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Review

A Review of Research on the Value Evaluation of Urban Underground Space

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Abstract: The contradiction between urban construction and sustainable development has led to an increasing demand for urban underground space (UUS). The value evaluation of urban underground space (UUSVE) is of great significance in promoting the rational development of UUS. Currently, no study has reviewed the literature on UUSVE. This paper provides a preliminary review of the legal basis and element composition of UUS, and the themes, evaluation objects, and evaluation methods of UUSVE, attempting to clarify the current status of UUSVE and analyze its future development trends. Finally, by summarizing the legal basis, element composition, research status and trends of UUSVE, three suggestions to strengthen UUSVE are proposed: (1) to strengthen the research on the shortcomings of UUSVE methods; (2) to build an evaluation index library and case library; and (3) to emphasize interdisciplinary collaboration, with a particular focus on the application research of machine learning.

Keywords: urban underground space; value evaluation; AI; evaluation model

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1. Introduction

The utilization of UUS is a strategy whose value that has been underestimated worldwide [1], mostly in developed countries and some developing countries. Some developed countries in Europe, America and Asia, such as the UK, Finland, and Singapore, utilized UUS early on, contributing advanced technical templates and development experience in underground tunnels, as well as demonstrating the secondary utilization of underground mining space and deep underground space development. Limited by their economic and technological levels, India, Iran, and other Asian and African developing countries display a relatively lower level of advancement in UUS development. Furthermore, despite its later start in the development and utilization of UUS compared to certain European and American nations, China has displayed rapid and extensive growth in this field over the past few decades. Presently, China's utilization of UUS stands at the forefront globally, surpassing that of many other countries [2]. In general, there are differences in the development of UUS worldwide, leading to many development modes, such as underground rail-transit-oriented development, full-function three-dimensional development, compact and intensive development and green development [3].

In addition, with the expansion of UUS development, problems associated with inefficient use, disorderly development and geological engineering disasters have emerged [4,5]. UUSVE is an effective means of managing UUS. Over the past decade, scholars have explored methods for the evaluation of the urban underground space value (UUSV) from various perspectives. This has led to the accumulation of certain research outcomes related to the economy, the environment, society, disaster prevention, and potential value of UUS. In the context of global urbanization, which has led to the need for the sustainable management of land resources, UUS development and utilization activities are being performed more frequently. However, the research emphasis varies worldwide, which is detrimental in promoting the results of UUSVE research and achieving the efficient and sustainable development of underground space.

This paper is structured as follows. Following the introduction to the concepts and composition of UUSV under different disciplinary scenarios, the paper summarizes the research topics, evaluation objects, and evaluation methods regarding UUSVE. It then discusses the future research emphasis and development directions of UUSVE and provides recommendations for future research.

2. Legal Basics and Conceptual Elements

The focus of this paper is UUS, which refers to the fixed part of the crust under the soil cover layer within an urban construction area. UUS is a powerful tool to expand the capacity of urban space and devise new urban development models. It is an interdisciplinary concept that involves fields such as economics, law, and geological engineering, with different connotations in different fields [6]. In the field of economics, UUS is the result of the reallocation and combination of underground space resources in economic activities [7]. In the field of law, UUS includes practical spaces below the surface that are formed naturally or artificially developed, which can be controlled by individuals in accordance with legal provisions and can generate benefits [8]. Many countries and regions have enacted laws or regulations to legalize and delineate the scope of land use in underground spaces. In common law countries, the underground space right is regarded as independent usufructuary right, and laws are created separately. For example, England established land development rights through the Urban and Rural Planning Act. Civil law countries regard the underground space right as an extension of the overground right. For example, the Chinese Civil Code stipulates that the right to use construction land may be established on the surface of the land, above or below the ground [9]. In addition, there are significant differences in the management of underground space resources among different countries, which are influenced by their land systems and the actual national conditions; please refer to Table 1 for details. In the field of geological engineering, underground space refers to the volume of space that can be exploited within a certain depth of the soil and rock in the lithosphere [10]. For example, in France, the depth is limited to 30 m below the ground, while the rest is designated for public use.

Correspondingly, there are different opinions regarding UUSV, which are characterized by the following points: (1) the comprehensive value brought by the underground space resources realizing the flow and producing an underground space service under market allocation; (2) the expense incurred to obtain the right to use underground space for a specified duration; (3) the potential development capacity of underground space resources within a certain depth range (Table 2).

Table 1. ITA member nations' exploitation restrictions on underground space resources. (Adapted from Barker et al. [8,11]).

Country \ Resource	Water	Oil/Gas	Coal	Metal and Mineral
Australia	Controlled by the state government.			
Belgium	According to the law.			
China	Owned by the state.			
Denmark	Government permission is needed.			
Finland	No restrictions.			Citizens or companies may engage in mining after government approval and the payment of compensation to landowners.

Table 1. *Cont.*

Country \ Resource	Water	Oil/Gas	Coal	Metal and Mineral
France	Wells exceeding the specified length require authorization.	Authorization and franchising are required.		
Germany	Land owners do not own water resources but have the right to apply for development.	Regulated by the Federal Mining Law but not owned by landowners.		Regulated by the Federal Mining Law. Landowners can exploit it with the federal government's permission.
Hungary	Permission for exploitation must be obtained.	May be developed only by state-owned organizations.		
Italy	Public water resources belong to the public, and special or catchment usages require approval.	Belonging to a country or region, the country or private company is granted development rights.		
Japan	There are already industrial or building groundwater withdrawal regulations.	Surface owners have priority in obtaining mining rights.		
Mexico	Water resources for public interest are public property.	Public property.		
Norway	Landowners can exploit groundwater without affecting others.	National property managed by the Federal Government.	Owned by landowners.	
South Africa	Landowners can exploit groundwater but not their Shanghai neighbors.	Managed by the State or its designated agent.	Landowners should not obstruct reasonable mining operations.	
Sweden	Parliamentary sanction is needed.			Need to obtain concessions and comply with environmental laws.
Switzerland	A concession must be obtained from the Canton.			
U.K.	Exploitation governed by law and requires a permit.		Public property can be extracted by contractors or operators with certificates.	Surface owner owns all metals and minerals except for gold, silver and uranium, which belong to the Crown.
U.S.A.	Restrictions at both State and National levels.	Private companies can develop resources under government control after agreement.		
Venezuela	Controlled by the Government.			

In the 1870s, developed countries such as Japan, the US, and the UK implemented construction practices including underground commerce, three-dimensional transportation, underground cities, and underground sewage disposal, initially focusing on economic value. Foster C D et al. proposed that the metro benefit cannot be evaluated solely based on economic profits, but its social value should be considered at the same time [12]. Riera P et al. introduced the externalities generated by the development of underground space into the reference indicators for land use decision-making, highlighting the practical significance of the study of UUSV [13]. Huang, Y. et al. evaluated the potential value of underground space resources, making the development and utilization of underground space more scientific and reasonable, and highlighting that the connotations of UUSV are being constantly expanded [14]. Jiang W et al. monetized the social and environmental benefits of underground transportation, providing a new way of calculating the comprehensive benefits of underground space [15]. Kaliampakos et al. pointed out that the development of underground space produces environmental value and disaster prevention value, thus increasing the connotations of UUSV [16].

