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REVIEW

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The next frontier: data-driven urban underground space planning orienting multiple development concepts

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Abstract

In recent years, the comprehensive and extensive development of urban underground space (UUS) has gained substantial popularity with the efficient guidance of UUS planning. This study discussed the research trends and paradigm shift in UUS planning over the past few decades. Bibliometric and comparative studies were conducted to identify the contributions of the research in this field. The analysis identified the overall temporal development trend of UUS planning and the research hot spots, namely, the primary use of UUS and UUS planning technology. Additionally, the study identified academic collaborative relationships through country and institution co-occurrence network analysis. The diversified development philosophy, planning systems, key planning scenarios, and data-driven technology pertaining to UUS planning have been extracted through keyword co-occurrence network analysis. Moreover, the planning systems, planning management, and planning practices for UUS in various countries, including Singapore, Japan, Finland, Canada, and China, were also systematically reviewed. By doing so, the worldwide UUS planning evolution has been identified. The paradigm shift for UUS planning has been clarified, involving technical method, result form, control mode, and control elements. Furthermore, the conceptual data-driven framework for UUS planning, which orients multiple development concepts, has been proposed to meet the requirement of next frontier development.

Keywords Urban underground space, Planning technology, Paradigm shift, Composite concept, CiteSpace

1 Introduction

As the world's population continues to grow, urbanization has become an irreversible trend [1]. With limited land resources, many cities are now facing an unprecedented challenge to balance the need for development and environmental protection. Therefore, the effective utilization of urban underground space (UUS) has become a hot topic of discussion. Extensive development practices worldwide have demonstrated the contribution of UUS to urban sustainability and resilience, and the comprehensive use of UUS (including underground municipal infrastructures, underground transportation facilities, underground public service spaces, civil defense spaces, etc.) has gradually become an imperative for solving the urban problems such as land scarcity, traffic congestion, and environmental degradation [2–5].

UUS has received increasing attention in recent years, and many scholars have conducted in-depth research concerning UUS use. In recent years, the rapid development of automatic and intelligent construction technology for underground engineering projects have enabled the extensive utilization of multifunctional underground spaces of a large scale in complicated urban built environment [6–8]. More importantly, the systematic and scientific planning systems for UUS have gradually formed, and the research regarding planning technology has been

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gaining popularity [9–15]. Nevertheless, the planning methods for both master and regulatory detailed plannings for UUS remain to be optimized [9, 12, 16, 17], since the corresponding planning concepts have transformed from simple functional use to multiple development goals involving sustainability, resilience, intelligence, livability, etc. Moreover, the emergence of new planning scenarios in key areas has also reshaped the system of UUS planning with a more specific and efficient control. In addition, the advanced spatial analytics methods have been incorporated into UUS planning research in the context of multisource spatiotemporal data environment [18–22].

To the best of our knowledge, no broad-ranging bibliometric study of research trends and influence networks of UUS planning has yet been conducted. Through data visualization, text analysis, and network analysis, the underlying hotspots and characteristics of UUS planning would be explicitly revealed, thus providing new insights for the planning research and planning practices with regard to UUS.

To bridge the aforementioned research gap, this study set out to identify the research trend and hotspots concerning UUS planning through bibliometric analysis. Furthermore, the UUS plannings in representative countries around the world would be systematically reviewed to make comparisons between planning practice and research. Ultimately, the paradigm shift of UUS planning would be discussed, and the corresponding data-driven planning framework would be proposed to meet the requirements of multiple emerging planning concepts of UUS. The main contributions of this study are twofold. Firstly, the bibliometric study concerning UUS planning would explicitly reveal the current gap between planning research and planning practices. Secondly, the identified paradigm shift and proposed planning framework would effectively extend the theoretical system of UUS planning to adapt to various emerging development concepts.

2 Data and methods

2.1 Data collection

The references for bibliometric analysis were collected from the Web of Science Core Collection on March 1, 2023. We searched the topic "underground space plan" with a time span from January 1, 1900 to December 31, 2022, which covers the information from abstract, title, and indexing. The document types involve "article", "proceeding paper", "review article", "book chapter", "editorial material", without the limit of language. Following the aforementioned steps, a total of 1308 references were obtained. Then, we adopted the intensive reading of the title and abstract to further screen the references. Among them, the references related to UUS planning concept, functional utilization mode, utilization law, planning technology, and planning management were identified to meet the requirements, whereas the technical research literature focusing on non-planning aspects was eliminated. Ultimately, 509 references were extracted as the fundamental database to conduct subsequent bibliometric analysis. The earliest literature found in the database was "Planning the development of underground space" by Sterling and Nelson in 1982 [13]. As such, the long-term time span of academic research pertaining to UUS planning could be identified as forty years from 1982 to 2022. To explicitly investigate the research trend, we extracted the references in the past five years as the short-term database, namely from 2017 to 2022.

Moreover, we have collected representative UUS plannings in the past few decades from all over the world through academic papers and official websites. These plannings, as well as the corresponding management and legal systems, would be compared to investigate the evolution of planning practice.

2.2 Analytical framework

As depicted in Fig. 1, the analytical framework of this study consists of two main parts: bibliometric analysis and comparative analysis of planning practice. Firstly, a general analysis was conducted on the bibliographic characteristics in the database to explore the temporal growth trends and conduct preliminary analysis on the most cited literature, in order to capture the research hotspots. Subsequently, bibliometric analysis was performed based on the long-term bibliographic database. Specifically, CiteSpace (version 6.1.R2) was used to construct the bibliometric network and perform co-occurrence analysis [23], which includes countries, institutions, and keywords of the references. Co-occurrence networks are generated based on the frequency of occurrence of two entities, such as keywords, in the same articles. When using CiteSpace to analyze such networks, there are a variety of metrics that can be used to measure their significance, including structural metrics such as modularity and the silhouette score [24]. The Q score, or modularity, measures the quality of the network's division into clusters. A Q score of over 0.3 is considered significant, with higher scores indicating a well-structured network. The S score, or silhouette score, measures the quality of a clustering configuration and ranges from -1 to + 1. A S score above 0.3, 0.5, or 0.7 is considered indicative of a homogenous, reasonable, or highly credible network, respectively. Furthermore, latest short-term bibliographic database was utilized for bibliometric analysis, which focused on keyword co-occurrence network analysis and timeline clustering analysis, thus forming a contrast with the results obtained from the long-term bibliometric analysis, and determining the changes in research trends and hotspots.

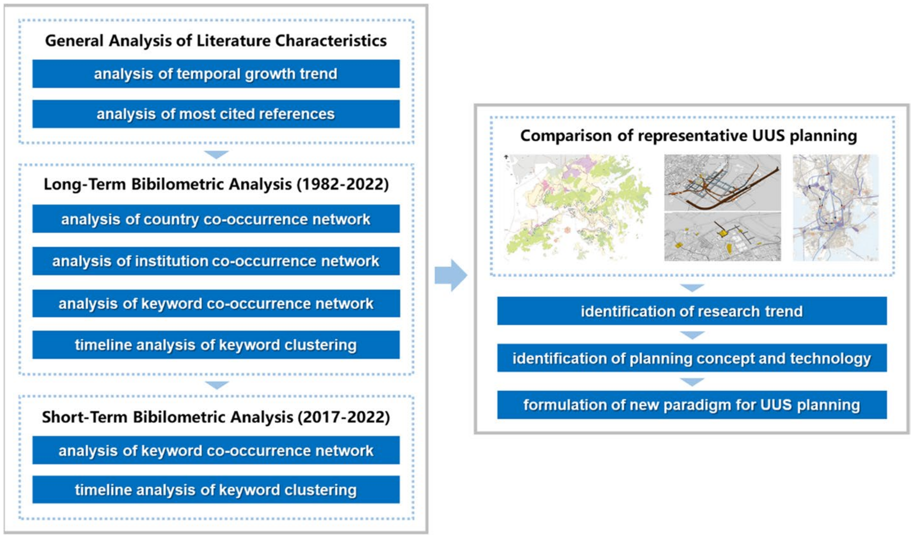

Fig. 1 Analytical framework

For long-term bibliographic analysis, the slice length of time span was set as 5 years, and the selection criteria was g-index method (k = 25). For short-term bibliographic analysis, the slice length was set as 1 year.

After that, we carried out a comparative analysis of the representative UUS plannings in various countries/regions, sorted out its main characteristics and evolution, and explored the development trend of planning practice. Under this analytical framework, the trend of the research level would be identified through bibliometric analysis. Combined with the comparative analysis of planning practice, the planning concept and planning technology development at the practical level would be studied and judged. Finally, a new paradigm of UUS planning would be formulated, thus building a forward-looking theoretical framework for the next frontier.

