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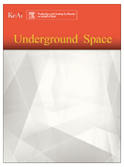

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Review Article

Review on data-informed planning for underground space

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Abstract

Urban underground space (UUS) development, guided by prudent planning, has emerged as a vital solution to the increasingly complex issues of urban built environments globally. Driven by the growing needs for human-centric urban design, low-carbon development, enhanced urban resilience, and alignment with sustainable development goals, UUS planning is rapidly shifting from experience-based approaches to evidence-based and data-driven methodologies. Yet, the broader landscape of this research field remains ambiguous, with the characteristics and future trajectories of such emerging planning technologies still to be clearly delineated. To this end, this systematic review delves into the burgeoning field of data-informed planning technologies for underground space (DIPTUS), examining how data-driven methods are revolutionizing the planning, design, and management of underground environments. Through a comprehensive bibliometric analysis of 134 articles published from 2014 to 2024, we identified key trends and mapped research themes within DIPTUS. Our narrative synthesis evaluated DIPTUS advancements across three dimensions: sensing and measurement, pattern and model, and planning and governance. The results indicate that DIPTUS exploits diverse data streams to quantitatively analyze UUS development. Utilizing advanced analytical tools such as spatial statistics, machine learning, and causal inference, these technologies uncover utilization patterns and planning optimization strategies. The review also underscores the increasing integration of planning and governance within DIPTUS, merging resource evaluation and demand forecasting, layout planning optimization, development benefits and spatial performance evaluation into a cohesive framework. Enhancements in 3D cadastral systems, innovative management models, and digital twin technologies further bolster this integrated approach. Despite significant strides, challenges in data integration, model complexity, and practical application persist. Lastly, we proposed a visionary framework to address these issues through interdisciplinary research and robust model development, aiming to fully harness DIPTUS's transformative potential for sustainable, resilient, and human-centered urban environments.

Keywords: Underground space; Spatial planning; Multisource big data; Bibliometric analysis

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1 Introduction

While the utilization of urban underground space (UUS) dates back centuries, the mid-19th century marked a turning point with the confluence of rapid urbanization and burgeoning urban populations. European cities, facing unprecedented pressures on infrastructure, transportation, and public health, turned to UUS development as a viable solution. Exemplified by the first metro line in operation in London and the prototype of a utility tunnel in Paris, this era witnessed a paradigm shift towards subterranean infrastructure development, primarily focused on alleviating congestion, optimizing resource transport, and housing essential utilities (Diamond & Kassel, 2018). This early focus on pragmatic solutions laid the groundwork for the multi-layered UUS planning concepts that would emerge in the following century. Visionary ideas such as Arturo Soria y Mata's Linear City (Collins, 1959; Rogers & Armstrong, 1969), Eugène Hénard's multi-level crossroads (Hénard, 1910; Rabinow, 1995; Wolf, 1974), Le

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Corbusier's Radiant City (Corbusier, 1933; Montavon et al., 2006), Megastructure promoted in Charte d'Athènes (Dunn et al., 2014), Hans Asplund's Two town (Hans, 1983), Peter Calthorpe's Transit-oriented development (TOD) (Calthorpe, 1995), the layered development principles proposed by Watanabe (1990) and Rönkä et al. (1998), all underscored the great potential of UUS development in shaping urban morphology and function.

Over the past few decades, along with evolving theories in UUS planning, there have been numerous significant developments in modern underground spaces. These include extensive underground pedestrian networks (Bélanger, 2007), complex developments in central business districts (Peng et al., 2020), advancements in municipal infrastructure (Lee et al., 2018), and the multifunctional use of subterranean resources and energy (X. Li et al., 2016). These practices have substantially contributed to local urban sustainability and efficiency. As the complexity and interactivity of various underground systems increase, spatial intervention policy tools become increasingly critical in regulating the comprehensive development of UUS. The UUS planning initiative in Helsinki represents a pivotal milestone, marking the first instance of master planning for underground space utilization and rock resource reservation (Vähäaho, 2014). A growing number of cities worldwide are exploring UUS planning practices, with Chinese cities being particularly prominent. Pioneering efforts in both academia and industry regarding UUS planning in China began three decades ago (Peng, 1990; Wang, 1988), leading to a well-developed planning system that includes master planning (Zhao et al., 2016) and regulatory detailed planning (Peng et al., 2020) implemented in hundreds of cities.

However, the escalating demands of modern urbanism characterized by sustainability, resilience, and citizen-centric design, coupled with increasing pressure on urban built environments, necessitate a paradigm shift in UUS planning. In other words, traditional planning techniques struggle to meet the demands of increasingly complex and diverse urban underground systems in aspects such as blueprint conceptualization, regulatory control, and scheme design. The recent surge in data-driven technologies presents an unparalleled opportunity to fulfill these aspirations (F. Peng et al., 2023). This shift in methodology for UUS planning is propelled by a dual imperative: evolving goals for the utilization of underground spaces and the transformative impact of data-informed planning techniques. Despite the expansion of digital planning toolkits, there still exists a critical gap in fully leveraging the potential of data-driven approaches to achieve integrated UUS planning (F. Peng et al., 2023).

Against this backdrop, data-informed planning technologies for underground space (DIPTUS) offers refinements across multiple stages, including planning research, planning formulation, and planning governance. During the planning research phase, DIPTUS uses high-resolution data to more effectively identify micro-level urban issues and accurately assess the UUS development patterns. These datasets enable more detailed analyses of UUS spatial structures, UUS vitality patterns, and functional zoning optimization. Moreover, the integration of multidimensional data enhances DIPTUS's ability to uncover complex interrelations in urban operations, such as analyzing residents' demands for underground public facilities through social media data or optimizing public service layouts using points of interest (POI) data. In the planning formulation phase, traditional planning designs often rely on the subjective judgment of planners, where experiential approaches to spatial development are challenging to implement and frequently result in imbalances between actual supply and demand for UUS. DIPTUS-based planning research services and methodologies, combined with artificial intelligence (AI)-driven algorithms, provide decision-making support for UUS demand forecasting, spatial layout, and other planning components. These tools enable dynamic simulations and predictive modeling, constructing urban development models that offer forward-looking insights for planning. In the planning governance phase, devices such as sensors (e.g., underground utility network monitors, geological radars) and mobile device positioning support a refined management model for UUS. Internet of Things (IoT) sensors, video surveillance, and flow meters enable real-time collection of operational data from UUS (e.g., metro passenger flows, underground parking utilization rates, and utility network flows), facilitating dynamic adjustments in response to anomalies. Multi-source big data also facilitates the dynamic evaluation and optimization of governance strategies through continuous monitoring and feedback. Furthermore, integrating information from social media, online surveys, and community feedback enhances public participation in governance, particularly in the context of organic urban renewal models for UUS management. Thus, DIPTUS uses big data capabilities to support real-time monitoring, rapid response, timely warnings, and feedback evaluation across multiple governance processes. Unlike traditional UUS planning, DIPTUS provides a dynamic, refined, and systematic framework for the theoretical research, development practices, and management operations of UUS. It enables more accurate assessments of existing challenges in UUS, offers precise support for planning formulation and decision-making, and contributes to elevating the level of refined urban governance.

To bridge the gap and further guide the research and technological development of DIPTUS, this study presented a systematic review of emerging DIPTUS, leveraging bibliometric analysis to underscore the field's rapid evolution and future prospects. The structure of the remaining parts is outlined as follows. Section 2 discusses the motivations for developing DIPTUS, analyzing contemporary planning concepts for UUS. Section 3 details the methods employed for the literature review, database construction, and bibliometric analysis. Section 4 reveals the insights derived from the bibliometric analysis and introduces an analytical framework for further research. Sections 5 to 7 systematically examine the state-of-the-art in DIPTUS, focusing on sensing and measurement, pattern and model, and planning and governance. Section 8 addresses technological challenges and outlines future pathways for DIPTUS development. Section 9 presents the primary conclusions of this study.

2 Motivation driving the development of DIPTUS

Past planning practices for UUS worldwide have been shaped by a range of critical motivations, encompassing the primary concepts and development goals tailored for the modern utilization of UUS. These diverse motivations have established the foundation for setting the ultimate targets in UUS planning, subsequently influencing the planning techniques employed to achieve the goals. To provide a coherent context for subsequent analysis, we begin by examining the prevailing motivations for developing DIPTUS. By tracing the trajectory of key literature and global planning practices, we identified four primary motivations that underpin the shift towards DIPTUS.

2.1 Human-centered planning and design for enhanced experience of UUS users

The doctrine of people-centered development has long been a predominant theme in contemporary city planning to improve the quality of community-level urban environments, as advocated by influential planners, sociologists, and critics (Calthorpe, 1995; Gehl, 2008; Jacobs, 1961; Whyte, 2003). In the realm of UUS planning, understanding the behavioral traits of users in underground spaces enhances the vitality of these environments, addressing the public activities requirements within underground spaces and fostering the creation of convenient environments. Early research analyzed the working environment of underground space users, assessing the psychological impacts of the environment on their attitudes and identifying significant factors influencing the perception of underground environments, laying the groundwork for what would become known as underground environmental psychology (Shu & Peng, 1990a, 1990b). In recent years, UUS has increasingly played a pivotal role as public activity centers in urban cores. The demands for quality in the operation of these spaces have escalated, prompting deeper explorations into the objective environmental elements such as air, light, sound, and thermal conditions (Tan et al., 2018; Wen et al., 2020; Y. Wu et al., 2022), as well as the psychological factors affecting underground space users (Kim & Lee, 2021; Sun et al., 2022; Yao et al., 2024). This ongoing trend underscores the need for planning approaches that prioritize user well-being and experience, driving the demand for more nuanced data and analytical tools.

2.2 Integrating low-carbon principles for underground infrastructures

In alignment with the global decarbonization movement prompted by the *Paris Agreement*, nations have committed to specific timelines for achieving peak carbon emissions and carbon neutrality. As critical facets of urban infrastructure, UUS is increasingly adopting low-carbon technologies across underground transportation, logistics, energy production, energy transmission, and energy storage systems (Qin et al., 2024). Drawing on principles of green architecture, the vision for low-carbon underground spaces encompasses creating systems that are highly efficient, consume minimal energy, and significantly reduce pollution and emissions. This vision necessitates an integrated approach to the application of ecological construction theories, energy-saving technologies, and sustainable materials throughout the entire lifecycle of a building project (L. Wang et al., 2024). Moreover, the evaluation of low-carbon benefits in underground spaces plays a pivotal role in decision-making processes, influencing strategies and policies at the municipal level (Qiao et al., 2019a). The integration of low-carbon considerations into UUS planning necessitates sophisticated data analysis and modeling techniques to assess the complex interplay between urban morphology, infrastructure design, and environmental impact (Wei et al., 2024).