Table 2. The connotations and value expression of UUS.

Research Area	Connotation	Research Objective	Value Expression
Economics	Scarce economic resources	To realize the optimal allocation of underground space resources	All benefits of underground space development
Law	Disposable and profitable rights	To clarify the attributes of underground space rights	Payment to obtain the right to use underground space for a certain period of time
Geological engineering	Space with rocks and soil as the environment	To determine the suitability of underground space development	The potential development value of underground space resources

In summary, UUSV encompasses both real and potential value. The real value comprises direct and indirect value, as shown in Figure 1. Direct value refers to the economic value generated by the UUS. For example, the opening of a metro will bring about the appreciation of the surface land, and the exploitation of underground mineral resources can increase the national economic income. Indirect value refers to the external value generated by UUS development, including social, environmental and disaster prevention value. For example, urban underground public transportation can help citizens to save time, and underground oil and gas storage can improve the ability to mitigate economic risks [17]. Potential value, on the other hand, denotes the comprehensive benefits that can be generated from the undeveloped underground space resources. Currently, the underground space resources that are considered to be able to support sustainable urban development include underground space, groundwater, geomaterials and geothermal energy [18].

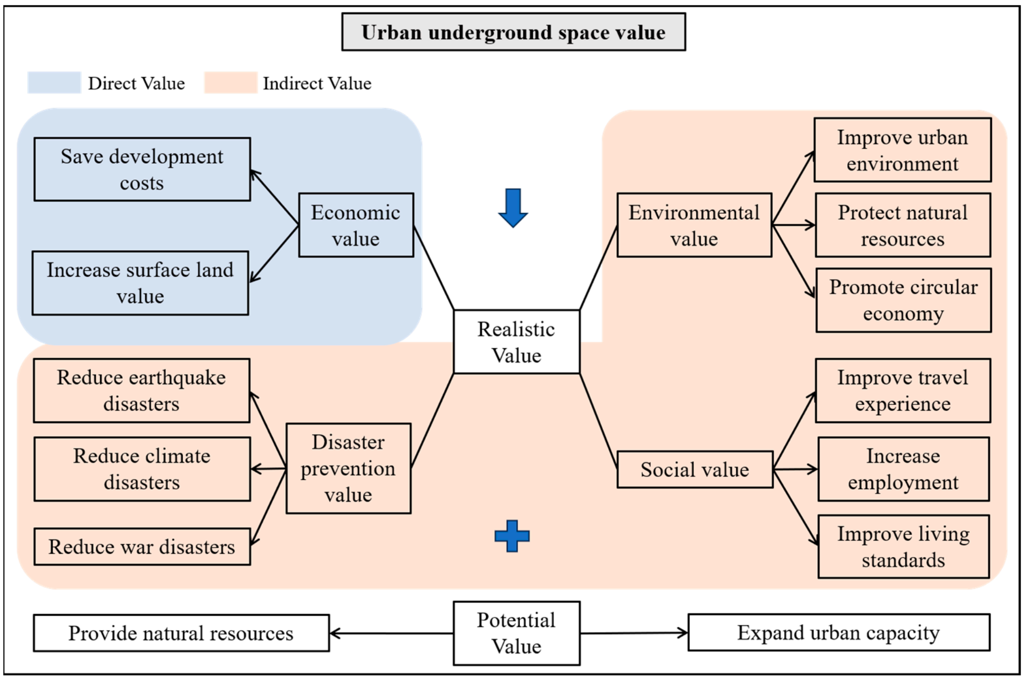

Figure 1. Types of UUSV.

2.1. Direct Value of UUS

Reducing the development costs and increasing the surface land's value are the two main components of direct value. The development costs include land expenses and construction costs, which vary in the vertical direction. As the vertical distance increases, the land expenses decrease while the construction costs increase. However, specifically, the expenses for the above-ground land near city centers greatly exceed the underground land expenses. In Figure 2, O represents the city center. The horizontal axis, S, represents the distance between the land and the city center, while the vertical axis represents the land price. The curve depicts the overground development cost, and the straight line represents the underground development cost. Due to the high price of the overground land near urban centers, the cost of developing overground space is higher than the cost of developing underground space. As proven by previous scholars, there is a balance point in the development costs between underground space and overground space E (Se, Pe). When S < Se, the underground development costs are lower than the above-ground costs [19]. A case study found that the costs of 11 underground commercial streets in Japan (1976–1980) were two to four times higher than those of surface buildings. When adding the land expenses, the cost of underground commercial streets was only one twelfth to one quarter of the cost of surface buildings [8]. The metro also attracts a large number of citizens to settle around it, causing an increase in the real estate demand and thus achieving land appreciation [20–22].

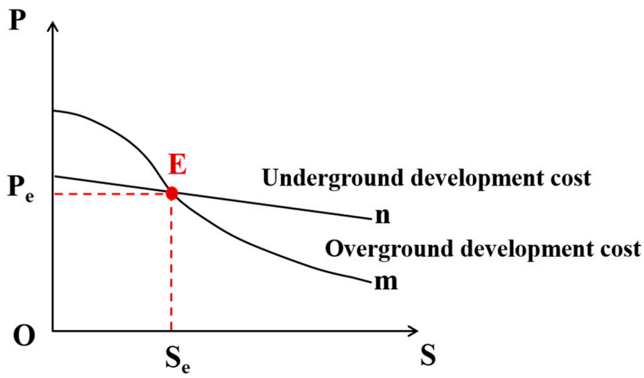

Figure 2. The relationship between development costs and location (adapted from Hu et al. [19]).

2.2. Indirect Value of UUS

2.2.1. Social Value

The development of UUS can improve travel experiences and increase employment and living standards. On one hand, the subway offers a rapid method of transport, boasts high capacity, and eliminates the need to wait at traffic lights, thus easing the burden of surface transportation, mitigating traffic congestion, and reducing citizens' commuting times. On the other hand, underground rail transit carries a minimal risk of traffic accidents, leading to a decrease in such incidents and an enhanced travel experience. The research by Litman et al. supports this perspective. By studying the comprehensive benefits of urban transportation systems in the United States, they found that the larger the urban rail system, the higher the per capita transit ridership, and the lower the traffic congestion and mortality rates [23]. In addition, the development and utilization of UUS have created more employment opportunities. Firstly, UUS provides a large number of direct employment positions, such as engineers, technicians, and construction workers in the construction of subways [24]. Secondly, it promotes the development of related industrial chains, indirectly increasing the employment opportunities, such as through the development of underground commercial spaces, the manufacturing of subway vehicles, and the maintenance of underground pipelines [25]. Meanwhile, due to the underground space sharing various pressures with the ground, citizens' living standards can be improved. These pressures include citizens' travel, the living environment, and personal safety issues. Specifically, the subway improves the travel experience, underground shopping malls provide citizens with more consumption and entertainment options, and underground parking lots, logistics, and storage alleviate most of the land shortage problems, freeing up more living space for citizens. In addition, underground sewage discharge, comprehensive pipe galleries, and other facilities improve the city's disaster emergency capabilities and can also serve as shelters during emergency events [26]. Japan is a typical country with scarce land resources, and urbanization has led to high population concentration, resulting in a decline in the quality of life of its residents. As a result, Japan has begun to change its urban development strategy and extend it to underground spaces, constructing underground spaces such as railways, basements, shops, passages, and sewage discharge systems, improving the living standards of its residents [27].