3 Bibliometric analysis of UUS planning

3.1 General analysis of literature characteristics

3.1.1 Analysis of temporal growth trend

Figure 2 displays the annual publication count and regression trendline of UUS planning-related literature in a long-term reference database. It can be observed that prior to 1990, there was only slight research interest in

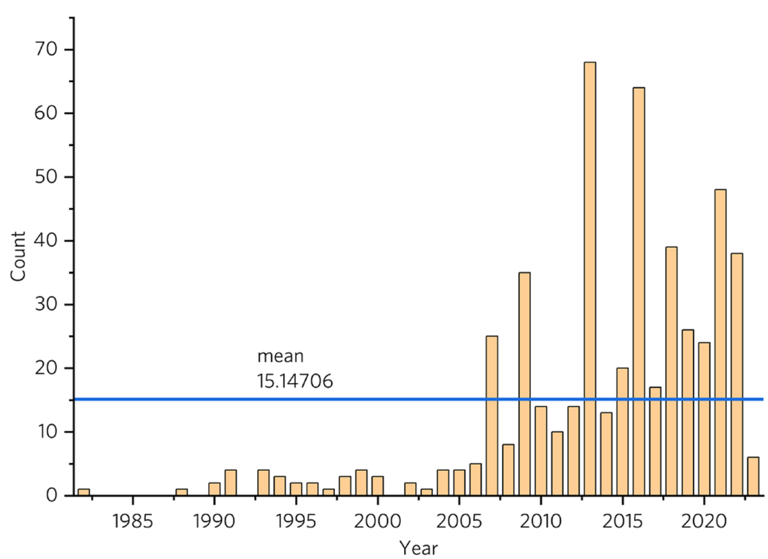

Fig. 2 Histogram of annual publication count

this field, whereas from 1990 to 2006, there was a relatively sustained level of research attention. Starting from 2007, there was a sharp increase in the number of publications in this field, and although the data fluctuates greatly, it shows an overall trend of high growth. The publication peaks occurred in 2013 and 2016, both exceeding 60 references. The distribution of peak years is consistent with the years of the annual academic conference of the international organization, the Associated research Centers for the Urban Underground Space (ACUUS), indicating the core driving role of this organization in the research field of UUS utilization [25]. Over a span of 40 years, the average annual publication count in this field was 15.15 publications.

3.1.2 Analysis of most cited references

To gain insight into the most influential literature in this field, we have compiled a list of the top 10 most cited references in the network (as shown in Table 1). Topping the list is the article "*Urban underground space: Solving the problems of todays cities*" by Broere [5], which has been cited 199 times since its publication in 2016. In this study, common infrastructure and environmental problems were paired with urban underground solutions, involving traffic congestion, pollution and noise, protection against natural disasters, lack of space and preservation of heritage and environment, and utilities and infrastructure. Similarly, other most cited reference such as "*Present state, problems and development trends of urban underground space in China*" also indicate the importance of UUS development from an overall perspective [4]. Moreover, it could be observed that the municipal infrastructure, from Paris sewers to modern utility tunnel, has always been the mainstream UUS development mode [26, 27]. Apart from the aforementioned literature, other highly cited references are concerned about planning system and methods of UUS, including land-use planning [14], master planning for UUS [9, 28], and detailed techniques such as resources evaluation [19], demand prediction [29], and threat analysis [30].

In view of the most cited references, the primary use of UUS, as well as the planning technology, has become the research hotspots in this field. Additionally, seven of the top 10 references are associated with China, indicating that China has become the main battlefield of UUS development and planning practice. More specific characteristics of research trend would be investigated in subsequent bibliometric analysis.

3.2 Long-term bibliometric analysis (1982–2022)

3.2.1 Analysis of country co-occurrence network

Figure 3 presents a national co-occurrence network of research papers related to UUS planning. China is the leading contributor with 208 publications, followed by the United States with 31. Other countries such as the United Kingdom (24), Japan (23), Italy (22), Singapore (22), the Netherlands (22), Russia (21), Switzerland (20), Australia (18), Canada (14), Spain (14), Germany (13), South Korea (13), and Greece (13) have also conducted significant research on UUS planning. Overall, Asia, Europe, and North America are the main regions where research on UUS planning is conducted, and this distribution is related to multiple factors such as climate

Table 1 Top 10 most cited references in the network

Title	Number of citations	Year	Source
Urban underground space: Solving the problems of today's cities [5]	199	2016	Tunnelling and Underground Space Technology
Mainstreaming sustainable development into a city's Master plan: A case of Urban Underground Space use [28]	193	2009	Land Use Policy
The Paris sewers and the rationalization of urban space [26]	128	1999	Transactions of the Institute of British Geographers
Development and applications of common utility tunnels in China [27]	91	2018	Tunnelling and Underground Space Technology
Advances in master planning of urban underground space (UUS) in China [9]	80	2016	Tunnelling and Underground Space Technology
A GIS-based evaluation method of underground space resources for urban spatial planning: Part 1 methodology [19]	79	2018	Tunnelling and Underground Space Technology
Present state, problems and development trends of urban underground space in China [4]	77	2016	Tunnelling and Underground Space Technology
Underground space in land-use planning [14]	75	1998	Tunnelling and Underground Space Technology
Criticality and threat analysis on utility tunnels for planning security policies of utilities in urban underground space [30]	67	2013	Expert Systems with Applications
Quantitative research on the capacity of urban underground space—The case of Shanghai, China [29]	65	2012	Tunnelling and Underground Space Technology

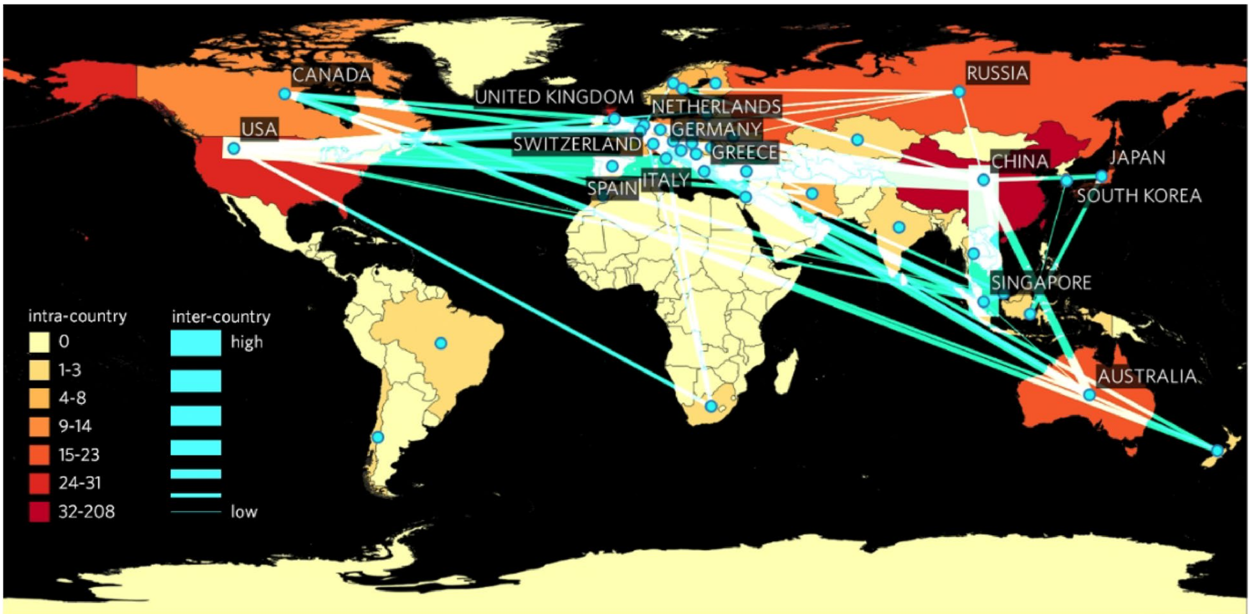

Fig. 3 Level of intra-country publications and inter-country collaborative publications (1982–2022). The color of layered style map indicates the total number of publications within a country, and the width of cyan lines connecting countries indicates the number of collaborative publications between countries

conditions, economic development, and population density in different countries [5, 16, 31].

In terms of international cooperation, strong inter-country partnerships have been observed between China and the United States, as well as between China and Singapore. Moreover, extensive collaboration exists among European countries, and China, Japan, Singapore, and South Korea have formed a transnational cooperation network in Asia. It is noteworthy that North America has not formed internal collaboration, as Canada and the United States have established connections with Asian, European, and Oceanian countries, but not with each other. In essence, Europe and Asia are the primary regions for academic research exchange and cooperation on UUS planning, whereas North America and Oceania participate as collaborators.

3.2.2 Analysis of institution co-occurrence network

Regarding the co-occurrence network of research institutions, the majority of the publications from the main research institutions were published in the last decade (as shown in Fig. 4), which is consistent with the previously revealed trend of literature growth. Among them, Chinese research institutions are widely distributed throughout the network and contribute the vast majority of the literature research. In terms of the number of publications, Tongji University is prominently in the first place among the research institutions, while other research institutions such as the PLA University of Science and Technology, National Technical University of Athens, Tsinghua University, Delft University of Technology, China University of Mining and Technology, Nanyang Technological University, Nanjing University, University of Birmingham, Chongqing University, and Shanghai Jiao Tong University have also accumulated a substantial amount of research results. In terms of institutional cooperation, most research institutions collaborate with other research institutions in their own country. Among them, Tongji University has established extensive cooperation with research institutions in Japan, Australia, and other countries in addition to domestic institutions, but such international cooperation is relatively rare in the co-occurrence network. This also indicates the localization feature of the current research on UUS planning, and more frequent international academic exchanges need to be promoted.