Given that the construction phase is the primary source of carbon emissions throughout the lifecycle of underground spaces (Kammen & Sunter, 2016; Wang et al., 2024), rational planning of underground spaces is critical for reducing urban carbon emissions. In the planning and design phase, integrating multi-source data enables a comprehensive assessment of development needs, facilitating coordinated and rational spatial layouts for both aboveground and underground spaces. DIPTUS optimizes the supply–demand balance of spatial development, providing more precise planning services for underground infrastructure such as transportation networks and utility pipelines, thereby effectively reducing excess carbon emissions during development and construction (Qiao et al., 2019a; Wei et al., 2024; Fan et al., 2022; Wang et al., 2024). Furthermore, during the operational management phase, the deployment of sensor networks and digital twin technologies enables real-time monitoring of buildings' energy consumption and environmental parameters. This facilitates dynamic adjustments to operational strategies by reducing carbon emissions and enhancing the use of clean energy (Boje et al., 2020). Additionally, through environmental data analysis and sustainable design, existing buildings' ventilation, lighting, humidity, and material use can be optimized to reduce operational energy consumption and energy-related emissions (Jalaei & Jrade, 2015). Overall, based on multi-source data, the planning, layout, and operational management of urban underground spaces can effectively reduce urban carbon emissions, enhance carbon use efficiency, and contribute to achieving dual carbon goals.

2.3 Enhancing urban resilience through robust UUS development

Modern UUS plays a critical role within resilient cities, where early research focused on leveraging subterranean spaces to improve infrastructure robustness against natural disasters, thus enhancing urban resilience (Adger, 2000; Mileti & Noji, 1999). Disaster risk management has increasingly been incorporated into the planning stages of these subterranean developments (Admiraal, 2012). Prior to the planning of underground facilities, it is critical to conduct comprehensive risk assessments, which informs the adoption of innovative spatial layouts and construction techniques that optimize the development of UUS (Sterling & Nelson, 2012). In addition, the monetization of resilience assessments has facilitated the quantification of the substantial value that urban underground municipal infrastructure contributes to urban resilience in disaster-prone contexts (Liu et al., 2024). By establishing a resilience assessment framework for UUS, researchers and urban planners can explore the symbiotic relationship between subterranean resilience and broader urban development at a city scale (Liu et al., 2024). This focus on resilience necessitates planning approaches that can model various disaster scenarios, assess the vulnerability of underground infrastructure, and optimize designs to enhance both the resilience of UUS themselves and their contribution to overall urban resilience (He et al., 2024; Kallianiotis et al., 2022; Lei et al., 2023).

2.4 Aligning UUS development with the sustainable development goals

In 2015, the United Nations General Assembly launched the 2030 Agenda for Sustainable Development, outlining 17 interconnected sustainable development goals (SDGs) with 169 specific targets designed to create a blueprint for a more sustainable future for all (United Nations, 2015). Studies have identified that 11 of the 17 goals can be linked to the utilization of UUS, highlighting their significant potential in advancing sustainable development (Peng et al., 2021). UUS embodies a dual relationship with sustainable development. On one hand, the development of UUS contributes significantly to urban sustainability by optimizing land use, reducing surface congestion, increasing energy efficiency, and enhancing environmental quality (Attarian & Safar Ali Najar, 2019; Bobylev, 2009; Kishii, 2016). On the other hand, the sustainable utilization of these underground infrastructures throughout their lifecycle remains a critical issue (Sterling et al., 2012; Vähäaho, 2014; Zargarian et al., 2016). This dual aspect is further supported by various quantitative models that have been developed to ensure that motivations for UUS development are practically integrated into planning and decision-making processes (Qiao et al., 2019b, 2017, 2019c, 2022a, 2022b). These models aid in assessing the impact of UUS on achieving SDGs, particularly those related to sustainable cities and communities, climate action, and responsible consumption and production.

3 Data and methods

As depicted in Fig. 1, we developed a set of tailored screening criteria for literature on DIPTUS, adhering to the basic principles outlined in the preferred reporting items for systematic reviews and meta-analysis (PRISMA) (Moher et al., 2010). Two researchers executed the literature selection to comprehensively map the state-of-the-art DIPTUS research. Initially, we devised a strategy for selecting relevant literature from the Web of Science (WoS) Core Collection. To capture the all-round scope pertinent to DIPTUS, our search focused on both the ontology of UUS and the associated research objectives. Consequently, we combined keywords related to holistic UUS concepts (e.g., underground space, subterranean space, subsurface space) with those pertaining to specific underground facilities (e.g., metro, subway, utility tunnel, underpass) and research objectives (e.g., planning, management, governance, decision). This approach aimed to cover the primary facets of DIPTUS. The search was restricted to the period from 2014 to 2024, and only articles published in English were considered.

Following the initial keyword search, we retrieved 10 199 records. After the removal of duplicates and mislabeled records, 5976 records remained. These articles were further assessed based on their titles, abstracts, and keywords to determine their eligibility. The records selected needed to meet two screening criteria simultaneously. Firstly, each record had to be closely related to at least one aspect of the motivation driving the development of DIPTUS. Secondly, the research output needed to be either a practical tool demonstrated by planning practice or provide essential insights for the planning analytics of UUS. Subsequent to the topic screening, the same stringent criteria were applied to full-text reviews to further refine and narrow the selection to a more accurate and targeted set of literature. Ultimately, a total of 134 articles were included for in-depth analysis in the subsequent stages of our study.

To thoroughly understand the research trends and technological characteristics of DIPTUS, we employed Bibliometrix (Aria & Cuccurullo, 2017), an R-based tool specifically designed for science mapping analysis, to perform a bibliometric analysis. Unlike previous literature reviews on UUS planning that primarily analyzed collaboration relationships across institutes and regions (F. Peng et al., 2023), our study concentrates on the technological advancements and research topics within this emerging field. The bibliometric analysis includes both descriptive and thematic mapping to delineate the evolutionary trends

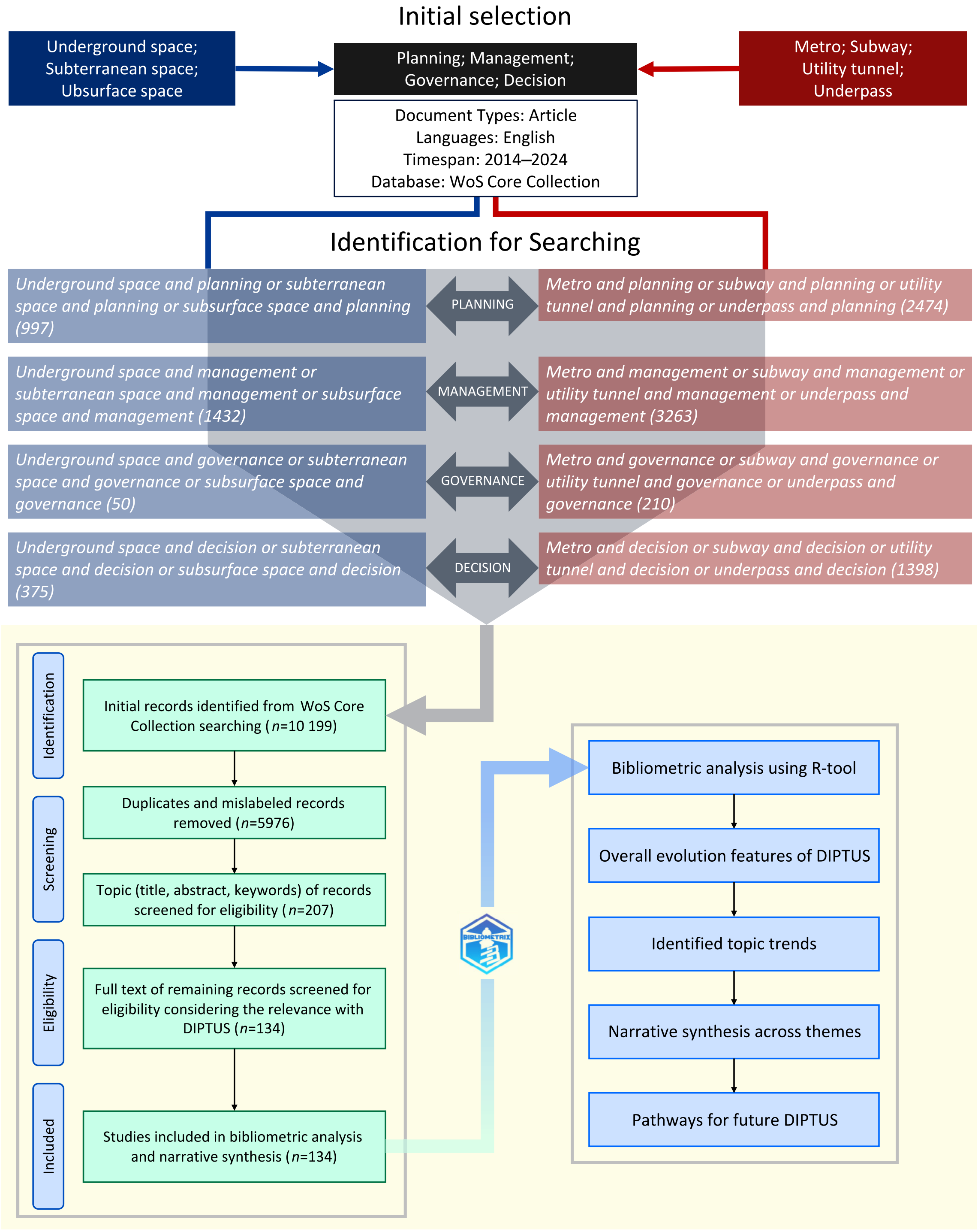

Fig. 1. PRISMA flow diagram and literature review process (*n* denotes the number of literatures).

and identify the critical themes within DIPTUS research. Regarding the wordcloud visualization, word occurrence was measured by word frequency, with the number of words displayed set at 100 to capture the most relevant terms. In our thematic map analysis, the number of units was also set at 100, and the minimum cluster frequency was set at 3, which was adjusted to suit the scale of literature specific to our study. Other parameters in Bibliometrix were set to default values, ensuring a balanced analytical approach while focusing on meaningful data representation.