2.2.2. Environmental Value

The utilization of UUS can improve the urban environment, protect natural resources, and promote a circular economy. Firstly, concerning the improvement of the urban environment, the impact of air pollution and urban pollution projects can be highlighted. Air pollution is one of the main factors affecting the urban environment, with the main sources of pollution being the exhaust emissions of motor vehicles such as private cars, taxis, and motorcycles [28]. Data from the Visual Capitalist website show that the carbon footprint per passenger km for private cars and buses is much higher than for the metro, as shown in Figure 3. Figure 4 indicates that traffic congestion, resulting in the frequent acceleration and deceleration of cars, generates more harmful emissions compared to uniform speed driving [29]. Therefore, in addition to reducing the exhaust emissions from various transportation vehicles themselves, underground rail transit can also help to decrease the additional exhaust emissions caused by ground traffic congestion. This, in turn, can reduce air pollution and enhance the urban environment [30]. Similarly, garbage stations, sewage treatment plants, and other facilities can also have a negative impact on the urban environment. The development and utilization of underground space can facilitate the underground transformation of urban pollution projects, thereby reducing their impact on the surface. The underground transformation of urban pollution projects can reduce their impact on the surface. For instance, Finland's Viikinmäki Center sewage treatment plant, constructed to safeguard the environment [31], boasts an annual sewage treatment capacity exceeding 100 million cubic meters. Situated underground, the processing plant frees up more space for ecological construction within the city, enhances green areas, and prevents noise and odors from disrupting the lives of nearby residents. Secondly, with regard to protecting natural resources, particularly land resources, water resources, and biodiversity, the development of underground space plays a crucial role. It minimizes surface construction activities, thus decreasing the harm to soil surfaces and biological habitats. Moreover, the establishment of underground rainwater collection and treatment systems can mitigate the soil erosion caused by rainwater runoff. The treated rainwater can be utilized for eco-friendly irrigation purposes and may even meet drinking water standards. Likewise, urban sewage, following treatment, can be repurposed as non-potable water, contributing to water conservation efforts [32]. Finally, the use of UUS facilitates the promotion of a circular economy. The core concepts of a circular economy are reduction, reuse, and resource utilization [33]. The focus of UUS utilization is on reducing the consumption of natural resources, reusing waste resources such as sewage and rainwater, and transforming underground spaces into their own energy sources. Benardos et al. conducted a study comparing the energy requirements of overground and underground residential buildings [34]. They discovered that the heating and cooling demands of overground buildings exceeded those of underground buildings, indicating that underground structures are more energy-efficient (Figure 5). Wandel, S. et al. proposed an underground capsule pipeline system and verified its technical feasibility, as well as its capacity to reduce space usage and carbon dioxide emissions by 30% in specific scenarios [35]. Hence, the utilization of UUS aligns well with the fundamental principles of the circular economy and represents a promising approach to foster economic circulation.

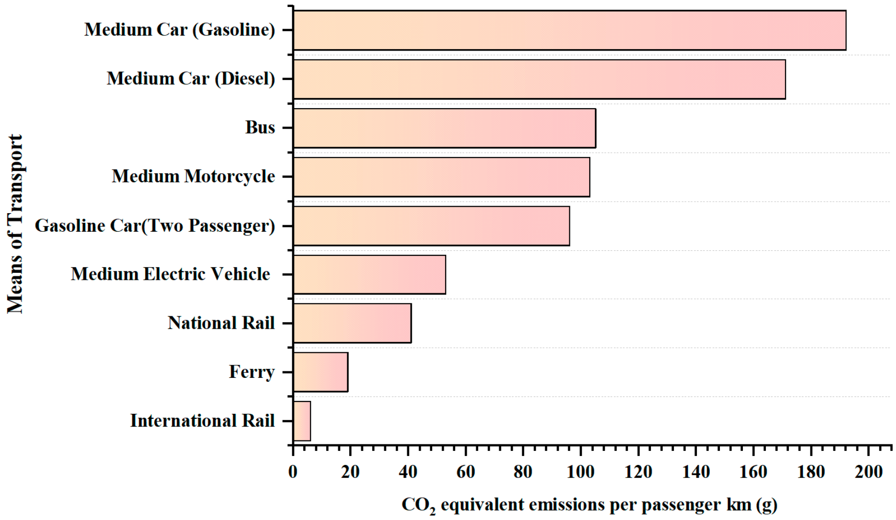

Figure 3. Exhaust emissions from different transportation modes (source: Visual Capitalist free data).

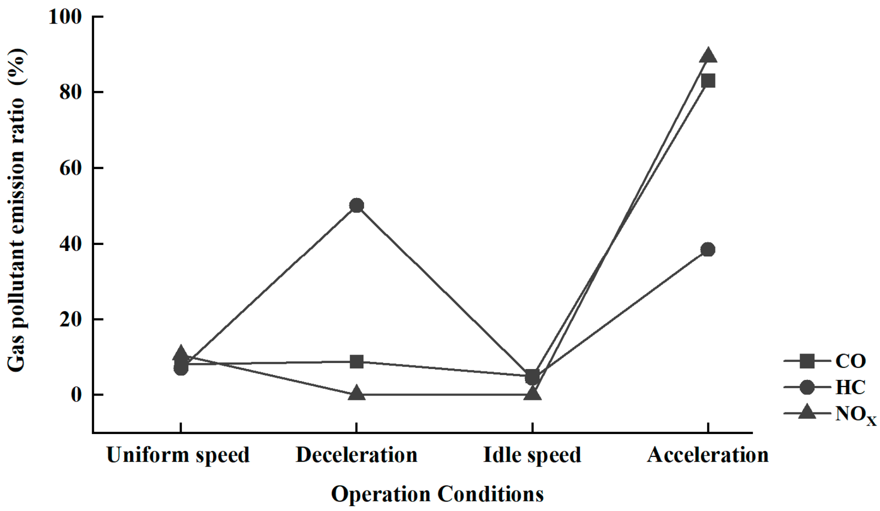

Figure 4. Ratio of exhaust emissions under different operation conditions (adapted from Fan et al. [29]).