3.2.3 Analysis of keyword co-occurrence network

As depicted in Fig. 5, the keyword co-occurrence network was divided into 14 clusters, with their labels hidden for a more concise visualization. The Q and S values were 0.8442 and 0.8953, respectively, indicating a well-structured and homogeneous network. The identified clusters encompass various topics related to UUS planning, involving *#1 urban underground space*, *#2 rail transit*, *#3 carbon dioxide*, *#5 underground urbanism*, *#6 layout pattern*, *#7 underground space use*, *#8 urban planning*, *#9 master plan*, *#10 disaster prevention*, *#11*

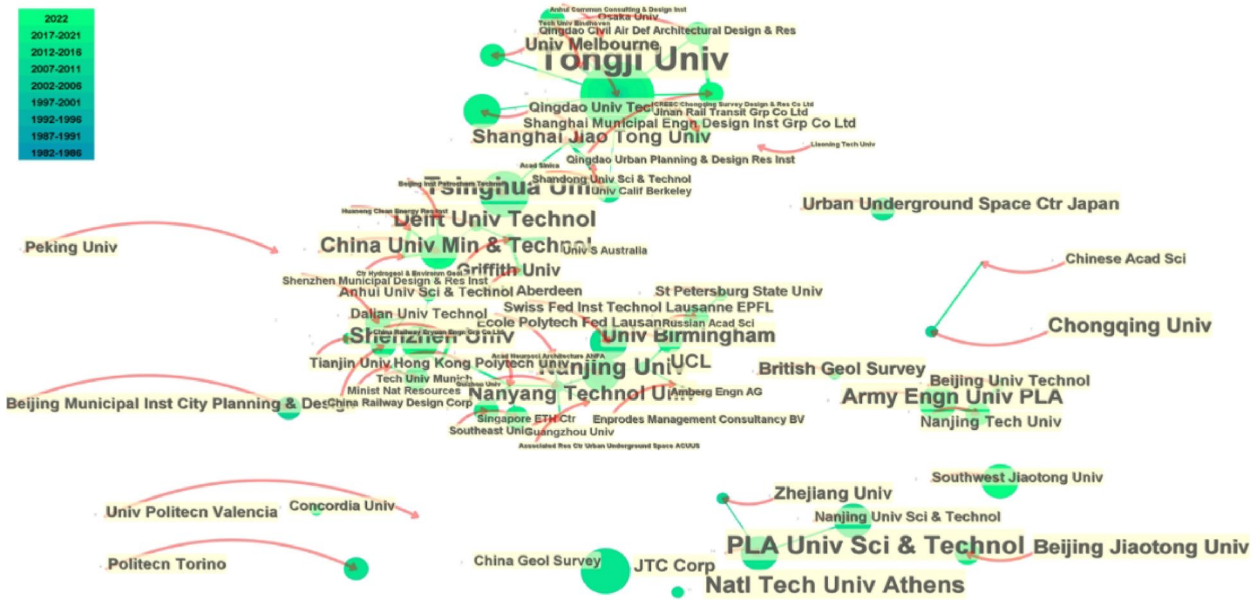

Fig. 4 Co-occurrence network of research institutions (1982–2022). Red curves are guidelines to link the labels and circles of specific institutions, and the rings with different colors represent the number of publications in distinct periods. The scales of both labels and circles indicate the accumulated number of publications of specific institutions

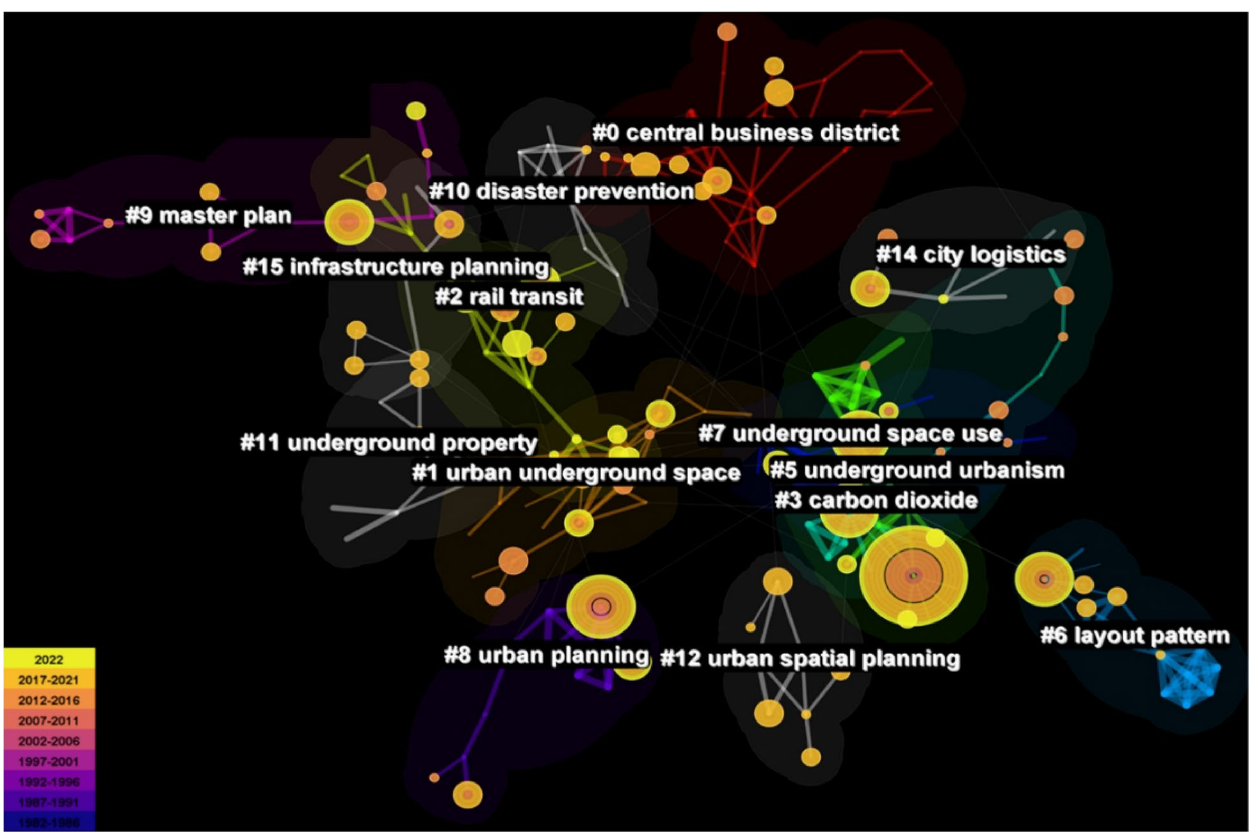

Fig. 5 Long-term co-occurrence network of keywords with clustering (1982–2022). White labels indicate the names of keyword clusters. The links with the same color belong to the same cluster. The rings with different colors represent the number of keyword occurrence in distinct periods. The scales of circles indicate the accumulated number of occurrences of specific keywords

underground property, *#12 urban spatial planning*, *#14 city logistics*, *#15 infrastructure planning*.

Among these clusters, three of them, namely *#0 central business district*, *#2 rail transit*, and *#3 carbon dioxide*, were notably large in scale, highlighting their significance in UUS planning research. The *#0 central business district* cluster included keywords such as central business district (CBD), regulatory detailed planning, and underground workplace. The development of UUS in CBDs has become increasingly important in high-end urbanization due to the scarcity of land resources in these areas [4]. Regulatory detailed planning for UUS, such as the UUS planning for Shanghai Hongqiao CBD, has proven to be an effective tool in guiding its implementation [12, 32]. The *#2 rail transit* cluster included keywords such as space syntax [33], accessibility [21], and multi-source data [18, 34, 35], indicating the frontier of UUS development. In densely populated or extreme climate regions with advanced rail transit networks [36–38], large-scale and multi-functional metro-led underground spaces (MUS) are likely to be developed [34, 39, 40]. The *#3 carbon dioxide* cluster included keywords such as climate change [41], low-carbon effects [42], and carbon dioxide sequestration [43]. Planners have recognized the monetary valuation of low carbon externalities derived from underground facilities [44–47], while deep underground spaces have expanded the use of UUS for efficient carbon dioxide storage [41].

Moreover, the identified clusters can be divided into two groups based on their focus. The first group relates to the use or function of modern UUS, and includes the aforementioned three clusters. Additionally, cluster *#5 underground urbanism* reflects UUS development in the context of urban redevelopment [48, 49] and new town development [50]. Clusters *#1 urban underground space* and *#7 underground space use* both focus on the primary use of UUS, which encompasses metro systems [34, 38, 51], underground roads [47, 52, 53], parking spaces [20, 53, 54], pedestrian networks [55–57], utility tunnels [58, 59], and public spaces [18, 25, 60]. Cluster *#10 disaster prevention* emphasizes the potential of UUS to mitigate the impact of natural disasters and air attacks [61–64], thereby enhancing urban resilience. Cluster *#14 city logistics* focuses on the innovative use of UUS for urban logistics systems, which involves integrating logistic networks with metro lines and underground roads to reduce the negative impacts (vehicle emissions, traffic congestion, etc.) of urban logistics on ground-level space[65, 66].

The second group pertains to UUS planning methods. Cluster *#6 layout pattern*, with keywords such as functional planning, commercial areas, and interaction characteristics, focuses on the scientific layout of complex UUS [67–69]. Clusters *#8 urban planning*, *#12 urban spatial planning*, and *#15 infrastructure planning* share many similarities, emphasizing the need for spatial planning systems for UUS on a global scale [2, 10, 13–15, 70, 71]. Cluster *#9 master plan* centers on the most universal UUS planning approach worldwide, namely the master planning for UUS, which typically involves upper level planning analysis, analysis and appraisal of current UUS situations, investigation and evaluation of UUS resources, forecast of functional demands and development volume of UUS, objectives and development strategies of UUS, overall layout planning of UUS, function systems planning, and UUS planning in the short term and future vision [9]. Lastly, cluster *#11 underground property* focuses on the development rights or ownership of UUS and the technical issues related to underground space administration [72, 73].