Following the mapping, a narrative synthesis was conducted for each identified theme to encapsulate the current state of DIPTUS development. Lastly, we proposed a visionary framework intended to chart the future course for DIPTUS development, aiming to guide ongoing research and application in this fast-growing field.

4 Bibliometric results and derived insights

4.1 Descriptive analysis

Among the 134 selected literatures, 390 scholars were involved, showcasing an international co-authorship rate of 21.64%. In the most recent five years, from 2020 to 2024, publication activity has notably increased, with 93 out of 134 papers published, representing 69.4% of the total.

The majority of scholars engaged in DIPTUS research hail from China, accounting for 74.4% (290 out of 390), followed by Singapore at 5.1% (20 out of 390), Australia at 3.8% (15 out of 390), Russia at 2.6% (10 out of 390), and both the United Kingdom and the United States at 2.1% each (8 out of 390). International and regional collaborations were observed, particularly between China and Singapore with 8 records, and China and Australia with 7 records. In terms of research institutions, Tongji University was the most prolific, contributing to 50.0% of the literature (67 out of 134), followed by Nanyang Technological University at 11.9% (16 out of 134), Army Engineering University of PLA and China University of Mining and Technology both at 9.0% (12 out of 134 each), and Shenzhen University at 7.5% (10 out of 134). Regarding publication sources, the conventional journal *Tunnelling and Underground Space Technology* hosted nearly half of the papers at 49.3% (66 out of 134), while the emerging journal *Underground Space* ranked second with 9.0% (12 out of 134) of the publications.

4.2 Keywords and thematic mapping analysis

4.2.1 Wordcloud and trend topics

As depicted in Fig. 2, we visualized the wordcloud using both keywords plus and the author's keywords. To ensure comprehensiveness in our analysis, we incorporated a necessary synonym list to integrate keywords of similar meanings. WoS produces a generalized set of keywords derived from both the author's keywords and the full text of the research. Prominently, keywords such as cities, design, resources, and sustainable development are prevalent, indicating that the planning for UUS as multifunctional resources has become a critical contributor to urban sustainability. Beyond planning concepts and planning objects, other crucial keywords include transport, model, management, performance, and system, reflecting an overarching trend towards technological advancement within DIPTUS. From a more detailed technological perspective, the visualization of initial keywords provided by the authors, such as sustainability, planning, and monetary valuation, highlights important research trends. Additionally, keywords such as spatial vitality, spatial analysis, spatial performance, GIS, urban resilience, digital twin, underground logistics system, virtual reality, emergency evacuation, safety, machine learning, and suitability evaluation underscore a variety of research topics. These topics cover both representative planning scenarios and emerging data-informed techniques, indicating a diversified spectrum of research within DIPTUS.

We further analyzed the evolution of trend topics dynamically based on the author's keywords. As illustrated in Fig. 3, the light blue line represents the timespan of each topic (keyword), while the corresponding red circle indicates the accumulated number of records for each topic, with a larger radius denoting more records. It was observed that from 2016 to 2018, sustainability remained the most prominent topic. However, since 2020, the focus has shifted towards metro-led underground space development. Additionally, cutting-edge spatial analytics and modeling techniques, such as virtual reality, digital twin, and machine learning, have emerged as hot topics in the past two years. Topics related to urban resilience are also gaining more popularity recently, surpassing the interest previously shown in sustainability. Furthermore, traditional planning tasks like suitability evaluation continue to receive attention, now supported by more advanced geological modeling techniques to provide robust support for UUS planning formulation.

4.2.2 Thematic mapping

We extended our analysis beyond individual keyword examination by implementing thematic mapping analysis based on co-occurrence network clusters to discern major research themes with distinct characteristics. As illustrated in Fig. 4, the size of each bubble on the graph represents the number of keyword occurrences within an identified cluster, determined by Callon's centrality and density rank within the network (Callon et al., 1991). The X-axis and Y-axis represent the relevance degree (centrality) and development degree (density), respectively, indicating the significance and growth potential of a theme.

The graph is divided into four quadrants, each corresponding to different types of identified themes (Cobo et al., 2015). In the upper left quadrant, niche themes are located, which are highly specialized and peripheral. These themes include geographical detector, dynamic, safety, suitability evaluation, Bayesian network, etc., most of which do not directly support DIPTUS.

In the upper right quadrant, motor themes represent well-developed and critical research fields. These include essential planning elements such as sustainability, integrated planning, and layout planning. Additionally, decision support techniques such as spatial analysis and monetary valuation, along with multisource data and 3D cadastre, support the UUS planning framework.

The lower left quadrant contains emerging or declining themes, primarily representing new areas of focus, including spatial performance, virtual reality, underground resource, and master planning. The first three themes

Fig. 2. Wordcloud generated by keywords plus (top) and author's keywords (bottom).

introduce new planning analytics and concepts. Despite being a traditional component of UUS planning, master planning has evolved significantly in the last decade, reflecting changes in DIPTUS-related approaches.

Finally, the lower right quadrant features basic themes. These are important but not yet fully developed themes, encompassing modern underground system modeling methods like 3D geological modeling, building information modelling (BIM), and digital twin. This quadrant also includes planning scenarios with high development value, which refer to the highly valuable underground space developments near metro stations.

It is important to note that while 3D geological modeling is a mature field within geological sciences, its application in urban underground space planning has not been proportionately developed. Although recent studies leverage efficient spatial data models to accurately represent complex subsurface geological structures, utilizing machine learning and artificial intelligence to enhance geological feature extraction and model precision, integration of these advanced models with optimization algorithms underscores their critical role in engineering applications. However, their relevance to the technical methodologies employed in urban underground space planning remains limited. Previous research integrating geographic information system (GIS) and BIM for 3D geological modeling has facilitated the assessment of underground space conditions and development suitability. Yet, there remains a crucial need for further advancements in 3D geological modeling to include real-time dynamic 3D positioning and rapid spatial data acquisition technologies. Such advancements are essential to meet the modernization needs of urban governance systems. These developments not only facilitate the visualization of geological information but also promote seamless integration with both urban aboveground and underground spatial planning, thereby enhancing the scientific rigor and efficiency of planning processes. This phenomenon is a critical observation, underscoring the need for more focused development and application of 3D geological modeling within the field of DIPTUS.

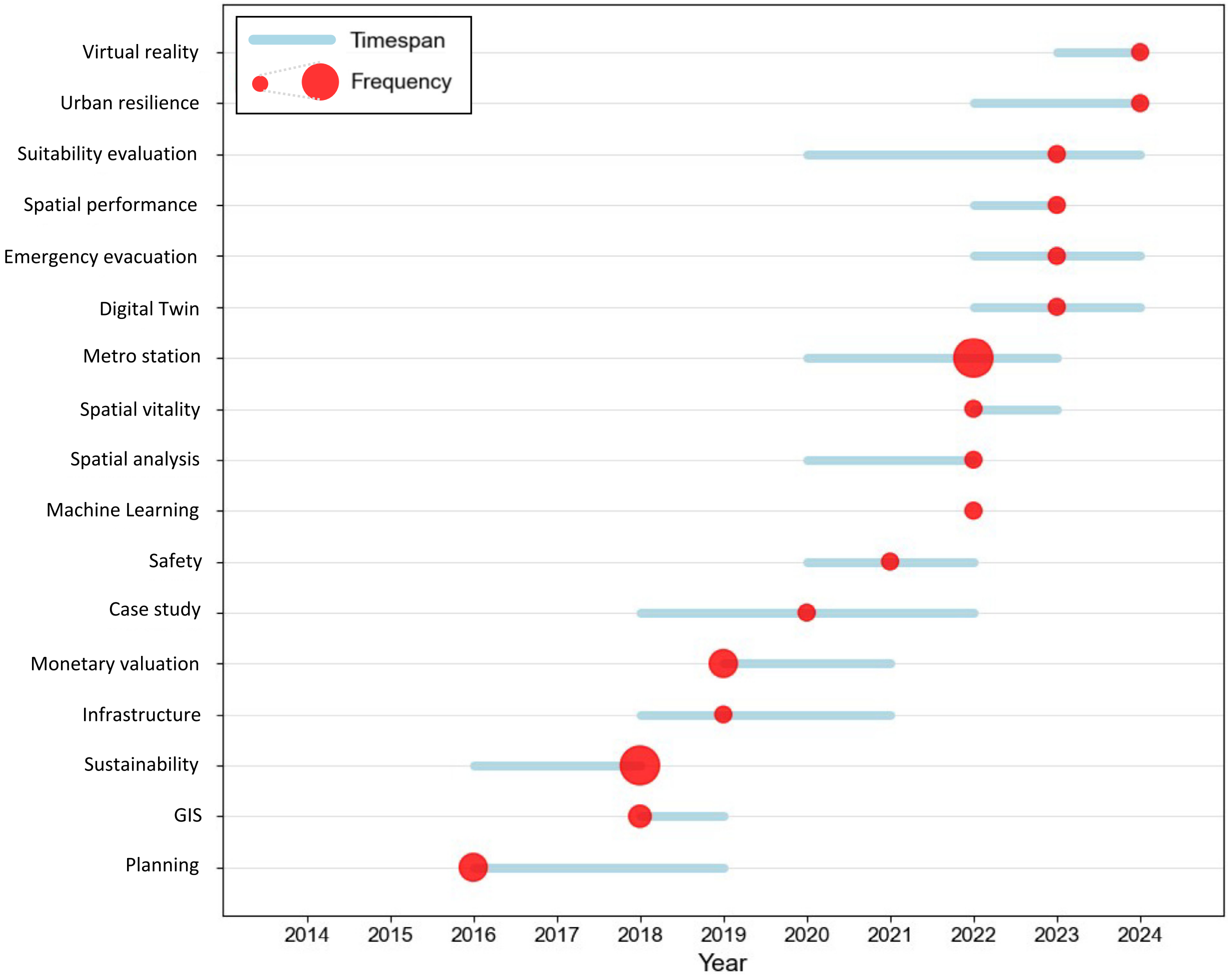

Fig. 3. Trend topics over time.

4.3 Derived insights and integrated themes for narrative synthesis

Bibliometric analysis reveals that the DIPTUS research is characterized by continuously evolving themes, engaging numerous digital technologies, and planning application scenarios. In terms of primary technological tools for planning formulation, the methodological core of DIPTUS includes resource evaluation models, demand forecasting models, layout allocation models, benefit evaluation models, performance evaluation models, and management and operation models for UUS. The complex connections between these areas and various research hotspots can be reclassified into three main categories: sensing & measurement, pattern & model, and planning & governance (see Fig. 5). Although these categories overlap to some extent, they approximately align with the technical logic of multi-source data collection, processing, analysis, modeling, and application. This classification also corresponds with the results of thematic mapping analysis. The following sections will detail the research progress in these three categories, providing a more nuanced technical analysis of DIPTUS's developmental characteristics.