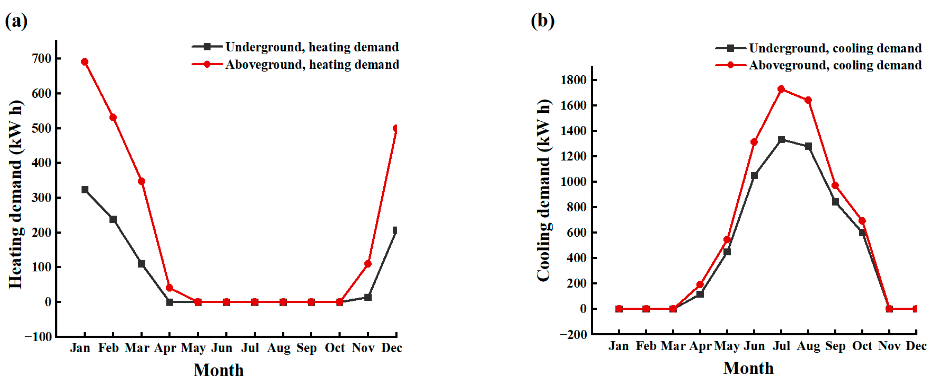

Figure 5. (**a**) Heating demand comparison regarding residential buildings; (**b**) cooling demand comparison regarding residential buildings (adapted from Benardos et al. [34]).

2.2.3. Disaster Prevention Value

The use of UUS can reduce earthquake, climate, and war disasters. A survey found that after the 1995 Osaka Kobe earthquake in Japan, buried pipelines sustained less damage than overground infrastructure. However, theoretically, the repair of underground spaces after earthquakes is more expensive than that of overground spaces. Nonetheless, underground spaces can improve the seismic performance of buildings through specific design features, such as foundation improvement techniques, concrete reinforcement, and the installation of isolation layers [36]. During the 2002 Denali Fault earthquake in Alaska, USA, multiple engineering measures proved the excellent performance of the underground seismic design of buildings [37]. Underground spaces can reduce the impact of climate and war disasters. In North America, underground pedestrian walkways are built to ensure the continuation of normal activities in harsh weather conditions. However, natural underground spaces are vulnerable to floods and require artificial construction to enable flood control and resistance capabilities. Japan built an "underground palace" drainage system in 1992 to reduce the occurrence of flood disasters. Countries around the world also focus on civil defense engineering construction. Such countries explore underground space planning and design that consider the needs of both peacetime and wartime in order to satisfy the wartime civil defense needs and improve the underground space utilization. Projects in this context include the Sonnenbau Tunnel in Lucerne, Switzerland, which can accommodate 27,000 people during wartime, as well as Sheshan Street in Wuhan, China and Fuzi Underground Street in Nanjing.

2.3. Potential Value of UUS

The potential value of UUS mainly includes the provision of natural resources and the expansion of the urban capacity. As mentioned earlier, the most valuable underground space resources include groundwater, geomaterials, geothermal energy, and underground space [18]. Groundwater is often an important water source for many cities, and it sometimes also serves as an emergency supply source for surface water. Geomaterials excavated during the development of underground space can be classified and processed to be used as building materials. Geothermal energy, especially shallow geothermal energy, is an excellent substitute for fossil energy; the recycling of shallow geothermal energy can reduce coal usage and exhaust gas pollution. Finally, underground space is an effective means of expanding the urban capacity [38–41].

From the above, it can be seen that the potential value of UUS is enormous, and any underground space has development value. However, due to the limitations of their natural conditions, some underground spaces have low value or are even unsuitable for development [14,42–44]. There are also contradictions and conflicts in the development of different underground space resources [45,46]. For example, the mining of coal inevitably pollutes the nearby underground water resources. In this case, appropriate measures should be sought to address such pollution. The construction of coal mine underground reservoirs to protect groundwater resources has been proposed and proven to be effective [47]. At the same time, the irreversibility of UUS development means that the space cannot be restored to its original state after development. Planning preparation and constraint system design before development and utilization are highly necessary; this may include formulating underground space plan, devising policies for underground space value evaluation, recording underground water use, and establishing underground space use systems [48].

The direct, indirect, and potential values of UUS make it crucial in the process of urban development. In order to fully utilize the resources of UUS, quantitative methods to assess its value are needed. After years of exploration, many fruitful research results have been obtained. The next chapter will discuss the research topics, evaluation objects, and methods of evaluating the value of UUS.

3. Research Review

3.1. Research Topic Analysis

The evolution of the research on UUSVE is closely related to the development of UUS. Its development extends from large-scale buildings' vertical extension to underground complexes and then to underground rail transit systems. The research topics have evolved from an initial focus on economic and comprehensive value to multi-value evaluation research covering potential value, environmental value, disaster prevention value, and social value. Specifically, the changes in the research topic can be divided into four phases, as shown in Figure 6.

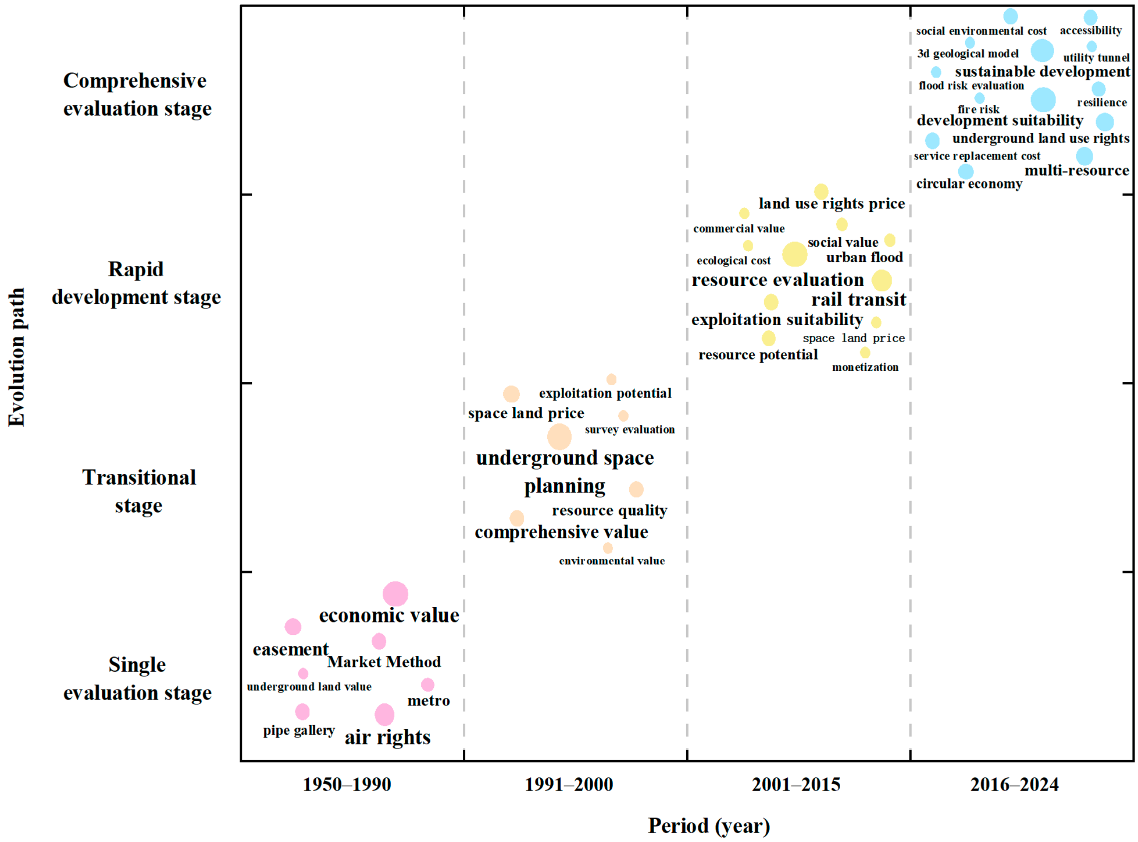

Figure 6. The evolution of UUSVE. (The different colors of the circles represent different periods of UUSVE topics, while the sizes of the circles indicate the level of attention. The larger the circle, the higher the level of attention to the corresponding topic).