3.2.4 Timeline analysis of keyword clustering

In view of the timeline analysis of keyword clustering (as depicted in Fig. 6), some temporal changes of research hotspots could be observed. Overall, all research clusters have maintained a sustained research interest, with the majority of research emerging between 2005 and 2010. Keywords such as underground space, urban planning, and space have accumulated a significant number of publications. In addition, keywords such as sustainable development, urban planning, infrastructure planning, socio-environmental externality, and urban development demonstrate obvious inter-cluster connections, indicating the crucial role of sustainable and ecological concepts in the field of urban underground space planning. Examining the research hotspots within each cluster, *#0 central business district*, *#1 urban underground space*, *#2 rail transit*, and *#7 underground space use* have maintained a high level of research interest across different time periods, forming multiple hotspots. This indicates the epoch-making significance of UUS development in key areas such as MUS and UUS in key areas like CBD.

3.3 Short-term bibliometric analysis (2017–2022)

3.3.1 Analysis of keyword co-occurrence network

One hundred ninety-four latest references were extracted for short-term bibliometric analysis, and the keyword co-occurrence network was depicted in Fig. 7. Likewise, the Q and S values were 0.8415 and 0.9378, respectively, indicating a well-structured and homogeneous network. A total of eight clusters were identified, which is different from the results from long-term bibliometric analysis. Three of these clusters, namely, *#0 urban planning*, *#1 infrastructure planning*, *#2 urban underground space*, were also detected in previous clustering, indicating that

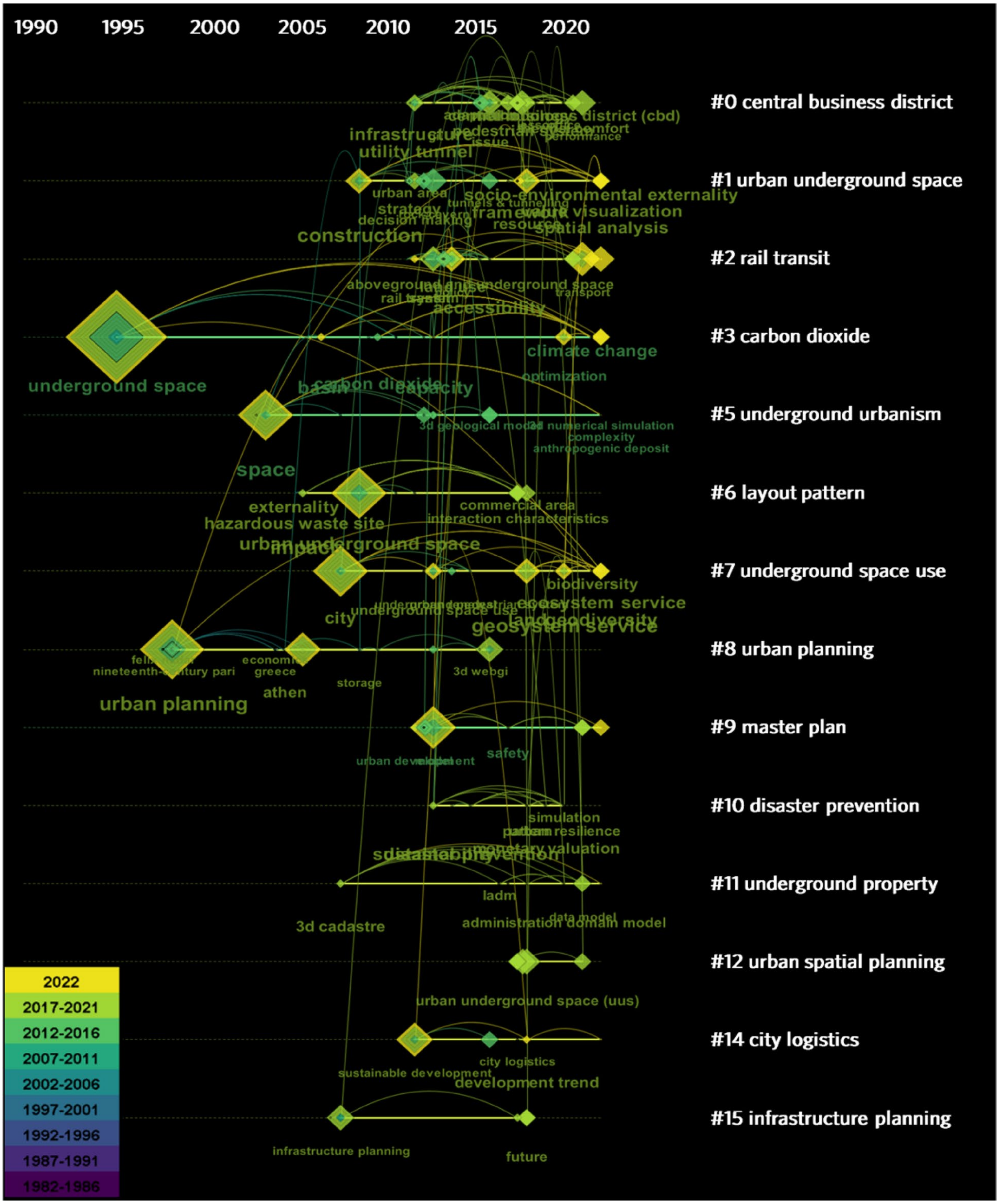

Fig. 6 Timeline view of long-term co-occurrence network of keywords with clustering (1982–2022)

they have always been research hotspots for UUS planning. Nevertheless, five new clusters were also identified in the short-term keyword co-occurrence network, namely, *#3 spatial analysis*, *#4 evaluation method*, *#5 integrated planning*, *#6 new development*, *#7 3d geodatabase*.

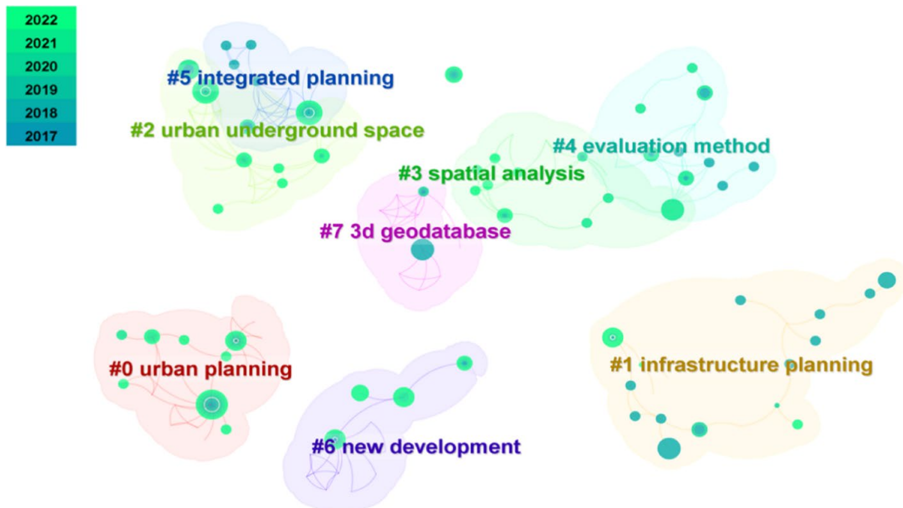

Fig. 7 Short-term co-occurrence network of keywords with clustering (2017–2022)

Regarding cluster *#3 spatial analysis*, it contains keywords such as spatial analysis, value visualization, and geographical detector. In effects, spatial analysis should be the most typical characteristic of data-driven UUS planning study. Nowadays, the adoption of geographic information system (GIS) and advanced spatial statistical methods such as geographical detector and spatial autocorrelation have enabled the subtle development mechanism of UUS from a spatial perspective [20, 22, 39, 54, 74]. For cluster *#4 evaluation method*, it is tightly associated with spatial analysis. Based on the multisource big data, a series of important quantitative evaluation, such as demand forecast [40], resources evaluation [19, 75], monetary benefits and costs [45, 61], spatial vitality [21, 35], and spatial performance [18, 49], could be fulfilled to support UUS planning. Concerning cluster *#5 integrated planning*, it derives from the previous cluster *#6 layout planning* in long-term keyword co-occurrence network, focusing on those keywords such as integrated planning, layout pattern, commercial area, and interaction characteristics. Essentially, this cluster centers on the integration of multiple function and complex spatial configuration of UUS on both macro and micro levels. The most representative research in this cluster should be the intelligent layout planning models for UUS master planning [76] and MUS detailed regulatory planning [68], which incorporate various function systems and planning strategies. Moreover, the in-depth analysis of the interplay between UUS development and surrounding built environment should be the basis for integrated UUS planning [34, 60, 69]. For cluster *#6 new development*, it encompasses keywords such as land use, disaster prevention, transport, station, basically reflecting the frontiers of modern UUS utilization pertaining to transport-oriented and resilient development [77, 78]. Regarding cluster *#7 3d geodatabase*, it contains keywords such as environment, 3d geodatabase, and citizen science. This cluster expands the previous cluster *#11 underground property* in long-term keyword co-occurrence network. In recent years, 3d geodatabase has become the fundamental of smart UUS, serving as a digital base for the digital twin of underground space and facilitating the intelligent decision making for UUS planning [79–82].

3.3.2 Timeline analysis of keyword clustering

As shown in Fig. 8, cluster *#5 integrated planning* and cluster *#7 3d geodatabase* did not show continuous research interest in the short-term bibliometric analysis, and their popularity declined early. However, the core clusters in the long-term analysis, such as cluster *#0 urban planning*, cluster *#1 infrastructure planning*, and cluster *#2 urban underground space*, still received long-term research attention. Both cluster *#0 urban planning* and cluster *#2 urban underground space* have continued to emerge as research hotspots. In addition, cluster *#3 spatial analysis* started in 2019, later than the other clusters, indicating a relatively delayed introduction of relevant multi-source spatiotemporal data and spatial analysis models in the field of UUS planning. Nevertheless, this cluster also showed a dense distribution of research hotspots over time, confirming the huge research potential of data-driven analytical techniques in UUS planning.