5 Sensing and measurement: how to characterize the underground space?

5.1 Role of multisource data in DIPTUS

Data is the core of DIPTUS, however, the data pertaining to UUS planning has been continuously evolving. For UUS, it is inherently challenging to comprehensively collect data through conventional field surveys due to the extreme complexity of geological conditions and underground structures. Moreover, the vast scale, and long timespan of urban underground data often prevent the establishment of official, publicly accessible data-sharing platforms, particularly in older urban districts. As a result, essential data reflecting the scale, function, and development depth in these areas are often elusive and cannot be

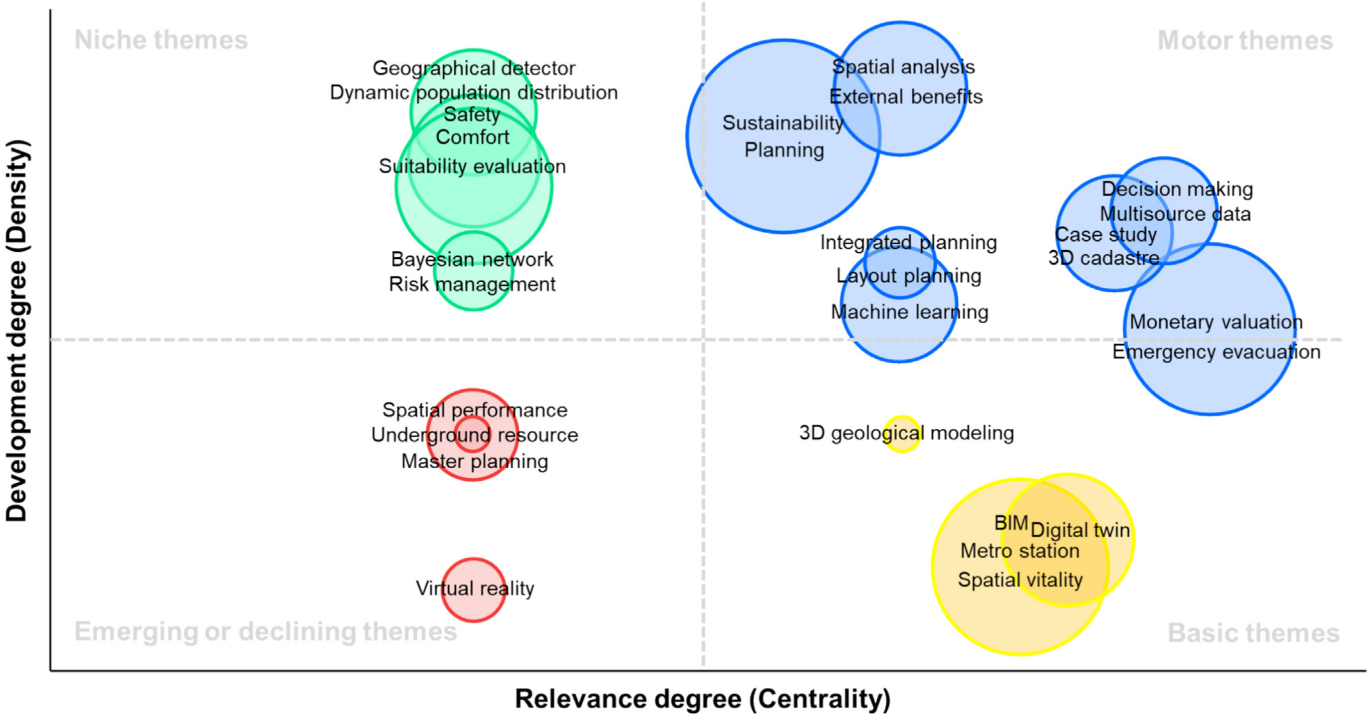

Fig. 4. Thematic map based on the network approach.

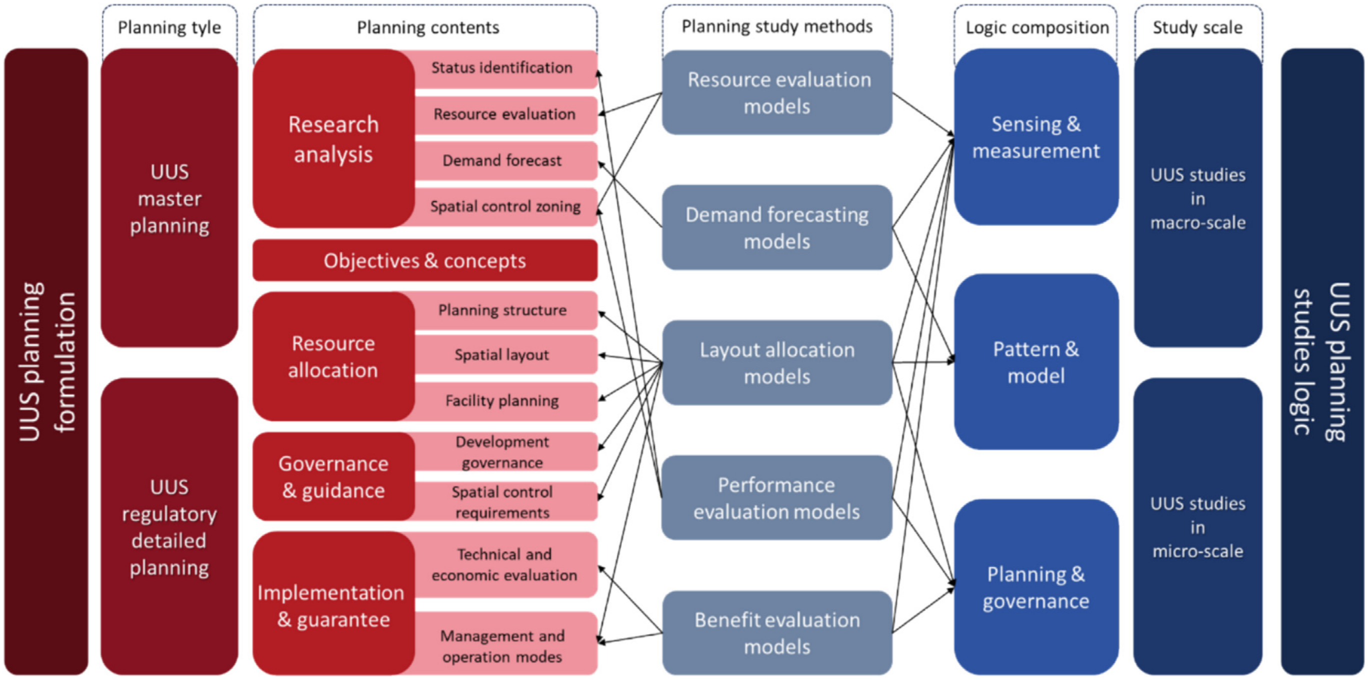

Fig. 5. Comparison of SP1 Electric interaction.

directly measured. In contrast, emerging multisource data underpinned by data-driven technologies offer comprehensive, high-precision, timely, large-scale, granular, and cost-effective data features, facilitating UUS planning significantly (F. Peng et al., 2023). Conventionally, the amount of data available from urban planning documents is limited, hindering an in-depth understanding of general principles governing the use of UUS. However, the use of multisource spatiotemporal data could overcome the limitations of traditional planning data by capturing spatiotemporal dynamics that would otherwise be missed. Such data acts as a complement and extension to existing planning data, thus optimizing and deepening the research scale of traditional underground space planning. By translating the urban underground development status on a large scale, either directly or indirectly, researchers can better capture pertinent underground space information, thereby advancing the digital transformation of urban underground space planning and design from a fresh perspective (Peng et al., 2024).

Characterized by high density, bias, and precision, these datasets necessitate careful integration with traditional planning data for effective utilization. Based upon the state-of-the-art study on DIPTUS, Tables 1–4 summarize the key attributes of multisource data currently relevant to UUS planning, including data types, data source, coverage, retrieval methods, temporal and spatial features, relevance to UUS, and UUS formulation applications. To be concise, the UUS formulation applications were coded into 6 digits in following tables (1 denotes Study Analysis, 2 denotes Objectives and Concepts, 3 denotes Resource Evaluation, 4 denotes Demand Forecasting, 5 denotes Spatial Layout, and 6 denotes Implementation and Guarantee).

Urban environments data is primarily sourced from GIS platforms, remote sensing, and mapping services, focusing on the natural and built environment and morphological characteristics. These datasets have longer update cycles but provide a direct or indirect depiction of regional statuses and natural features. Urban socioeconomic data, similar in update frequency to geographical data, offers insights into the population, economy, and land values, significantly influencing UUS development. Urban system operation data, derived from location service providers and urban operational platforms, captures high-frequency, comprehensive, and fine-grained operational information of city facilities. Lastly, urban spatial activities data tracks the real-time trajectories and spatiotemporal behaviors of individuals within the city. Sourced from location service providers, telecom operators, and internet companies, such data offers abundant details and precision but poses accessibility challenges due to privacy concerns.

The integration of multi-source data provides a rich informational foundation for UUS planning, yet its heterogeneity poses significant challenges. Multi-source heterogeneous data encompass datasets from diverse origins, formats, resolutions, and semantics, such as vector data from GIS, time-series remote sensing imagery, socioeconomic statistics, and real-time sensor data. These datasets exhibit differences in spatiotemporal scales, data structures, and semantic definitions, leading to issues such as data inconsistency, missing values, and noise. For instance, the high-frequency updates of urban spatial activity data contrast with the low-frequency updates of geological data, necessitating spatiotemporal alignment during integration. Similarly, the classification standards of socioeconomic

Table 1
Multisource data supporting DIPTUS (for urban environments).