3.1.1. Single Evaluation Stage (1950–1990)

The first phase (1950–1990) mainly focused on the evaluation of economic and comprehensive value. Due to differences in management systems, initially Western countries regarded UUS as an easement, and they mainly evaluated the easement value of underground pipelines or metros. For example, they estimated the impact of underground pipelines on the overall value of the land and the amount of compensation required under different uses of underground land [49–51]. Alternatively, it was regarded as a spatial right, and a valuation model was established to calculate stratified land prices [52]. During this period, the development of underground transportation increased, and its economic or comprehensive benefits became the focus of attention. As a major research trend, scholars evaluated the benefits of underground transportation by quantifying the impacts of metros and other underground transportation projects on passengers, traffic conditions, and society [53,54]. These explorations laid a foundation for the research of UUSVE.

3.1.2. Transitional Stage (1991–2000)

The second phase (1991–2000) saw research that shifted from a singular focus to a multifaceted approach, taking into account economic, integrated, environmental, and potential values. By the end of the 20th century, many developed nations had accumulated substantial experience in UUS development, viewing UUS planning as an integral part of land use planning. Methods were proposed to assess the impact of underground buildings on the environment [55]. Notably, after the occurrence of underground fires in Japan, the construction of underground streets was restricted, leading to higher-quality UUS design. However, due to the construction costs, the indoor living comfort of underground buildings is lower. Based on this, Nishi et al. evaluated the indoor environmental value of UUS by investigating residents' willingness to pay for the environmental remediation of UUS [56]. Furthermore, with the increase in the number of UUS developments, the evaluation of its potential value became crucial. This was primarily achieved by identifying areas with the highest UUS development potential [42] or considering UUS resource quality to determine its subarea use and construction technologies [14], thus providing a decision-making basis for UUS development.

3.1.3. Rapid Development Stage (2001–2010)

The third phase (2001–2010) was the period during which the research content became more abundant, leading to a significant increase in research output. The economic value of UUS continued to be highly relevant. However, with the emergence of the negative effects of UUS usage, such as floods, fires, explosions, earthquakes, etc., the evaluation of UUS's disaster prevention value became important, and the urban flood was an important target [57]. Meanwhile, many developing countries entered a period of increased underground rail transit construction, resulting in a large number of research studies on the evaluation of rail transit's economic, social, environmental and comprehensive value. The monetization of unquantifiable social and environmental value provided new ideas for indirect evaluation [58]. Additionally, due to UUS's blind exploitation leading to land resource waste, the importance of evaluating its potential value increased. This mainly involved establishing an evaluation index system and assigning index weights to select appropriate evaluation models to assess UUS' development suitability, underground resource potential, etc.

3.1.4. Comprehensive Evaluation Stage (2011–2024)

The fourth phase (2011–2024) is ongoing and encompasses the comprehensive study of UUSVE, covering various aspects of the field. The utilization rate of UUS in countries around the world, especially in developing countries, is rapidly increasing. India is building extensive subway and road infrastructure, Brazil is rapidly promoting underground project development, the Arab region is committed to building urban transportation systems [16], and China's subway construction speed is growing rapidly. At this point, the international community has accumulated a wealth of experience and many academic achievements in UUS development, gradually emphasizing its sustainable use [59]. In terms of economic value evaluation, a large number of profitable UUS projects involve the calculation of land use rights prices, including metros, underground commercial spaces, and underground parking lots [60,61]. In terms of indirect value assessment, accessibility has been introduced into the social value of UUS [62]. The focus on assessing the potential value of UUS is steadily increasing, with some scholars seeking to establish procedures to assess the sustainability of UUS [63]. In the realm of sustainability assessment, the resilience of UUS has garnered significant attention and importance [64–66]. The circular economy serves as a practical framework for sustainable concepts, and urban underground space plays a pivotal role in supporting its implementation. Evaluating the effectiveness of the circular economy has also captured the interest among researchers. As studies progress, scholars observe that while traditional UUSVE is relatively well-established, different evaluation methods serve distinct purposes. There is a lack of comprehensive assessments that integrate various types of value, thereby failing to provide managers with comprehensive information. Consequently, a multi-resource evaluation approach has been proposed as a crucial method to combine various types of value [38,46].

Overall, UUSVE is closely linked to the concept of urban sustainable development. Whether from an economic, non-economic, or potential economic perspective, the significance of urban sustainable development compels managers and users to plan and utilize UUS judiciously.

3.2. Evaluation Objects

The rapid development of UUS development technology has led to a variety of UUS uses, such as underground (UG) commerce, residences, transportation, storage, industry, infrastructure, and defense (refer to Table 3). Different types of evaluation for UUS serve distinct purposes, and the objects being evaluated under different criteria also vary (Figure 7). This section primarily outlines the evaluation objects and related research content of regarding the aforementioned uses of UUS.

Table 3. Real and potential utilization/functions of UUS in different countries (adapted from Lin et al. [2,27,67–71]).

Country \ Utilization	Commerce	Residence	Transport	Storage	Industry	Infrastructure	Defense
China	UG shopping facilities, UG malls, etc.	Hotels, basements, etc.	Subways, pedestrian systems, parking lots, UG roads/ expressways, etc.	Gold, oil storage, etc.	Exploitation of mineral and water resources, etc.	Utility tunnels, Multipurpose utility tunnels (MUTs), etc.	Shelters, civil air defense, etc.
Singapore	UG malls, etc.	Basements, etc.	Metros, expressways, parking lots, roads, etc.	Oil, hydrocarbon product storage, UG ammunition facilities, etc.	Extraction of water resources and building materials, etc.	MUTs, data centers, energy centers, sewage systems, electrical cables, etc.	Arsenals, bomb shelters, etc.
Japan	Semi-UG shopping malls, UG shopping malls, commercial basements, etc.	Super-basements, etc.	UG roads/ expressways, pedestrian systems, parking lots, UG passages, roads, metros, etc.	Food storage, commodity storage, nuclear waste material storage, oil and gas storage tanks, etc.	Exploitation of oil and natural gas, etc.	MUTs, water drainage systems, electrical supply lines, transformer stations, sewage treatment plants, plazas, museums, cinemas, etc.	Disaster Preparedness centers, earthquake/ cosmic ray observation stations, etc.
Britain	UG commercial street, shop, bookstore, etc.	Basements, hotel, UG home, etc.	Railways, pipeline, etc.	Wine cellar, UG ammunition depot, gold storage, hydrogen storage, etc.	Exploitation of coal, iron ore, oil, and natural gas, etc.	MUTs, UG drainage systems, museums, etc.	Bomb shelters, caves, UG cities, etc.
France	UG shops, UG commercial streets, etc.	Basements, etc.	UG roads/ expressways, tunnels, subways, parking, etc.	Hydrogen storage, nuclear waste material storage, oil storage, etc.	Exploitation of iron ore, bauxite, uranium ore, etc.	MUTs, sewer museums, gas pipelines, cables, catacombs, plazas, libraries, museums, etc.	Shelters, etc.