Regarding inter-cluster research, weak cross-research phenomena were observed in the short-term analysis between cluster *#0 urban planning* and cluster *#1 infrastructure planning*, cluster *#2 urban underground space*

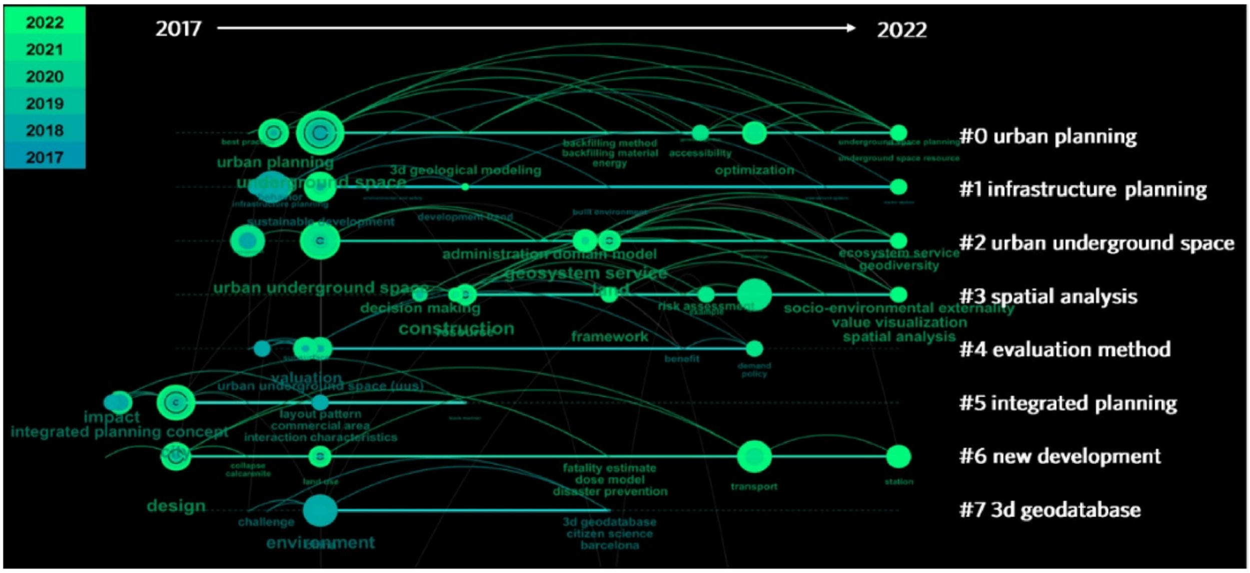

Fig. 8 Timeline view of short-term co-occurrence network of keywords with clustering (2017–2022)

and cluster *#5 integrated planning*, and cluster *#3 spatial analysis* and cluster *#4 evaluation method*. This suggests that spatial analysis techniques have to some extent promoted the modeling of UUS evaluation methods, and UUS planning has continued to integrate with various scenarios and functional planning.

4 Comparative study of UUS planning practices

UUS development has been widely applied to urban incremental expansion and stock renewal in developed countries or regions, where urbanization started early. In the late 19th and early twentieth centuries, engineers or architects such as Soria Mata (1882), Eugène Hénard (1910), Harvey Wiley Corbett (1913), and Le Corbusier (1933) proposed planning concepts for UUS based on existing early urban underground space utilization practices [83]. In the 1970s, Sweden began exploring methods for overall planning of underground space and theoretical research [71].

In 1982, Sterling and Nelson from the University of Minnesota conducted a city-wide study on underground space planning and utilization in Minneapolis [13]. In 1986, Helsinki, Finland developed a city-wide underground space allocation plan, becoming the first city in the world to carry out overall planning for underground space [84]. Subsequently, countries such as Japan [11], Singapore [10], the Netherlands [85], Germany [15], and Canada [36] have carried out relevant planning practices or strategic research on UUS. Generally, the existing planning practices for UUS mainly focus on development strategy research, and there are relatively few countries that have established a relatively complete planning system or developed planning schemes with legal effect. To conduct a comparative study, the characteristics and focuses of UUS planning practices in representative regions such as Singapore, Japan, Finland (Helsinki), Canada (Toronto and Montreal), and China would be investigated thoroughly. These research cases all present outstanding performances regarding UUS development, and their socio-economic development conditions, climate environment, built environment density, and political system vary substantially, which can help examine the development path of UUS planning and management from different perspectives. Among them, Singapore and Japan showcase the UUS planning characteristics of developed countries in the high-density built environment of East Asia. Finland and Canada represent UUS development with climate and environment as the dominant factors, and their planning and control ideas also differ. As the largest developing country, China has extensive practical experience in UUS planning and is constantly innovating its planning management system, which can be used for reference with the UUS planning of the aforementioned first mover countries.

4.1 Singapore

Singapore does not have a separate underground space planning system but incorporates it into the existing two-level urban planning system. Long-term planning, similar to China's urban master planning, explicitly proposes the overall requirements for underground space resource development in the 2021 revised plan, with particular attention to the development of underground rock cave space, transportation facilities, municipal public facilities, and logistics systems. On the other hand, the master plan, similar to China's detailed planning, can be further divided into land use zoning (legal planning) and special and detailed control planning (non-legal planning). For seven specific regions in the country, both the master plan and the corresponding urban design guidelines already include control requirements related to the construction of underground basements and underground pedestrian or vehicular connections [86]. In 2019, the special and detailed control plan (SDCP) presented guidance control requirements for underground space development in the Marina Bay (as shown in Fig. 9), Jurong Innovation District, and Punggol Digital District in the form of three-dimensional planning, including development functions, construction scope, development depth, and connection requirements. Notably, the layer by layer 3D geological model for Singapore has been constructed based on extensive borehole data [87], which would efficiently facilitate the UUS planning driven by geotechnical big data.

4.2 Japan

Due to strict land private ownership, UUS development in Japan is mainly located beneath public land such as roads, squares, and parks, and integrates into a complex underground space network through underground complex, rail transit stations, and utility tunnel. The Urban Planning Law explicitly states that underground space utilization planning is part of Japan's urban planning system, ensuring the legal effect of planning [11]. Japan's UUS planning system could be classified into master planning for underground space at the overall level, guiding planning for underground utilization at the detailed level, and special planning for underground transportation networks, underground streets, and utility tunnel at the specific level. Specifically, those underground complexes jointly developed by government departments and private enterprises with public participation are the important component of UUS plannings in Japan. Moreover, Japan has made extensive efforts to enhance urban resilience by developing large-scale underground infrastructures. The metropolitan area outer underground discharge channel located in Kasukabe, which is the largest man-made underground flood prevention facility in the world, is an exemplary case for resilience-oriented UUS use [88].

4.3 Finland

Helsinki is the region with the most advanced development of underground space in Finland [70, 84]. The development of UUS in Helsinki is not motivated by the cold climate, but rather by the excellent geological conditions of the rock and the need of local residents for open space on the ground, which requires a large amount of urban infrastructure to be developed underground [70]. The urban planning system in Helsinki includes a master plan, a detailed plan, and a street and park plan. The master planning of underground space is independently prepared under the guidance of the principles of the city's master plan and is approved by the city council to obtain legal effect. In 1986, Helsinki developed the first city-wide underground space allocation plan [84]. In 2010, the first underground master plan was approved by the city council [70]. In 2017, the relevant departments in Helsinki launched a new round of revisions to the master planning of underground space, which was approved by the city council in 2021 (as shown in Fig. 10). The plan specifies the reserved space and coordination relationships of important underground transportation and municipal infrastructure within the city, and proposes

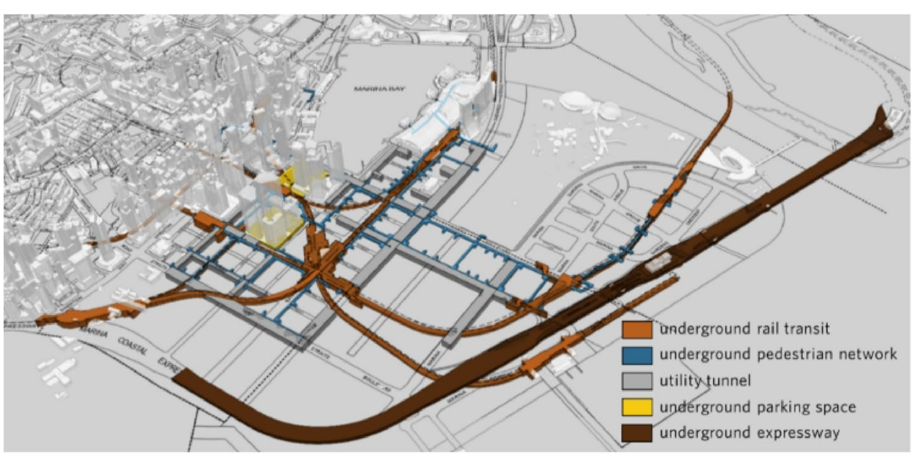

Fig. 9 3D map of SDCP for underground space in Marina Bay, Singapore (modified from https://www.ura.gov.sg/maps/index.html)