Data categories	Data subcategories	Data sources	Data coverage	Retrieval methods	Temporal features	Spatial features	Relevance to UUS	UUS formulation applications
Urban environments data	Traditional urban planning data	Official planning results, including textual and image information, etc.	Low	Medium	Low frequency	Medium-grained	Direct	1,2,3,4,5,6
	Satellite remote sensing and image data	Unofficial geographic information service platforms, remote sensing data centers, map data platforms	Medium	Easy	Low frequency	Coarse-grained	Indirect	1,3
	DMSP/OLS Nighttime Lighting Data		Medium	Easy	Medium frequency	Coarse-grained	Indirect	1
	OSM Data		Medium	Easy	Low frequency	Medium-grained	Indirect	1,3,4,5,6
	Hydrographic and geological engineering data		Low	Medium	Low frequency	Coarse-grained	Direct	2,3
	Open-source map data		Medium	Easy	Low frequency	Medium-grained	Direct	1
	Urban climate data		Low	Easy	Low frequency	Coarse-grained	Indirect	1,5,6

Table 2
Multisource data supporting DIPTUS (for socioeconomic status).

Data categories	Data subcategories	Data sources	Data coverage	Retrieval methods	Temporal features	Spatial features	Relevance to UUS	UUS formulation applications
Urban socioeconomic status data	Population statistics and distribution data	Government statistical yearbook, survey research, documentation, other opensource data information platforms	Medium	Easy	Low frequency	Coarse-grained	Indirect	1,3,4,5
	Urban GDP economic data		Medium	Easy	Low frequency	Coarse-grained	Indirect	1,3,5
	Urban Housing price data	Real Estate Management Service Website	Medium	Medium	Medium frequency	Medium-grained	Indirect	1,5,6
	Urban benchmark land value	Official city policies and documents	Low	Easy	Low frequency	Coarse-grained	Indirect	1,5,6
	Urban e-commerce data	Shopping and consumer website operators, e-commerce official web and APP platforms	Medium	Medium	Medium frequency	Medium-grained	Indirect	1,5,6

Table 3
Multisource data supporting DIPTUS (for urban system operation).

Data categories	Data subcategories	Data sources	Data coverage	Retrieval methods	Temporal features	Spatial features	Relevance to UUS	UUS formulation applications
Urban system operation data	POI/POA data	Location service providers	High	Medium	Medium frequency	Fine-grained	Direct	1,5,6
	Automatic fare collection system data (AFC)	Public rail transit corporation	High	Hard	High frequency	Fine-grained	Direct	1,2,3,4,5,6
	City street view images	Map information platform/field photography	High	Medium	Medium frequency	Fine-grained	Indirect	1,5
	Intelligent sensor and facilities data	Urban platform data management center	High	Hard	High frequency	Fine-grained	Direct	1,2,3,4,5,6

Table 4
Multisource data supporting DIPTUS (for spatial activities).

Data categories	Data subcategories	Data sources	Data coverage	Retrieval methods	Temporal features	Spatial features	Relevance to UUS	UUS formulation applications
Urban spatial activities data	Location based services (LBS)	telecommunications operator	High	Hard	High frequency	Coarse-grained	Indirect	1,2,3,4,5,6
	GPS travel data	Taxi, bike-sharing operating companies, etc.	Medium	Hard	High frequency	Fine-grained	Indirect	1,2,3,4,5,6
	APP location service data/ Mobile movement spatiotemporal path data	APP Internet Inc.	High	Hard	High frequency	Fine-grained	Indirect	1,2,3,4,5,6

data may not align with the land-use classifications used by planning authorities, resulting in semantic heterogeneity. To address these challenges, data cleaning techniques, such as format standardization, interpolation for missing values, and wavelet denoising, can be employed alongside data fusion algorithms, including Bayesian inference and deep learning-based fusion, to enhance data quality and consistency. These techniques not only facilitate the effective integration of multi-source data but also lay the foundation for the digital and intelligent transformation of underground space planning (Cui & Guo, 2007; Meng et al., 2020).

Overall, integrating dynamic sensing devices for UUS with smart urban platforms enhances data collection and safety monitoring of underground infrastructure through sensor networks and big data technologies (Du et al., 2023; Zhao et al., 2023). A more proactive sensing system integrated with existing multisource spatiotemporal data is likely to optimize the operational management for underground facilities, specifically municipal infrastructure (Hu et al., 2023). Furthermore, it contributes to the development of a more digitized and intelligent UUS planning and management platform (Wang et al., 2022; Yu & Guo, 2022), thus supporting the data-informed decisions.

5.2 Models for quantitatively characterizing UUS

The application of multisource data significantly enhances the quantification of UUS development characteristics across key areas. Firstly, the data-informed models enable precise measurement of the factors influencing UUS utilization. Research in this domain typically focuses on the macro-level dynamics within cities, analyzing how urban socio-economic development indicators correlate with the extent and nature of UUS development. The involving factors include population distribution (Chen et al., 2022b), economic growth (H. Li et al., 2016; Qiao et al., 2017), the built environment (Cui et al., 2013; Dong et al., 2023a; X. Li et al., 2016; Peng et al., 2019; Qi & Li, 2018; Yuan et al., 2020), and natural environmental conditions (Peng & Peng, 2018a; Zargarian et al., 2016). These studies further encompass investigations into the spatiotemporal characteristics and influence of various underground facilities such as public services and parking (X. Dong et al., 2021; Dong et al., 2023b, 2023c; Fang et al., 2022).

Secondly, the spatial quality of UUS could be effectively quantified using emerging big data. These studies focus on evaluating the spatial quality and characteristics of existing underground spaces, supporting the renewal and optimization of UUS projects. By integrating multisource data—including urban points of interest (POIs), population density, real-time mobility distribution, location-based service data, and smart card data—research can pinpoint the spatial performance characteristics of UUS within metro-led areas (Ma et al., 2023a; Xu & Chen, 2021), assess the development levels of existing underground facilities (Bobylev, 2016b; Qiao et al., 2024), delineate the spatial vitality features of metro-led underground space (Dong et al., 2021b), and measure the quality of interior design within underground commercial areas (Sun et al., 2020; Sun & Leng, 2021).

Lastly, the evaluation of underground resources and risk assessment has long been a fundamental aspect of data-informed characterization for UUS development. Research in this area primarily integrates factors such as engineering geology, hydrogeology, soil environment, and topography to conduct a three-dimensional comprehensive analysis of the development capacity, quality, and suitability of shallow, intermediate, and deep underground spaces, as well as the associated resource and environmental risks (Dou et al., 2021, 2022; Hishammuddin et al., 2024; Hou et al., 2016; Ni et al., 2024; Peng & Peng, 2018a, 2018b; Price et al., 2018; Xi et al., 2022; Xu et al., 2023; Yan et al., 2023; Zhang et al., 2020; Zhou et al., 2019). This analysis assesses the potential and rationality of future underground space development, constituting a conventional and crucial component of UUS planning.

6 From pattern to model: how to simulate the underground space development?

6.1 Uncovering the spatial pattern of UUS utilization

For current master planning and detailed planning techniques for UUS, the critical process of evaluation indicator selection and parameter setting typically adopts empirical qualitative or semi-quantitative methods (Bobylev, 2016a; Peng et al., 2020; Zhao et al., 2016). Moreover, these conventional static blueprint planning approaches overlook the dynamic development of socio-economic factors and micro-level urban activities, leading to a lack of understanding of the refined utilization patterns of UUS, which makes it challenging to achieve the goal of maximizing spatial efficiency in UUS development (F. Peng et al., 2023). In response, both academia and industry are seizing the opportunity provided by emerging multisource data to explore refined spatial planning methods based on pattern mining.

In recent years, data science methods have been progressively applied to the study of UUS planning, effectively advancing the identification of patterns in UUS. Many scholars utilized techniques such as spatial configuration computation (Huang et al., 2024; W. Li et al., 2023; van der Hoeven & van Nes, 2014), spatial statistics (Dong et al., 2021a, 2023b), Bayesian methods (Wu et al., 2018; Xu et al., 2023), game theory (Kurakova & Khomyak, 2016), machine learning (Chimunhu et al., 2022; Luan et al., 2023; Zhou et al., 2022), big data analysis (Dong et al., 2023c; Du et al., 2023; Ma & Peng, 2023), and causal inference (W. Wang et al., 2024) to explore quantitative utilization patterns of UUS. These methods were applied in multiple domains including resource evaluation, demand forecasting, resources allocation, benefit evaluation, performance measurement, and management of UUS.

6.2 Pattern-based modelling for UUS optimization

Despite the presence of various data-driven tools that explore the development patterns of existing UUS, these deducted patterns are approximations of real spatial laws. They struggle to effectively link with real-world planning systems and only provide broad, rudimentary decision-making suggestions. Additionally, the extraction of spatial patterns from existing UUS utilization reflects specific spatiotemporal contexts, which cannot be equated with a unified, high-quality development pattern for underground spaces. Currently, pattern-based optimization models for UUS still have limited practical impact on real planning and decision-making, and research in this area remains in its nascent stages.

However, some conducive scholarly explorations have been made. For instance, using spatiotemporal big data and spatial statistics to explore comprehensive patterns of metro-led underground space in China (Dong et al., 2023c), thereby providing localized theoretical support for planning and layout objective functions (Dong et al., 2022). Furthermore, bivariate spatial autocorrelation analysis was utilized to identify the mismatch regions between UUS development density and intensity that need to be redeveloped (Dong et al., 2023b). Additionally, some machine learning models and causal inference models can aid in making decisions about the renewal functions of underground spaces and development management patterns (Qiao et al., 2024; W. Wang et al., 2024). However, it is crucial to note that the decision support applications of these patterns depend on the precise selection of input data (i.e., selection of underground space development cases) and struggle to break free from the confines of existing pattern choices, rendering them incapable of simulating decision-making scenarios for entirely new plans.

In recent years, research on the application of generative AI in urban planning and construction has gained increasing attention. Using large language models such as DeepSeek and ChatGPT, generative AI technologies employ methods including diffusion models, generative adversarial networks (GANs), variational autoencoders (VAEs), and transformers to improve AI-generated content (AIGC)-enhanced frameworks for architecture and urban planning design. These AI technologies have significantly advanced planning evaluation, plan formulation, scheme refinement, and the development of urban visualization management platforms (Gan et al., 2023; Jiang et al., 2024; Li et al., 2025). In the realm of underground space planning, generative AI technologies offer substantial potential for optimizing spatial utilization and enhancing user experience. For example, using Beijing Metro Line 8 as a case study, a VAE framework was utilized to model the implicit distribution of thermal perception data collected from over 5000 users within metro stations. This approach facilitated the investigation of gender-specific differences in environmental perception and the influence of dynamic environmental variables. Additionally, approximately 2500 visual images of underground spaces were used, with comfort levels measured, to develop a parametric generative network (StepGN) for the 3D generative design of visual comfort. This research was applied to optimize the interior scenes of Wujiaochang Metro Station in Shanghai. Moreover, the latest large language models have also facilitated fast knowledge graph modeling for underground public spaces to accurately capture public perceptions (Pan et al., 2025). Although AI models have significantly advanced decision-making support and evaluation in underground space planning, it is crucial to note that the decision support applications of these patterns depend on the precise selection of input data (i.e., selection of underground space development cases) and struggle to break free from the confines of existing pattern choices, rendering them incapable of simulating decision-making scenarios for entirely new plans.

