier is properly utilised or overlooked. It also enables comparative analysis between various urban carriers and different cities, thus tailor-made policies can be designed and implemented in referring to specific urban carriers and the local contexts of different cities. Consequently, economic growth can be promoted, social needs can be better met, and quality environment can be provided for cities in a sustainable way.

The limitation of this study is appreciated: The introduced UCC guiding index framework is theoretically-based, and it is recommended for future research to conduct empirical studies for the application of UCC guiding index framework established in this study. Furthermore, investigation can also be conducted upon the UCC status between different cities across different application scenarios.

CRediT authorship contribution statement

Yitian Ren: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Liyin Shen:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing. **Xiaoxuan Wei:** Formal analysis, Investigation, Writing – review & editing. **Jinhuan Wang:** Conceptualization, Methodology, Data curation, formal analysis, Writing - original draft. **Guangyu Cheng:** Data curation, Validation, Writing – review & editing.

Declaration of Competing Interest

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

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