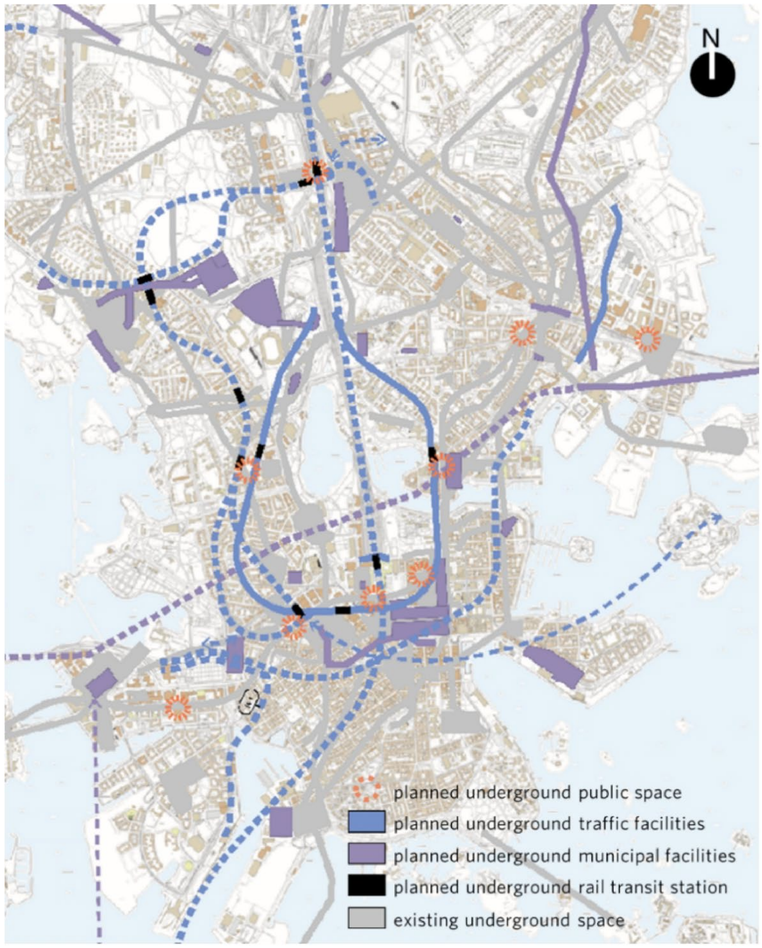

Fig. 10 Master planning for UUS in Helsinki (modified from https://kartta.hel.fi/?sukkaId=2017%E2%80%91001746)

key areas for the construction of underground public service facilities and pedestrian systems, further improving the development strategy of rock underground space. During the compilation of the underground master plan of Helsinki, a series of positive effects of UUS use such as contribution to an environmentally sustainable and aesthetically acceptable landscape, anticipated structural longevity, and maintaining the opportunity for urban development by future generations, has been considered and integrated, which manifests sustainable and human-oriented development concepts [89].

4.4 Canada

Toronto and Montreal are typical cities in Canada for the development of underground spaces, exhibiting similar characteristics in underground space planning. In 1964, based on the successful experience of developing the underground passage between Montreal's Place Ville-Marie and the Central Station, Vincent Ponte was spontaneously authorized by landowners to carry out unified underground space design for a seven-hectare plot of land in downtown Montreal, which became the earliest strategic underground space planning in the area. Due to economic factors, the above planning was not fully implemented, and no new underground space planning was formulated for over 20 years. In 1984, Montreal's planning department began to compile the master plan for an underground pedestrian network, proposing the principle of underground space connectivity and using the plan as a construction guide for land development [25]. Similarly, in the 1960s, Toronto planning commissioner Matthew Lawson proposed the development plan for underground spaces based on the concept of "separating people and vehicles," but it was not implemented due to excessive financial investment. Later, in 1995, the city government enacted the "Underground pedestrian system design guidelines," and in 2011, the "PATH pedestrian network master plan" was completed, clarifying the development principles of the underground pedestrian system and its complementary and extensional positioning as a surface pedestrian system [36]. In 2012, the newly revised "Design guidelines for PATH and other climate-controlled pedestrian networks" put forward detailed design requirements for eight aspects, including indoor pedestrian passageways, public spaces, accessibility, entrances and exits, wayfinding, decorative lighting, accessibility facilities, and safety, standardizing the construction of the underground pedestrian system. Overall, the construction of underground spaces in Canada is primarily led by private developers, with government departments only providing corresponding planning guidelines and policy guidance. Unlike Singapore and Finland, Toronto and Montreal have not constructed a systematic underground space planning system [25, 36]. Existing plans are only special plans for the underground pedestrian system, which do not have legal effect as they have not been approved by local city councils. In addition, the UUS utilization in Montreal since 1962 has a long list of humanization experiences, involving the ingenious artworks and various cultural activities in subway stations [90]. Through both human-oriented design and the cooperation of the government and private stakeholders, one of the most large-scale and vigorous underground cities has been developed in Canada.

4.5 China

The development of underground spaces in Chinese cities originated from the large-scale construction of civil defense projects in the early days. It gradually combined with urban construction and utilized underground spaces to solve urban problems and achieve efficient use of spatial resources. In the practice of underground space development, major Chinese cities or urban key areas have carried out a large number of master planning and detailed planning for UUS, and gradually established a relatively complete planning system [9, 12].

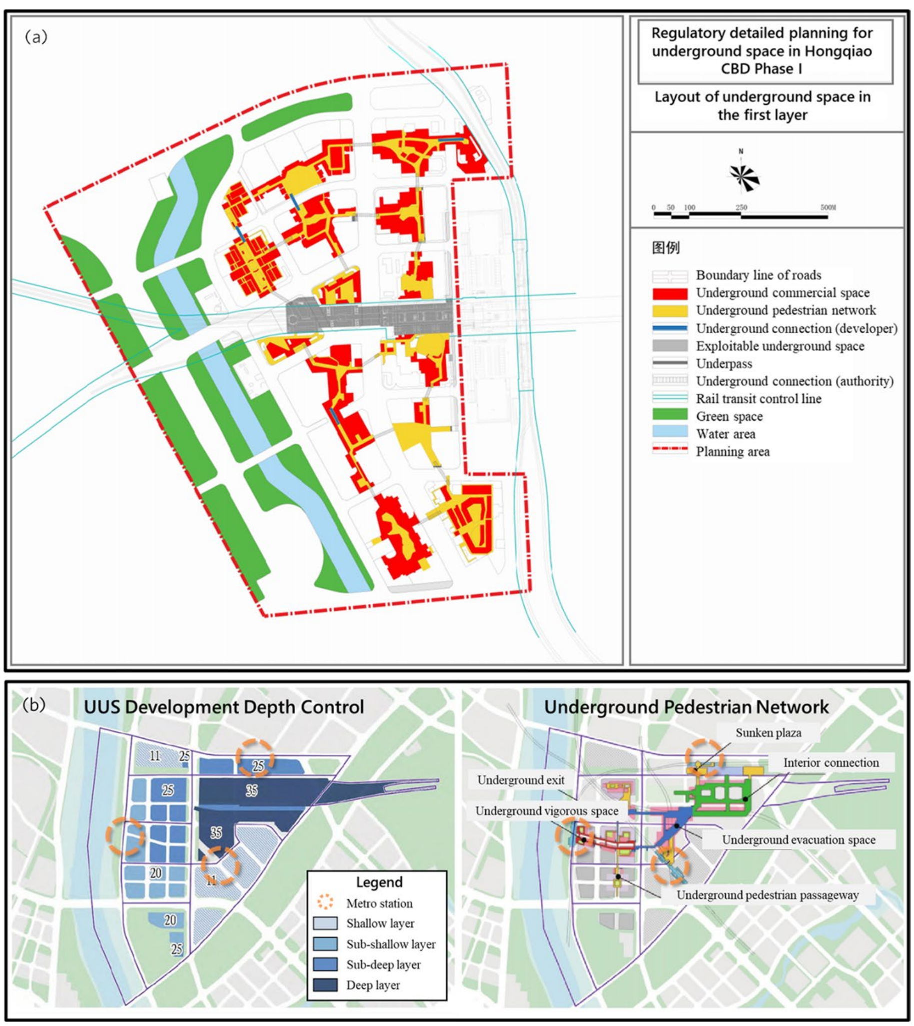

Fig. 11 Representative UUS plannings in China. **a** regulatory detailed planning for UUS in Shanghai Hongqiao CBD (modified from literature [12]. **b** regulatory detailed planning for UUS in Beijing Sub-City Center (modified from literature [17])

Prior to 1997, the use of UUS mainly focused on civil defense projects, military-civilian combined projects, and municipal pipeline laying. In terms of planning and preparation, single professional planning was the predominant approach, and the comprehensive concept of UUS had not yet been proposed. In 1997, the Ministry of Housing and Urban–Rural Development of the People's Republic of China issued the "*Regulations on the Management of Urban Underground Space Development and Utilization*," which clearly defined that UUS planning is an important part of urban planning and effectively promoted the preparation and practice of UUS planning in Chinese cities. In 2007, the *Urban and Rural Planning Law* formally established the urban and rural planning system for the development of incremental land in China, and UUS planning, as a comprehensive special planning, was also incorporated into the urban and rural planning of various regions in China, establishing a standardized and systematic UUS planning practice system. As depicted in Fig. 11, regulatory detailed planning for UUS in Shanghai Hongqiao CBD is a representative planning practice that the implementation effects of UUS development are guaranteed through a set of explicit imperatives, indicators, and rules [12].