With the aid of digital techniques such as BIM and GIS, the pattern-based simulation models for underground space could be further refined, though these models are commonly applied to daily operation and management rather than planning. It is reported that BIM can be utilized to model the architectural design and layouts of underground commercial streets. By employing PyroSim and Pathfinder softwares to model various fire scenarios and the most unfavorable fire sources, more effective evacuation plans and management strategies can be developed (Li et al., 2024b). Virtual reality technology is employed to construct three-dimensional virtual scenarios to explore the impact of underground environments on users (Chan et al., 2024; Li et al., 2021). Integration of GPS data with GIS and BIM platforms facilitates the exploration of flood risk assessments and predictive mitigation measures for metro systems (Lyu et al., 2019). Additionally, by quantifying dynamic urban population distribution and evacuation demands, a multi-step greedy algorithm and a social force model (SFM) with specific parameters were developed. These enable simulation and analysis on an integrated digital platform for urban modeling (L. Peng et al., 2023). Multi-agent systems and scenario planning are applied to formulate decisions and safety risk analyses for UUS development (Chen et al., 2022a; Wang et al., 2021; Wei et al., 2024; Zhang et al., 2023). Furthermore, employing a network-based urban logical structure and analysis method, three-dimensional urban environments and urban network logical models are established using 3D GIS and BIM technologies, with simulations conducted for urban emergency response processes (Cui et al., 2019).

7 Planning and governance: how to plan and manage the underground space?

7.1 Evolving planning approaches in DIPTUS

In response to the development needs of DIPTUS, a range of data-informed approaches characterized by quantitative modeling, and designed to enhance planning practice, are rapidly advancing and being integrated into various levels of UUS planning. Sensing and measurement, along with patterns and models as technological means, collectively support the ultimate goal of DIPTUS: planning and governance, thus creating an integration across three themes (see Fig. 6). For the narrative synthesis in following subsections, these evolving approaches are recategorized into three groups to align with the key planning processes, namely resource evaluation and demand forecasting, layout planning optimization, and development benefits and spatial performance evaluation.

7.1.1 Resource evaluation and demand forecasting

Comprehensive assessment of underground space resources integrates evaluations of existing natural conditions and socio-economic development to inform decision-making for the zoning of UUS plan. This process encompasses assessments of resource distribution, capacity, quality, developmental potential, and suitability for utilization. By constructing an index system, weighting methodologies, and mathematical models, the evaluation facilitates a thorough understanding of potentials of various underground resources. This customized system synthesizes urban multi-source data to tailor the assessment indices based on specific evaluation content and planning objectives. Generally, the indices are categorized into two major types: those based on natural conditions and those grounded in socio-economic factors. Indices based on natural conditions primarily consider geological, hydrological, topographical, ecological, and adverse environmental factors. Such indices are applied using three-dimensional visualization technologies to assess the value of shallow, mid-level, and deep underground resources (Dou et al., 2021; Hou et al., 2016; Price et al., 2018; Zhang et al., 2020). In parallel, socio-economic indices incorporate demographic distribution, transportation infrastructure, land use, development intensity, and location positioning, alongside economic indicators like gross domestic production and benchmark land prices, and constraints such as historic, water, and ecological protection areas. These indices form a layered assessment framework, enhancing the evaluation system's ability to address varied socio-economic conditions (X. Li et al., 2016; Peng & Peng, 2018a, 2018b; Wu et al., 2023; Zhu et al., 2016).

Currently, many cities have developed three-dimensional resource assessment models for urban underground space, based on geological environment data. For example, Beijing's sub-center conducted a comprehensive underground space resource survey and evaluation across its 155 km^2 area around 2016. This initiative facilitated the estimation of underground space resource quantities and supported a comprehensive evaluation of their potential (Beijing Geology Prospecting and Developing Bureau, 2017). Similarly, the Xiong'an New Area in Hebei Province delineated 40 000 units across its entire region by analyzing factors such as the distribution and thickness of water-bearing sand layers, groundwater depth, land subsidence,

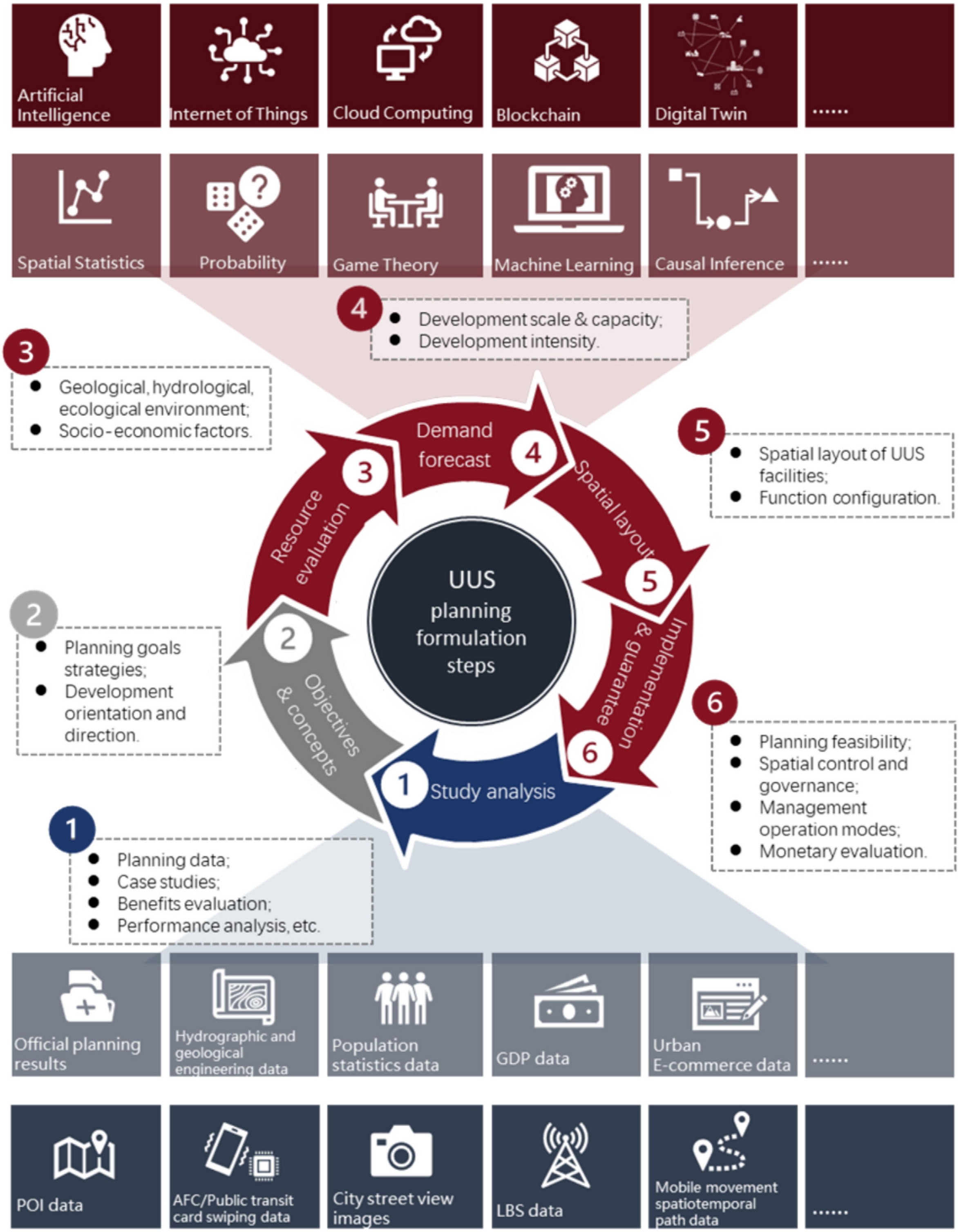

Fig. 6. Logic integration of DIPTUS across three themes.

and liquefaction of sand. This enabled a multi-level underground space resource assessment, ultimately determining that approximately 80% of the area is suitable or generally suitable for underground space development (Han et al., 2024).

Unlike resource value assessment which objectively analyzes potential for UUS development, demand forecasting involves a more subjective consideration of the development scale and intensity envisioned in planning practices. This includes determining the size, functional layout, and developmental sequencing of underground construction, which directly influences the control mechanisms of regulatory detailed planning for UUS. Current methods and indices for forecasting urban underground space demand are diverse (Xia et al., 2022a). Mainstream forecasting methods include those based on ecological needs, categorical integrations, functional demands, land use intensity, comprehensive needs, and graded evaluations (Cao & Feng, 2013; Zhao et al., 2016). However, the indices used to measure the scale of UUS demand are relatively complex. Considering the dynamic nature of modern UUS utilization, which evolves in response to socio-economic policy changes, necessitates nonlinear analytical approaches. Increasingly, researchers are employing multi-source data that more effectively capture the dynamics of social development, and they are studying the driving factors that influence UUS development to estimate demand. For instance, constructing quantitative models to analyze relationships and evolutionary characteristics relevant to UUS utilization can indirectly forecast demand and scale (Ge et al., 2024; He et al., 2012; Xia et al., 2022a; Zeng & Chen, 2018). Essentially, by discovering the patterns and quantitative relationships between various factors and UUS demand, researchers can use forecasting indices to further calculate the developmental capacity.