Table 3. *Cont.*

Utilization / Country	Commerce	Residence	Transport	Storage	Industry	Infrastructure	Defense
Germany	UG shops, UG commercial streets, cinemas, etc.	UG worker dormitories, etc.	Subway, parking lots, UG garages, etc.	CO_2, gas, radioactive waste storage, etc.	Exploitation of coal, potassium salt, etc.	Utility tunnels, MUTs, art museums, music halls, etc.	Rocket factories, UG cities, etc.
Sweden	UG shops, UG streets, etc.	Hotels, etc.	Railways, parking lots, railway stations, etc.	UG foodstuff refrigerators, gas, foods storage, etc.	Exploitation of water, mineral resources, etc.	Sewage-treatment plants, UG nuclear power plants, music halls, etc.	Civil defense posts, shelters, etc.
Norway	UG shops, UG commercial streets, basement restaurants, etc.	UG towns, etc.	Subways, tunnels, etc.	Refrigerators, carbon dioxide storage, etc.	Exploitation of minerals, metal resources, etc.	Sewage-treatment plants, cables, theaters, libraries, semi-UG planetariums, pools, gymnasiums, etc.	shelters, etc.
Finland	UG shopping mall, UG commercial street, etc.	Basements, etc.	Subways, parking lots, etc.	Nuclear waste storage, fertilizer storage, food storage, coal storage, etc.	Exploitation of metals minerals, fossil oil, natural gas, etc.	Water supply systems, sewage treatment plants, pools, amusement parks, etc.	Shelters, UG castles, etc.
Russia	UG shopping malls, UG commercial streets, etc.	Basements, etc.	Subways, pedestrian systems, rapid rail, etc.	Cabins, nuclear weapon storage, gas storage, oil depots, etc.	Exploitation of fossil oil, natural gas, coal, etc.	MUTs, drainage systems, libraries, memorial halls, museums, etc.	Command centers, UG city, air-raid shelters, etc.
America	Shopping malls, retail, etc.	Soil-covered buildings, UG bunkers, etc.	Metro, roads/ expressways, pedestrian systems, freight tunnels, tram loops, freight lanes, etc.	UG general warehouses, gold storage, etc.	Exploitation of fossil oil, natural gas, coal, etc.	Water supply systems, sewage treatment systems, MUTs, plazas, libraries, etc.	Operations centers, anti-aircraft cabins, etc.
Canada	UG super-markets, offices, cinemas, etc.	UG homes, hotels, UG towns, etc.	Pedestrian systems, metro, expressways, parking spaces, etc.	Nuclear waste storage, natural gas storage, oil storage, etc.	Exploitation of oil sand, natural gas, etc.	MUTs, transmission lines, laboratories, libraries, banks, etc.	Bomb shelters, UG cities, etc.
Australia	Shops, bars, bookstores, etc.	UG towns, hotels, etc.	Subways, parking lots, etc.	Wine cellars, fossil fuel storage, compressed air storage, etc.	Exploitation of coal, bauxite resource, etc.	Garbage collection tube system, rainwater and flood management system, churches, casinos, etc.	Bomb shelters, etc.
New Zealand	Art centers, retail, bars, etc.	Hotels, basements, etc.	Subways, tunnels, parking lots, roads, etc.	Wine cellars, oil, gas, chemical storage, goods storage, etc.	Exploitation of gold ore, iron mining, etc.	Sewer lines, museums, libraries, UG congress hall, etc.	Bomb shelters, etc.

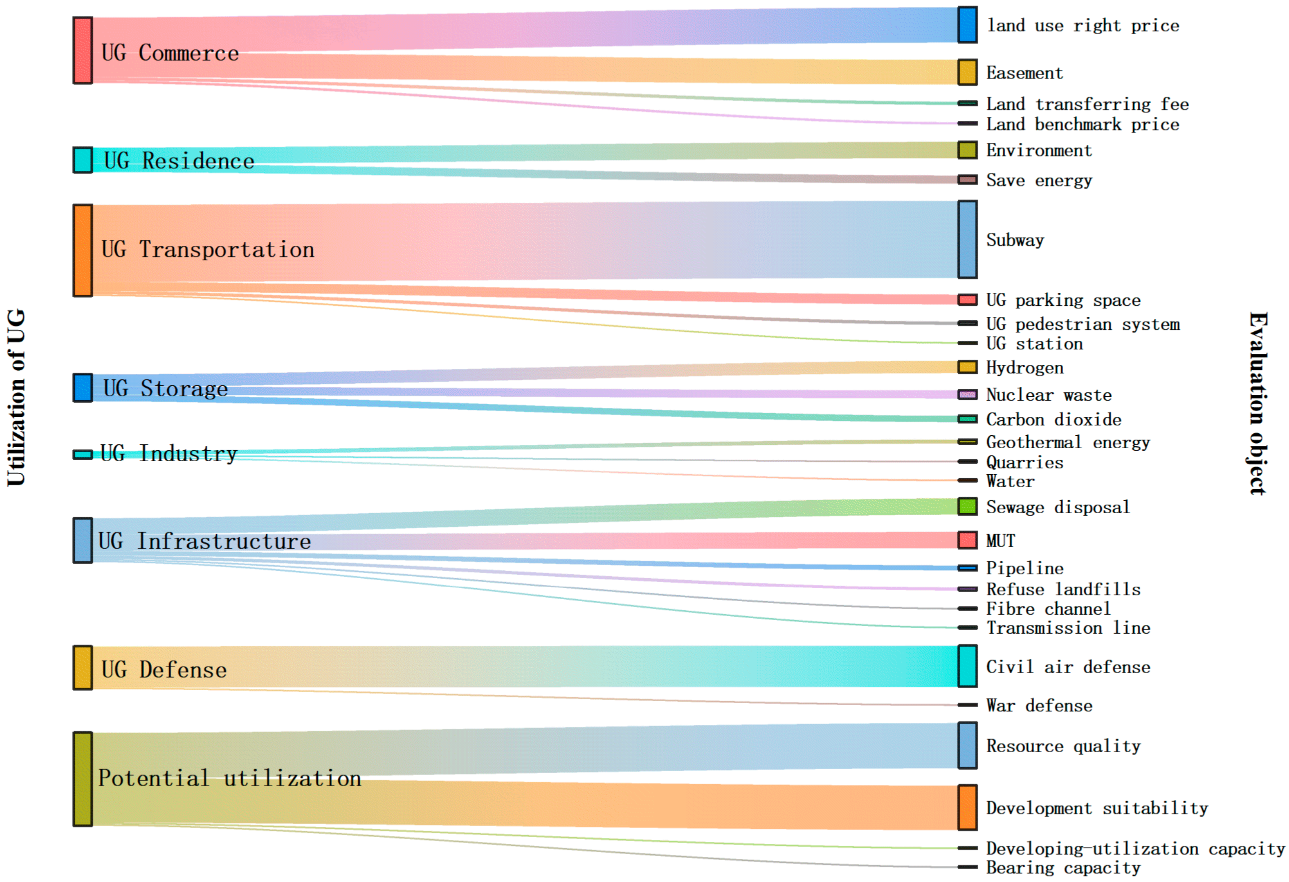

Figure 7. Evaluation objects of UUSV.