Since 2019, the territorial spatial planning system has gradually been established in China. In this context, UUS planning belongs to the category of "special planning" at the city, county, and township levels, and could still be divided into two types of master planning and detailed planning based on the planning scope and control requirements. Moreover, all kinds of underground resources (underground energy, underground mineral resources, groundwater resources, underground cultural relics, etc.) rather than simply underground spaces are incorporated into the territorial spatial planning [91]. During the planning process, each region further refines the underground space planning system according to its own situation: For instance, Beijing has built a "city-wide (master planning)—district (district planning)—specific area (detailed planning)" underground space planning system [17].

In the past few years, some cutting-edge planning techniques have been experimentally adopted for UUS plannings in Chinese cities. For instance, the intelligent layout planning models driven by multisource big data and heuristics algorithms have been successfully applied to UUS plannings at both district (Luohu district in Shenzhen [76]) and subdistrict (Chengyang district in Qingdao [68, 92]) levels. Moreover, the monetary valuation model of UUS externalities, as well as the visualization of positive and negative externalities derived from UUS development, have been incorporated into the thematic study for UUS planning in Shinan district in Qngdao [22, 74, 93]. It could be found that the data-driven techniques have been playing a more and more crucial role in UUS plannings in China.

4.6 Commonalities and differences

In summary, aforementioned countries' UUS planning systems share common elements, such as the use of the master planning and detailed planning to guide UUS development. Meanwhile, they also differ in the specific details

Table 2 Comparison of the UUS planning systems in selected case countries

Country	Level	Focus	Representative Planning Projects
Singapore	No separate UUS planning; Long-term plan; Master plan; Special detailed and control plan	resource development of underground rock cave space, transportation facilities, municipal public facilities, and logistics systems	SDCP for UUS development in Marina Bay, Jurong Innovation District, and Punggol Digital District
Japan	Master planning; Guiding planning; Specilaized planning	underground street, rail transit stations, utility tunnel, underground transportation networks	Planning for underground space development in Tokyo Metropolitan Area
Finland	Master plan; Detailed plan; Street and park plan	underground infrastructure development, coordination relationships of important underground transportation and municipal infrastructure, construction of underground public service facilities and pedestrian systems	Helsinki underground space allocation plan; Helsinki underground master plan
Canada	No separate UUS planning; Special planning	underground pedestrian network, development principles of the underground pedestrian system and its complementary and extensional positioning	PATH pedestrian network master plan
China	Territorial spatial planning; Master planning; Detailed planning	military-civilian combined projects, underground public space, underground infrastructure, underground energy, underground mineral resources, groundwater resources, underground cultural relics	Regulatory detailed planning for UUS in Shanghai Hongqiao CBD; Regulatory detailed planning for UUS in Beijing Sub-City Center

of their planning systems. To present an explicit comparison, Table 2 furhter summarizes the main charateristics of UUS planning systems in selected case countries.

5 Discussion

5.1 Identification of research trend and planning evolution

5.1.1 Identification of research trend

The research interest in UUS planning began to soar around 2007 and has consistently maintained a high growth trend. Regional collaboration has been established among research institutions worldwide, while major research sites such as China and the United States have formed cross-regional international academic collaborations with academic institutions from other countries. Long-term and short-term bibliometric analyses reveal three main trends in the field's development:

(1) Early research on planning ontology focused on analyzing the importance of underground space utilization forms and development. However, in the past decade, it has increasingly shifted towards the study of planning systems at different levels, such as master planning and regulatory detailed planning. Key planning scenarios such as urban renewal, metro-led development, and the construction of high-end CBD have become the forefront of UUS planning research.
(2) The development philosophy of UUS planning has become increasingly diverse, with low-carbon, energy-saving, ecological, resilient, sustainable, intensive, vibrant, and people-oriented concepts gradually integrated into cutting-edge research. Related planning and design methods have continued to improve, showing a trend towards integration, gradually reshaping the theoretical foundation of UUS planning.
(3) Emerging multi-source spatiotemporal data represented by open street map (OSM), point of interest (POI), location-based service (LBS), etc., are continuously empowering UUS planning research. Based on multidisciplinary knowledge such as spatial morphology, spatial statistics, machine learning, urban modeling, and complex decision theory, data-driven decision support models have been developed for advanced UUS planning analysis, evaluation, visualization, layout, etc. Furthermore, the construction of 3D geospatial databases has become the digital foundation for intelligent underground space planning.

5.1.2 Identification of planning evolution

In the context of planning practice, based on the UUS planning experiences of various countries in the past few decades, three evolutionary features of planning can be extracted:

(1) From the perspective of practical experience, various countries have consolidated a series of achievements in planning system, planning technology, planning management and other aspects. Although the regulatory detailed planning for UUS has not been widely popularized in different regions of the world, using the master planning for UUS or incorporating UUS development and control requirements into overall spatial planning has become an effective planning approach to guide the orderly utilization of underground space resources.
(2) There is an apparent time lag between current planning practice and planning research. Except for using GIS for basic spatial analysis and visualization, other data-driven planning techniques have not been widely applied in planning preparation in spite of the intelligent methods adoption in minor cases. Fundamentally, emerging planning technologies based on multi-source spatiotemporal data can provide qualitative and sequential support for planning decisions, but cannot establish accurate mapping relationships with real planning control indicators, and require further study.
(3) In addition, due to the different geographic resource endowments of various countries, the focus of their UUS planning also differs. However, overall, it still focuses on functional systems such as underground transportation, municipal infrastructure, and public services, and constantly tends towards integrated utilization and comprehensive development. China's recent advocacy of the concept of territorial spatial planning has further expanded the concept of underground space resources, incorporating all-element resources such as underground energy, groundwater resources, underground mineral deposits, and underground historical relics, which is a significant innovation in UUS planning practice.

5.2 Paradigm shift for UUS planning

The introduction of multisource spatiotemporal data, data-driven techniques, and emerging planning concepts will have a profound impact on the theoretical and technical systems of UUS planning, thereby promoting the bidirectional evolution of planning research and planning practice. Based on aforementioned analysis, it can be foreseen that the paradigm shift of UUS planning will be reflected in four aspects, namely, technological methods, result forms, control modes, and control elements.

5.2.1 Transformation of technological method: from empiricism to evidence-based planning

Qualitative and quantitative methods should be combined for research at all levels of UUS planning. However, at present, expert experience and case analogy are still the dominant modes for compiling UUS planning, with only a small amount of quantitative research tools introduced in modules such as resource assessment and demand prediction. In fact, expert experience is the researcher's subjective cognition of the utilization law of underground space, and planning based on it is also the optimization of spatial resources. However, due to insufficient understanding of the refined utilization law of underground space, there is still a gap between the goal of maximizing underground space utilization efficiency and the current situation.

Nowadays, smart city development aims to provide support tools such as research, analysis, program design, evaluation, and tracking for planning and design through accurate data analysis, modeling, and prediction methods. In effects, data-driven UUS planning driven by multisource spatiotemporal data and conventional data is a data augmented design method following evidence-based research paradigm [94].

Conventional underground space planning research has a small sample size, making it difficult to conduct in-depth research on the universal laws of underground space utilization. With the emergence of multisource spatiotemporal big data, full-sample, high-precision, fine-grained, and low-cost underground space planning research is gradually becoming possible. Although multisource spatiotemporal data is not specifically designed for spatial planning, it provides powerful tools for accurate description of built environment features and spatial behavior patterns. Planners and researchers can construct more sophisticated analytical models based on this, and verify and correct research results through specific spatiotemporal data, thereby avoiding cognitive bias caused by a single subjective experience.

5.2.2 Transformation of result forms: from spatial creation to digital twins

The results of conventional UUS planning include special research reports, planning texts, planning instructions, and planning drawings. The series of results documents are intended to scientifically regulate underground space development activities within the planning scope and promote the physical creation of space entities. In the emerging data environment, the purpose of spatial creation remains unchanged, but the expression form of planning intention will be more diversified. Visualized and interactive digital space models will be included in the planning results along with text materials and electronic archives.

In other words, in data-driven UUS planning, spatiotemporal data is not only the production material of planning but also the main product of planning. Based on technologies such as GIS, building information model (BIM), city information model (CIM), etc., accurate mapping of physical underground space and digital underground space need to be constructed, forming digital twins of planning results. Once equipped with powerful data-driven models, the planning supervision could be well conducted to examine the spatial performance [18, 49, 60] and UUS development impacts on built environment [95, 96]. From spatial creation to digital twins, it is not only the diversified expression of UUS planning results but also the upgrading of the technical system and planning concept. The emergence of digital twins will promote the effective connection and feedback between planning and operation, and improve the accuracy and efficiency of planning decision-making.

5.2.3 Transformation of control mode: from blueprint planning to dynamic planning

For a long time, UUS planning has been more inclined towards blueprint-style planning, aiming to depict the ultimate ideal picture of underground space development through rational tools. The currently advocated data-driven planning technology also belongs to this type of comprehensive rational planning. However, practical experience in underground space planning in many cities has shown that due to the difficulty of accurately controlling the various factors affecting underground space development, there is often a significant gap between planning goals and actual construction.

As a type of public policy, underground space planning requires effective responses to various uncertainties and conflicts of interest among multiple stakeholders. Relying solely on static blueprint planning cannot effectively implement planning policies within the planning period. Therefore, the dynamic underground space planning and control mode that integrates the thinking of gradualism, public participation, and communication and collaboration is the trend. Compared with blueprint-style planning, dynamic underground space planning and control emphasizes the planning growth guided by the entire construction process, achieving a balance between ideal blueprints and real problems through the iterative mode of "planning preparation-evaluation-update."