7.1.2 Layout planning optimization

The layout of UUS planning is a crucial component for both master and detailed planning levels, yet there are limited established data-informed methods for such work. Traditionally, layouts are determined based on the semi-quantitative evaluation on aboveground built environments combined with the personal expertise of planners. To improve the rationality and efficiency of layout planning schemes, spatial-computation-based generative technologies for UUS layout planning have rapidly evolved in recent years (F. Peng et al., 2023). However, UUS development in long-term planning is an extremely complex process (Besner, 2016), particularly in the context of urban redevelopment, where complex-built environments and established stakeholder interests make planning decisions much more challenging. Nowadays, emerging multi-source data and urban science methods have provided new solution to better serve planning and drafting for the multi-dimensional layout of urban complexes (Zhou et al., 2024b). Data-informed techniques such as multi-agent models, multiple objective optimization, digital twins, have been pioneeringly applied to UUS layout planning issues from single-point underground facility site selection to generating whole-system underground layout plans (Dong et al., 2022; Hu et al., 2020; Jin et al., 2021; Shao & Wang, 2022; Zhou et al., 2024b). Among various underground space layout models, the research focus has been specific areas such as metro-led underground space (Dong et al., 2023a, 2021b, 2022; Liu et al., 2022), urban core districts (Chen et al., 2022b; Zhang et al., 2023), and underground mineral resource areas (G. Li et al., 2022; W. Li et al., 2023). In addition to the layout planning generation, scholars are also investigating on the spatial analytics models to optimize existing underground facilitates layouts, thereby scientifically guiding the planning and implementation of UUS development. The trend involves municipal facilities (Hu et al., 2020; Zhao et al., 2018), public service facilities (Xu & Chen, 2022), parking facilities (Dong et al., 2021a), and disaster prevention facilities (Jin et al., 2021; L. Peng et al., 2023).

Whilst emerging data-informed layout planning models have alleviated the earlier reliance on empiricism for UUS layout generation and optimization, these approaches are still largely defined as tools to assist planners in making rational decisions. The paradigm of intelligent planning with human–machine interaction in the field of underground space continues to evolve, which calls for a more profound integration of human wisdom and computing intelligence.

7.1.3 Development benefits and spatial performance evaluation

For UUS planners, it is crucial to assess the spatial performance in relation to the urban developmental status, thereby informing refined planning decisions based upon the components and configuration of UUS spatial performance. Such performance evaluation incorporates metric representations, allowing for the selection of either direct observational measures of spatial performance or indirect indices that are causally linked to the performance, to construct a comprehensive evaluation framework. This framework places a keen focus on the holistic developmental outcomes of existing UUS and the efficiency of their multifaceted utilizations. Evaluations are conducted at both macro and micro levels; the macro-level assessments pertain to the overall functionality of underground facilities, analyzing the collective impact and efficacy of UUS development across urban scale, and identifying configurational and developmental levels of UUS to support overarching strategic planning decisions (Chen et al., 2018; Ma & Peng, 2023; Ma et al., 2022). On the micro-level, performance evaluations focus on specific types of underground facilities such as metro-led public underground space, analyzing their functional efficacy within confined urban areas. These evaluations consider various aspects, including transportation development benefits (Ma & Peng, 2018, 2021), spatial configuration (Wu & Yuan, 2018; Zhao & Künzli, 2016), spatial efficiency and vitality (Dong et al., 2021b; Ma et al., 2023b, 2021), as well as construction environment quality and user comfort (X. Dong et al., 2021; Tanaka & Nishi, 1997; Wang et al., 2023).

Moreover, urban planners are tasked with evaluating the value and impacts of underground space development during post-planning-implementation, and such evaluation is also applicable in preliminary planning analysis. In recent years, the social and environmental benefits of UUS have garnered significant attention, with assessment methods evolving from qualitative analyses to monetized quantitative evaluations. The benefit assessment of underground spaces involves monetizing both the market (internal benefits) and non-market (external benefits) values (Kaliampakos et al., 2016; Qiao et al., 2019b). Internal benefits refer to the direct revenues or economic returns from UUS utilization, such as income from underground commerce, parking, and metro, as well as fees from the use of underground logistics, storage, and municipal facilities. External benefits, reflecting social, environmental, and disaster mitigation advantages (Qiao et al., 2022a, 2022b), lack direct market prices and require specific monetized evaluation methods to quantify their value. Currently, methods like the service replacement cost method (Qiao et al., 2019c) are widely utilized for cost-benefit analysis of various underground facilities, including underground roads (Ma & Peng, 2021), rail transit (Qiao et al., 2019c), and utility tunnels (Zhang et al., 2021), providing a rational basis for UUS planning.

7.2 Governance as a broader issue of DIPTUS

Planning is recognized as a spatial intervention policy tool, and DIPTUS is no exception. To achieve better governance of UUS in a broader sense, scholars are actively exploring how digital tools can be utilized for areas such as three-dimensional cadastres, development management mode, and digital twin planning systems.

7.2.1 Three-dimensional cadastres

With the continuous development of diverse underground facilities, existing cadastral management tools do not meet the registration requirements for the physical or legal information of three-dimensional property objects (Ho et al., 2013). Consequently, an increasing number of scholars are considering how to transform the traditional, extensive two-dimensional cadastral management system into a more refined three-dimensional cadastral system that integrates thoughts on above-ground, ground-level, and UUS. By integrating multi-source urban data, this system aims to become a crucial means for effectively managing multidimensional spaces and contributing to urban sustainable development (Guler, 2024). In recent years, countries such as China, South Korea, Singapore, Australia, Norway, Denmark, Sweden, and Poland have initiated studies and practices on three-dimensional cadastres (Bennett et al., 2010; Dawidowicz & Zróbek, 2018; Guo et al., 2013; Ho & Rajabifard, 2016; Ho et al., 2013; Kim & Heo, 2017). Utilizing 3D digital information and communication technologies, three-dimensional cadastral systems can define, manage, and register complex rights, restrictions, and responsibilities of land assets in UUS, including legal aspects, scope, boundaries, and locations (Qiao & Peng, 2023). Currently, the registration techniques for UUS can be broadly categorized into three models: (i) adding three-dimensional information to the existing two-dimensional cadastres, (ii) a hybrid of two-dimensional and three-dimensional cadastres, and (iii) a fully three-dimensional cadastral model (Qiao & Peng, 2023).

7.2.2 Development management mode

The development management mode focuses on enhancing spatial control and governance of UUS during the implementation of planning. This mode involves coordinated planning, layout patterns, design proposals, and operational measures for UUS. In recent years, China has conducted a series of emblematic explorations in UUS planning and design in terms of the development mode. Depending on the connectivity features of the UUS, three primary modes have emerged: independent, connected, and integrated, with each mode presenting four major interfaces of UUS development: property rights interface, design interface, construction interface, and operational interface (W. Wang et al., 2024). An example of the independent mode is the early development of the UUS in Lujiazui central business district in Shanghai, where each block's developer was responsible for the construction, design, and operation of the UUS within their respective blocks, holding the corresponding property rights (Qiao & Peng, 2016). As underground construction technology advances and policy regulations are refined, the UUS development management mode has become increasingly diverse. The Hongqiao Business District core area phase one exemplifies the connected development mode, exploring the construction of integrated basements within the blocks as the smallest units, and connecting UUS units across municipal roads (Peng et al., 2020; Qiao & Peng, 2016). The Shanghai West Bund Media Port adopts an integrated development mode, developing an entire area across municipal roads and multiple adjacent blocks, eliminating building setback requirements within the entire development area, and ensuring a unified elevation and spatial quality across the connected range (W. Wang et al., 2024). With the aid of causal inference methods such as fuzzy-set qualitative comparative analysis, the feasible development mode for specific UUS could be determined, thus providing a basis for planning decisions (He et al., 2014; W. Wang et al., 2024).

7.2.3 Digital twin planning system

Digital twin technologies, traditionally applied to above-ground spaces, have been less explored in underground environments (Shao & Wang, 2022). Recent scholarly efforts have introduced the concept of a five-dimensional digital twin framework to underground spaces, delineating five key components: physical entity, twin model, data fusion, real-time perception, and optimal control. Additionally, they have summarized four methodological categories for underground space modeling: geological body modeling, behavioral modeling, machine modeling, and structural body modeling (Gong et al., 2024). Strictly speaking, there has yet to be a dedicated digital twin platform specifically for underground space planning or practical application. However, digital twin technology has already permeated various aspects of the construction and operational maintenance of underground facilities, laying a solid foundation for digitally coordinated planning. Current studies on urban underground space digital twins typically base themselves on geological modeling, constructing BIM and GIS virtual scenarios and three-dimensional geographic databases. These are extensively applied in data visualization, three-dimensional modeling, data monitoring, and the management of underground facility development (Lee et al., 2018; Ma & Ren, 2017; Xia et al., 2022b).

In practical applications, many practitioners have used GIS, BIM, and digital twin technologies to advance the development of smart cities and intelligent infrastructure. In China, many regions have actively pursued a transition from digital city to intelligent and smart city, comprehensively supporting the modernization of urban governance systems and capabilities. In Beijing's Tongzhou sub-center, the city information modeling (CIM) platform has been established to enable refined, three-dimensional, and dynamic management of both above-ground and underground urban data. By integrating AI, the CIM platform incorporates the global image intelligent recognition technology CIMAI, which facilitates dynamic urban simulation and intelligent predictive analysis (Wu, 2018; Z. Wu et al., 2022). Additionally, the infrastructure smart service system (iS3) has been developed to create an integrated intelligent decision-making service system for the full lifecycle of urban infrastructure, encompassing data collection, processing, representation, and analysis. This system has been applied to intelligent tunnel construction projects in regions such as Shanghai and Ningbo (Tang et al., 2019; Zhu et al., 2018, 2017). In Singapore, the integration of GIS systems has enabled the collection and compilation of data from approximately 60 000 underground boreholes across the nation, forming the basis for the AI-driven GEM2S platform. This platform provides visualization and interactive manipulation of 3D geological models. Furthermore, advanced geological data management functionalities support the design of underground projects and establish a foundational database for Singapore's future underground space planning (Pan et al., 2019, 2018). These initiatives demonstrate the transformative potential of GIS, BIM, and digital twin technologies in enhancing urban intelligence and infrastructure management, paving the way for sustainable and efficient urban development.

Overall, research on underground space digital twins predominantly revolves around several directions: the design of digital twin architectures for underground spaces (Belfadel et al., 2023; Gürdür Broo et al., 2022), construction of underground structures (T. Li et al., 2024; X. Wu et al., 2022; Ye et al., 2023), disaster mitigation assessment (Han et al., 2020; Li et al., 2024a; Shao & Wang, 2022), monitoring and modeling of the underground geological environment (Shi & Wang, 2022), and data visualization and full lifecycle maintenance (M. Li et al., 2023; Wang & Yin, 2022; Zhu et al., 2018). These studies serve various urban applications such as municipal underground infrastructure (Lee et al., 2023; M. Li et al., 2022; Son & Kim, 2016), underground logistics facilities (Belfadel et al., 2023), and underground tunnel traffic systems (Yu et al., 2021; Zhang et al., 2024; Zhou et al., 2024a).