3.2.1. UG Commerce

The evaluation object of UG commerce is primarily the price of underground space usage rights, which represents the total present value of future underground space rental. The right to use underground space entails the privilege of utilizing and deriving benefits from the space within a specific three-dimensional range below the surface, while the rent for underground space pertains to the fees levied for the right to utilize the underground space. UG complexes, shops, and commercial venues linked to UG tracks all fall within the concept of UG commerce. Traditionally, it has been assumed that the price of underground space usage rights is lower than that of overground space [72]. However, in reality, some urban centers possess significant commercial value at the underground ground floor, making the price of underground space usage rights an area of considerable research interest.

Different countries have varying terms to describe the right to use underground space. From a legal standpoint, the concepts of the "right to use construction land" in China's Property Law, "easement" in the Swiss Civil Code, "superficies" in the German Civil Code, and "space ground right" in Taiwan have been introduced. China's Mass Rapid Transit Law encompasses both underground and surface land use rights. Conversely, the "distinguishing right above ground" in Japanese civil law pertains solely to the use of underground space. Academically, terms such as "land use right price", "land transferring fee", "land benchmark price", and "easement" all refer to land use rights for UUS [73–78]. The evaluation of UUS land use rights has historically posed challenges due to the differing land systems, yet it remains a topic associated with a significant market demand and research interest. Nonetheless, there has been a recent decline in the popularity of related research.

3.2.2. UG Residences

UG residences are spaces that are either partially or entirely situated below the surface and are used for residential purposes. In comparison to overground residences, UG residences boast lower energy consumption, heightened disaster resistance, and reduced noise levels, rendering this a crucial application of underground space [79,80]. Historically, regions facing severe land scarcities or challenging surface climate conditions have actively employed UUS to fulfil residential needs. The ongoing advancements in building technology and materials have introduced sustainable development prerequisites for underground residential constructions. For instance, the "Rhodiola Hut" on the UK's North Norfolk Coast exemplifies a semi-underground residential building that possesses an environmentally friendly design, energy efficiency, temperature control capabilities, and a rainwater collection system [81]. To promote the sustainable development of underground housing, considerations such as price, quality, and energy efficiency are paramount from the user's perspective. While some scholars have assessed the internal environmental benefits of underground housing and compared the energy consumption of overground and underground structures, the aspect of pricing is often overlooked, likely due to the limited development of underground housing in the real estate market [34,56,82]. Developers, on the other hand, must evaluate the feasibility of underground residential projects. Ming et al.'s survey of potential users sought to assess the risks associated with underground residential ventures, offering valuable insights for developers in this sector [80].

3.2.3. UG Transportation

The origins of UG transportation can be traced back to the London metro in the 1860s. Since then, various UG transport facilities, such as parking spaces, pedestrian systems, and stations, have emerged. Presently, more than 50 countries worldwide possess subway systems, and many nations already have developed UG rail transit networks. For instance, Singapore's Mass Rapid Transit System (MRT), recognized as one of the most advanced public transportation systems globally, operates with 113 subway stations and recorded the highest daily passenger volume in 2019, serving 3.5 million individuals [83].

The construction of UG transportation entails high costs, irreversibility in terms of development, and substantial volumes. Extensive preliminary research is essential to maximize the project's developmental benefits. In associated studies, the societal, environmental, and economic impacts of subway openings are typically assessed, alongside the pricing of underground parking spaces [84–86]. UG garages commonly serve as ancillary facilities for commercial and residential purposes, transferring ownership alongside commercial and residential properties, so there is a high demand for transfer price evaluation. Moreover, being enclosed spaces with high levels of pedestrian traffic, there is a need to evaluate their disaster prevention and ventilation capabilities [87]. While there is existing research in this area, it remains limited in quantity and requires further enhancement in the future.

3.2.4. UG Storage

UG storage represents a significant innovation in utilizing subterranean spaces. Initially, these spaces were primarily used for the storage of grains, vegetables, or wine; however, they have evolved into valuable assets for waste management. Carbon dioxide, nuclear waste, and other challenging substances can be effectively addressed through underground storage solutions. Numerous countries globally have adopted UG storage technologies for carbon dioxide and nuclear waste to tackle these persistent issues. Ongoing studies aim to develop diverse technologies for the sealing of carbon dioxide and nuclear waste underground, to assess the economic and technical viability of storage projects, to determine the storage capacity of underground spaces, and to minimize their impacts on the surface environment [88–91]. Furthermore, underground spaces serve as ideal repositories for natural gas, oil, gold, and other resources [92,93]. Evaluating the sealing capabilities of underground gas storage and the water-tightness of sealed underground oil storage is crucial in ensuring their safe functioning [94,95]. Additionally, underground reservoirs facilitate the storage of mine water, safeguarding the water resources of disused mines [96].

The potential applications of underground storage spaces are vast, yet certain risks, such as the impact of underground nuclear waste on subterranean resources, warrant further investigation. To address these challenges, continued research efforts are required to enhance our understanding and mitigate potential risks effectively.

3.2.5. UG Industry

An important aspect of UG industry involves the exploitation of underground space resources. These resources pertain to materials that can be developed and utilized within specific technical parameters in naturally occurring or artificially constructed spaces beneath the Earth's surface [97]. They primarily encompass water resources, mineral deposits, geothermal energy, and underground spaces. Underground space resources are characterized by high development costs, vertical layer utilization, irreversibility in terms of development, and significant externalities [98]. Consequently, conducting thorough evaluations of underground space resources before their exploitation and utilization is crucial. For instance, studies have examined the economic value of groundwater extraction [99–102] and the environmental benefits derived from geothermal energy utilization [103,104]. These analyses offer valuable insights that can guide the sustainable utilization of underground space resources.

3.2.6. UG Infrastructure

UG infrastructure encompasses both public facilities (such as libraries, gymnasiums, museums, etc.) and municipal facilities (such as MUTs, sewage disposal, refuse landfills, fiber channels, transmission lines, etc.). Among these, MUTs garner significant attention. Evolving from the traditional pipe gallery, which primarily accommodates water pipes and cables separately, the MUT integrates nearly all municipal facilities underground to establish an extensive UG pipeline system. The construction of such MUTs addresses the escalating infrastructure demands and the public's expectations for an enhanced urban ground environment. The implementation of such projects would not only foster sustainable city development but also elevate the standard of urban governance [6,69,105–108].