The difficulty of managing dynamic underground space planning lies in the complexity of underground space management departments, which often suffer from the problem of "multi-headed management, no one in charge." Data flow is not smooth between departments, and information transmission efficiency is low. With the significantly improved utilization level of multi-source spatiotemporal data, it becomes possible to construct a planning and governance platform that integrates data collection, data integration, and planning supervision. Dynamic underground space planning and control will gradually replace the static blueprint planning mode.

5.2.4 Transformation of control elements: from single element to all elements

With the gradual establishment of the national spatial planning system, China's spatial planning has entered a new stage of unified management of the whole region and all elements, providing a new insight for UUS development in other countries. Conventional UUS planning focuses on the single element of space utilization but fails to consider other elements of underground space, which still deviates from the goals of territorial spatial planning.

In fact, underground resources, including underground energy, mineral resources, groundwater resources, and underground space resources, are abundant below the surface. The development of modern civilization's underground space is constantly advancing to greater depths, and the value of underground energy and non-space resources is increasingly apparent in this historical process. Underground energy development and underground ecosystem construction will become important support for future urban construction. Therefore, the control elements of underground space planning will gradually shift from spatial resources to the whole region and all elements, which will be in line with the goals of territorial spatial planning.

5.3 Conceptual data-driven framework for UUS planning orienting multiple development concepts

Based on the previous research and analysis, we propose a data-driven conceptual framework for underground space planning (as shown in Fig. 12) to address various emerging development ideas. Among these ideas, we prioritize sustainable, humanistic, resilience, intelligent, and low-carbon (SHRIL) as the fundamental development goals of this framework, and identify typical planning and governance tasks for each corresponding goal. The bottom-up driver of this framework is a digital twin platform designed for underground space planning. By deploying a wide range of underground space Internet of Things (IoT) sensors and establishing rules for extracting underground property information, this platform will collect and integrate various types of data to form an underground space engineering database, a fundamental spatiotemporal database, a thematic database, a real-time IoT sensing database, and an internet web-crawling database. These databases will be dynamically updated to form a multi-source data cloud platform for both desktop and mobile devices.

At the planning application level, "data mining, quantitative analysis, decision support, scenario analysis, scenario prediction, space translation, rule generation, and public participation" will be carried out based on the multi-source space–time data planning and management platform, to assist in the preparation of the master and detailed planning for UUS.

Data-driven UUS planning and governance should span the entire life cycle of UUS and actively promote the collaborative management of "government regulators, underground space investors, underground space planners, and urban residents." The platform will be embedded with management modules such as planning approval, implementation, and supervision, and regular performance evaluations of the planning implementation will be conducted to optimize and adjust the existing planning and control, forming a progressive and dynamic UUS planning.

In future research, there is a need to further enhance the digital integration depth and level of integration to meet the UUS planning needs under the SHIRL concept. In terms of data visualization, efforts will be made to integrate cutting-edge technologies such as BIM, GIS, and CIM with planning results to achieve a digital twin of UUS, focusing on building a planning management system with spatial basic data as the "form" and spatial performance data as the "essence". In terms of data storage, full use will be made of the decentralized, traceable, and tamper-proof characteristics of blockchain technology to strengthen the secure use of sensitive data such as civil defense and the privacy protection of individual behavior data, and to optimize the hierarchical classification management mechanism and platform data integration and storage standards for massive and multi-source data in many areas such as social economy, engineering construction, and spatial development.

6 Conclusions

To conclude, researchers have consistently focused on UUS planning in recent decades, and the planning practices have been widely conducted around the world. Through bibliometric analysis and comparative study concerning UUS planning, the research trend as well as the paradigm shift in this field has been identified. The main findings of this study are listed as follows.

(1) Based on general analysis regarding literature characteristics, the overall temporal development trend of UUS planning was observed. Moreover, the anal-

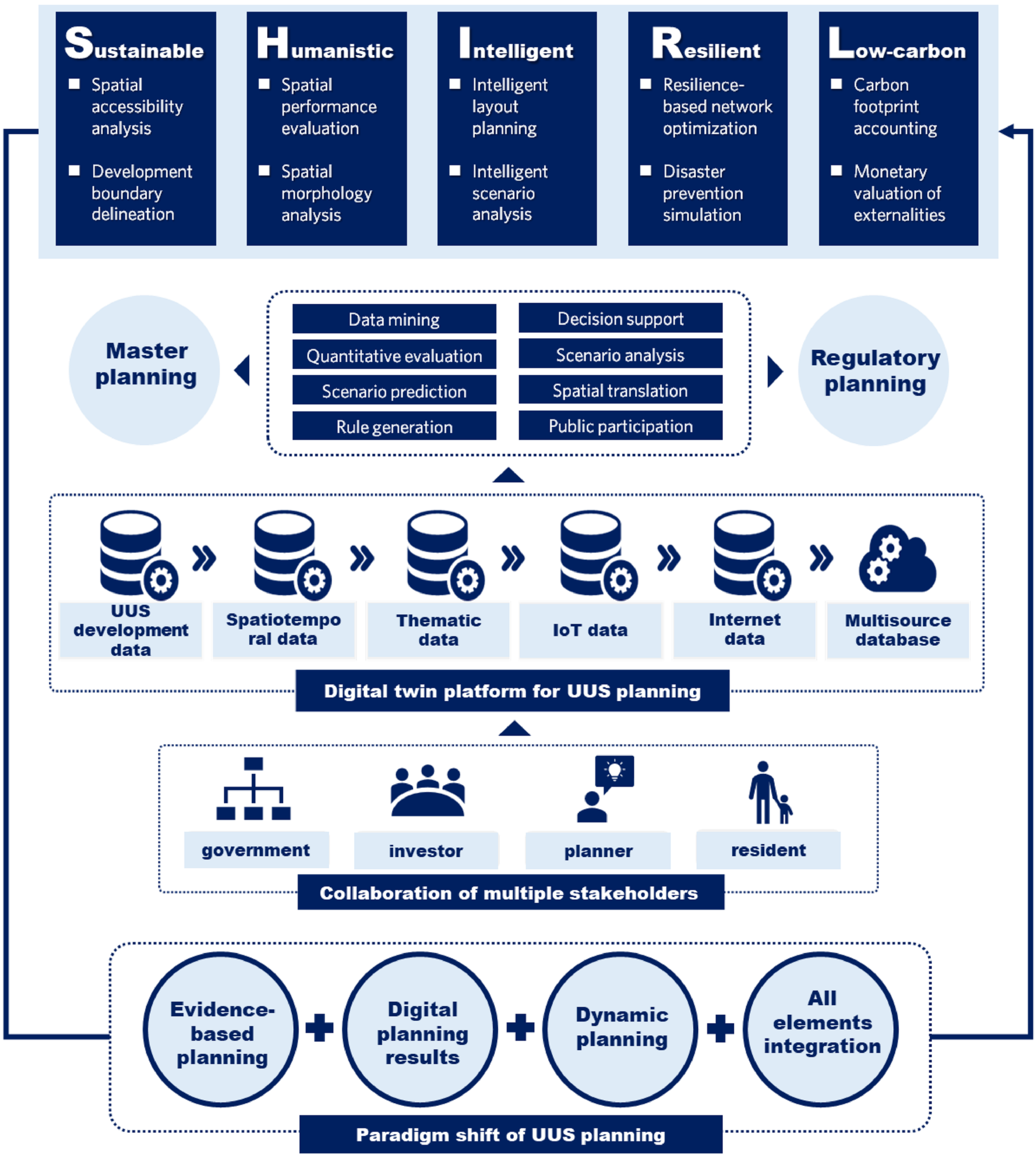

Fig. 12 Conceptual data-driven framework for UUS planning orienting SHIRL development concepts

ysis on most cited references initially identified the research hot spots, namely, the primary use of UUS, and UUS planning technology.

(2) Academic collaborative relationships have been identified through country and institution co-occurrence network analysis. The diversified development philosophy, planning systems, key planning scenarios, and data-driven technology pertaining to UUS planning have been extracted through both long-term and short-term keyword co-occurrence network analysis. The results indicate that the multidisiplinary data-driven method as well as the emerging spaitotemporal big data are empowering the UUS planning technology.

(3) The planning systems, planning management, and planning practices for UUS in Singapore, Japan, Helsinki, Canada, and China have been systematically reviewed, thereby identifying the worldwide UUS planning evolution. The results show that the multi-level UUS planning system including master planning, detailed planning, and special planning was an effective measure to guide UUS development.
(4) The paradigm shift for UUS planning have been clarified, involving technical method, result form, control mode, and control elements. Furthermore, the conceptual data-driven framework for UUS planning orienting SHIRL development concepts have been proposed to meet the requirement of next frontier development.

Authors' contributions
Conceptualization: Fang-Le Peng, Yun-Hao Dong. Methodology: Yun-Hao Dong, Wei-Xi Wang, Chen-Xiao Ma. Formal analysis and investigation: Fang-Le Peng. Writing—original draft preparation: Fang-Le Peng, Yun-Hao Dong. Writing—review and editing: Fang-Le Peng. Funding acquisition: Fang-Le Peng. Literature Search: Yun-Hao Dong, Wei-Xi Wang, Chen-Xiao Ma. Supervision: Fang-Le Peng. The author(s) read and approved the final manuscript.

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Availability of data and materials
The research data will be made available on reasonable request.

Declarations

Competing interests
Fang-Le Peng is an editorial board member for Smart Construction and Sustainable Cities and was not involved in the editorial review, or the decision to publish, this article. All authors declare that there are no other competing interests.

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