8 Challenges and pathways for a better underground future

Building on the preceding literature review, DIPTUS, while not yet coalescing into a complete technological framework, has embarked on varied degrees of technical exploration across different stages of planning research and formulation. By employing data-driven techniques, DIPTUS enables the sensing and measurement of characteristics pivotal to UUS development, identifies primary driving factors, and engages in knowledge distillation to summarize the patterns of UUS evolution. This has led to the creation of a suite of research analysis tools and planning technology models for UUS planning. However, the development of DIPTUS also faces numerous challenges, which were partially described in a non-systematic fashion from a technological review perspective earlier in this study. To delve deeper, we categorize these research challenges into three main types, adhering to the analytical dimensions of the previous narrative synthesis.

(1) Integration challenge in the multidimensional sensing and measurement system: The advent of big data has significantly enhanced the analytical capabilities for UUS planning. However, these data were not originally collected with the intent of supporting planning and management. Firstly, there is an urgent need for an efficient sensing system that adheres to a unified data standard to integrate the diverse and heterogeneous data relevant to UUS planning. Secondly, the development of a tailored inventory that defines basic indicators and establishes corresponding measurement methodologies is critical to support the DIPTUS framework.

(2) Complexity challenge of pattern-based planning models: The modern UUS is an extremely complex urban system, wherein deciphering the sophisticated and diverse utilization patterns poses significant challenges. Integrating geospatial analytics with cutting-edge data-informed tools such as AI provides promising new avenues for mining these patterns; however, a comprehensive interdisciplinary approach is essential to fully understand the nuanced interactions within the tripartite framework of human-society-environment. Moreover, to ensure the reliability and interpretability of these models for decision-making in UUS planning, it is crucial that pattern-based models maintain a robust connection with the sensing and measurement systems.

(3) Application challenge of governance-oriented planning management: Although methods for formulating UUS planning across various spatial scales are rapidly evolving, the connections between different planning approaches—including resource evaluation, demand forecasting, layout planning optimization, and spatial performance and benefits evaluation—are notably weak. This indicates that DIPTUS methods for planning formulation struggle to be effectively integrated and applied to real-world planning tasks. Additionally, special attention needs to be directed towards model refinement in specific planning scenarios, such as metro-led underground space development and urban redevelopment. Beyond the initial application of planning formulation, the importance of post-planning management for the life-cycle of UUS is increasingly recognized. This research gap could potentially be bridged through the incorporation of planning, engineering, and management disciplines based on a robust digital twin planning platform. However, technical guidelines for such a digital twin platform require further investigation to ensure alignment with governance requirements.

The challenges outlined above represent significant breakthroughs for the development of DIPTUS and will also lay the foundation for the future advancements of this technology. The ultimate goal of DIPTUS is to enhance humanity's precise and efficient management of underground space resources in a long-term vision. To this

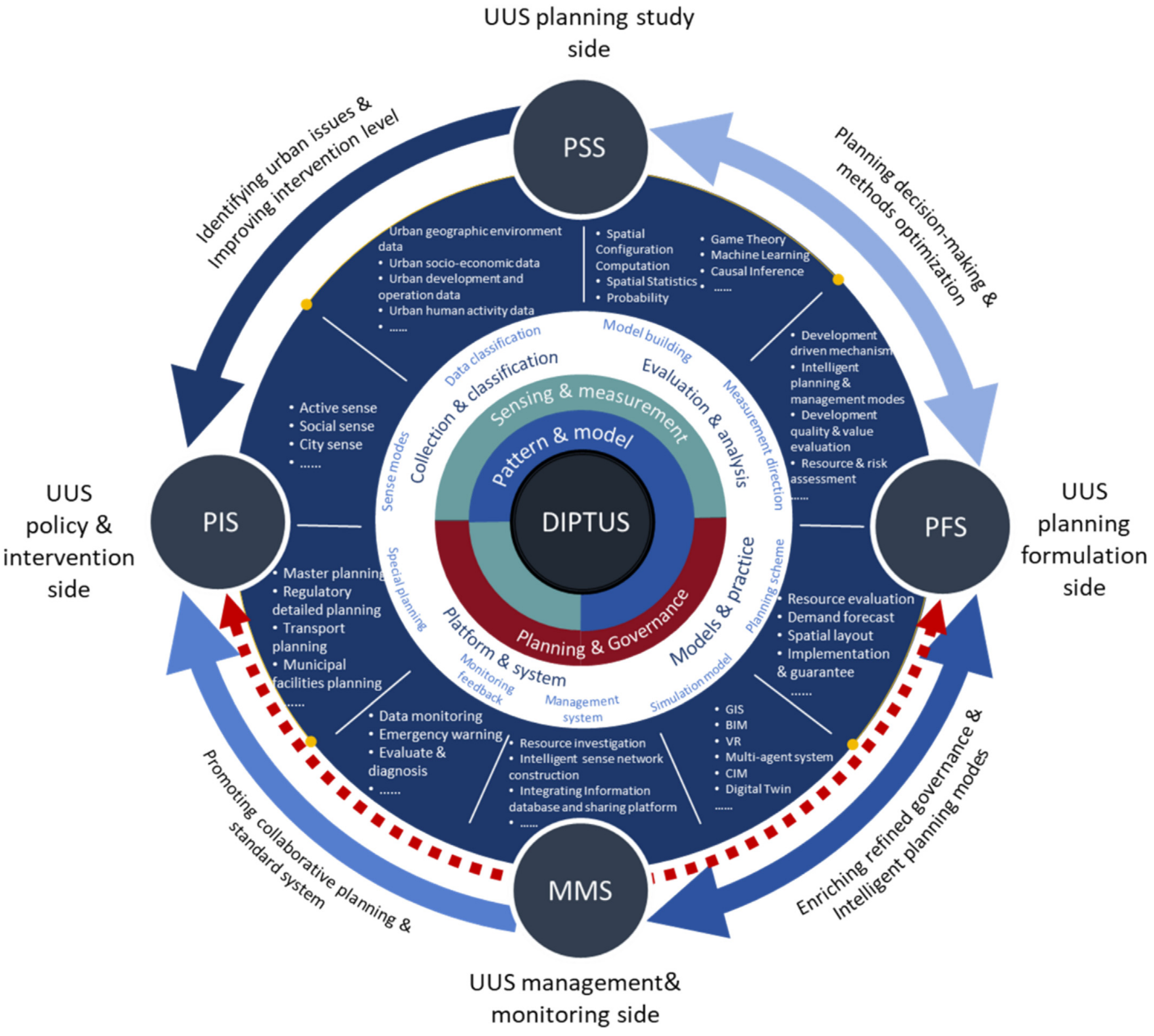

Fig. 7. A visionary framework for DIPTUS.

end, we propose a visionary framework that not only integrates current research trends but also offers a potential discussion framework for addressing imminent technological challenges (see Fig. 7). This framework is closely linked to the three main themes identified in the previous narrative synthesis and can be further divided into several detailed components.

The transition from planning study side (PSS) to planning formulation side (PFS) represents the evolution from academic planning research to practical planning formulation. DIPTUS enhances such research by leveraging multi-source data to analyze underground issues, assess development characteristics, summarize development patterns, and construct useful planning models, thereby bolstering decision-making support for planning.

The complexity inherent in planning underscores the utility of DIPTUS across sensing & measurement, pattern & model, and planning & governance. It becomes crucial to integrate multi-source data to assess the current scenario and refine measurement analysis and planning methods using DIPTUS, ultimately impacting planning control and urban governance. The movement from PFS to management and monitoring side (MMS) entails integrating planning data and outcomes into the management and operation platforms, enriching the entire process from planning initiation to management. Subsequently, from MMS to PFS, there is an improvement in planning formulation by addressing issues identified during planning management and monitoring.

In MMS, the integration of three themes is critical. It involves a thorough investigation of UUS resources and information collection through DIPTUS. This integration deepens the use of simulation models such as GIS, BIM, and digital twins, promoting intelligent full-cycle management and operations, and shaping the planning modes of UUS.

Transitioning from MMS to policy intervention side (PIS), the intelligent management platform monitors and evaluates the state of UUS development in real time, providing feedback to the planning policy sphere, which in turn suggests interventions and guidance for resolving existing issues.

Collectively, PSS, MMS, and PFS influence the PIS framework. Both PSS and MMS propose amendments for policy interventions by identifying issues and providing feedback on existing development. Planning policy also shapes the content of UUS planning and design, with the outcomes of UUS planning subsequently integrated back into the planning policy, thereby enhancing the integrity of the planning system.

9 Conclusions

The increasingly deteriorating urban built environment underscore the need for innovative UUS development strategies, specifically the emerging technologies for UUS planning. This systematic review probes into the evolving domain of DIPTUS, showcasing how data-centric methods are redefining the planning, design, and management of underground urban realms. We scrutinized 134 articles from 2014 to 2024, applying bibliometric techniques and thematic mapping to distill prominent trends and research themes. There are several key insights obtained from this review.

(1) Evolving motivations: The drive towards DIPTUS is fueled by demands for human-centric design, low-carbon footprints, bolstered urban resilience, and adherence to sustainable development goals. This marks a paradigm shift from empirical to data-oriented UUS planning.
(2) Critical role of multisource data: DIPTUS capitalizes on varied data sources regarding urban environments, socioeconomic status, urban system operation, and spatial activities, to deeply analyze and quantify development in UUS.
(3) Advancements in pattern-based modeling: Innovative data science methodologies such as spatial statistics, machine learning, and causal inference are increasingly utilized to decode spatial usage patterns and forge refined planning models.
(4) Integrated planning and governance: DIPTUS champions a unified approach to UUS planning by amalgamating resource evaluation and demand forecasting, layout planning optimization, development benefits and spatial performance evaluation. It also supports cutting-edge developments in 3D cadastral systems, new management models, and digital twin technologies.

Despite these significant strides, the integration of data, model complexity, and practical enactment presents ongoing challenges. Our proposed future direction involves an interdisciplinary approach, the establishment of standardized data frameworks, and the creation of robust, interpretable models. These strategies are designed to enhance decision-making throughout the lifecycle of underground urban developments. Bridging the gap between theoretical data models and practical implementation, DIPTUS aspires to maximize the potential of modern UUS development, thereby fostering more sustainable, resilient, and human-centered urban futures.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Fang-Le Peng: Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Wei-Xi Wang:** Writing – original draft, Visualization, Resources, Data curation. **Yong-Kang Qiao:** Validation, Resources, Investigation, Data curation. **Chen-Xiao Ma:** Visualization, Resources, Formal analysis. **Yun-Hao Dong:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

Dr. Fang-Le Peng is an editorial board member for *Underground Space* and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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