Given the substantial workload and financial investment involved, evaluating the construction benefits of these projects is imperative. Research in this area predominantly focuses on economic and comprehensive value assessments. As the implementation of MUT projects gains momentum, the assessment of the comprehensive value of MUTs is expected to emerge as a new focal point in research endeavors.

3.2.7. UG Defense

UG defense plays a crucial role in ensuring national security and the safety of both lives and property. These facilities include two categories, UG civil defense engineering and UG fortifications, each with its own design and function requirements; together, they constitute an important component of the national defense system. Civil defense engineering mainly refers to UG facilities that provide shelter and protection for personnel and materials during war or natural disasters, including UG shelters, UG passages, combat command centers, etc. [109]. UG fortifications focus on military needs, including military factories and warehouses. Military factories and warehouses are important types of infrastructure to ensure the smooth progress of military operations. They can produce military supplies and store them, providing sustained and stable support to the military. The construction of UG defense facilities may have a certain impact on the environment. Therefore, before development, the geological conditions, the safety of the facilities, the construction costs, and the social benefits should be evaluated, and the performance of the facilities must also be tested before they are operated [110–112].

3.2.8. Potential Utilization

The potential use of UUS depends on the type and quantity of underground space resources, so the potential capacity of underground space needs to be evaluated. This can help land planners to carry out scientific underground space development and utilization planning. The research content in this regard includes the suitability of underground space resource development, the carrying capacity of underground space resources, and the comprehensive quality of underground space. Specifically, the evaluation of the development suitability is based on the geological and environmental characteristics and socio-economic conditions indicators, and the evaluation results indicate the appropriate development intensity of an underground space [43]. Carrying capacity assessment involves a comprehensive evaluation of the quantity and quality of underground space resources to determine the resource endowment and supply capacity of the underground space. The evaluation results indicate the maximum development capacity of the underground space resources [44]. The comprehensive quality assessment obtains the comprehensive quality level by overlaying the vector data of various influencing factors and the quality of the underground space resources, reflecting the difficulty and potential of underground space development and utilization under certain technical conditions [113].

UUSVE is essentially based on the evaluation objects mentioned above. After a detailed description of the evaluation objects, the corresponding evaluation methods will be discussed in the next section.

3.3. Evaluation Methods

UUSVE is an important means to realize UUSV. With the expansion of UUS development, it is being gradually expanded into a multi-value evaluation system (Figure 8).

3.3.1. Direct Valuation Method

Underground space resources can generate economic value, and the methods used to evaluate this vary depending on the type of resource.

To some extent, the economic evaluation of UG commerce, UG transport, etc., can continue to use traditional land valuation methods, but there are certain limitations [114]. Rhodes R M, Gela G et al. suggested that the compensation method and boundary element method can be used as auxiliary valuation methods [50,115]. Alternatively, based on the combination of two or more traditional valuation methods, an underground space land use right valuation model can be established by introducing spatial allocation theory, the Kriging interpolation method, etc. [116,117]. In addition, UUS can be regarded as a public good, and the price of underground space use rights can be roughly evaluated through market research or the observation of its socially recognized value [118,119]. However, the workload required in this task is large and the results are not sufficiently reliable. Other methods such as the shadow price method or feature price method are more flexible and intuitive and are also suitable for calculating the land use rights price, but they require a large amount of sample data, which can be difficult to collect systematically. This may result in missing data and significant errors [120,121]. Spatial Design Network Analysis (sDNA) has lower data requirements and is based on geographic information processing software and Python, used to analyze the road network's accessibility; this method has high accuracy in calculating the rail transit, land value, and land use potential [122].

UG storage projects generally require investment funding support, and investors need to understand the profitability of the project. Therefore, the economic evaluation of UG storage facilities is crucial, and related research, especially the economic evaluation of UG natural gas storage facilities, is quite extensive [123,124]. The most commonly used economic evaluation method is the Discounted Cash Flow Method (DCF), which considers the capital return generated after the future expected income is used to pay the development and operating costs. The discounted capital return at the evaluation point represents the corresponding economic value [125]. Due to the seasonal nature of the natural gas demand, there are two types of DCF. One calculates the intrinsic value, which is the difference between the cost of purchasing natural gas in summer and the selling price of natural gas in the winter. The other calculates the extrinsic value, showing that storage facilities can be used multiple times to increase the value. In general, the first type of value is suitable for projects with shorter usage times, while the second type of value is suitable for projects with more extended usage times [126].

UG water resources are scarce and therefore have economic value. Many countries around the world have published relevant research, mainly focusing on groundwater quality and pollution [127]. The economic value of groundwater resources can be evaluated using methods such as the Contingent Valuation Method (CVM), the Production Function Approach (PFA), and fuzzy mathematical model. The CVM directly examines the willingness of respondents to pay for goods or services in a hypothetical market through a questionnaire survey and uses this as a value measurement [128]. This method has certain limitations, as citizens in different regions have different income levels, resulting in significant differences in the payment prices that can be given. Generally, regions with higher income levels will exhibit greater willingness to pay. However, due to the complexity of groundwater resource assessment, this method is currently relatively applicable and can utilize regression models to reduce or eliminate bias among the respondents when analyzing the data [129]. The PFA is used to estimate the value of industrial water and drinking water quality, and it was employed by Martínez-Paz to calculate the cost of groundwater resources [130]. However, the PFA itself cannot directly evaluate the cost of groundwater resources; rather, it describes the functional relationship between the input and output of production factors, making it relatively cumbersome to use. The CVM and PFA are derived from the overground water pricing method, ignoring the coupling effect between groundwater and other underground space resources, which makes traditional mathematical models difficult to apply. Fuzzy mathematical models can consider environmental, social, economic and other indicators and their corresponding importance. Although the application effect is not ideal, it is indeed a meaningful solution that needs further improvement in the future [131].

The research on the economic evaluation of UG infrastructure is mainly focused on the MUT. As this type of project involves investment, the evaluation focuses on an economic cost analysis, and the most commonly used method is cost benefit analysis. Although the evaluation is based on economic value, scholars also consider external benefits when selecting the evaluation indicators [108,132,133]. In addition, there are relatively few economic evaluations in the context of UG defense and UG residences.

3.3.2. Indirect Valuation Method

UUS with different uses will generate different types of indirect value.

For UG transport, UG infrastructure, and UG storage, the indirect value of UUS cannot be assessed using the above economic evaluation methods due to the lack of a tangible income or output. The "National Economic Comprehensive Evaluation Method" in the Soviet Union's "Infrastructure Investment Economic Benefit Standard Law" (approved in 1980) considers converting the indirect value of the subway into data such as the time reduction value, traffic accident rate, and environmental improvement rate, achieving the quantification of its indirect value. The "with or without comparison method" and "overground and underground comparison method" were proposed based on this method. However, their indicator selection ignores the negative externality value [78]. In response to this, scholars have adopted the Travel Cost Method (TCM), Service Replacement Cost Method (SRCM), and Contingent Valuation Method (CVM) to incorporate both positive and negative externalities into the indicator system. The TCM uses costs such as transportation and tourism expenses to calculate the economic benefits or losses that environmental quality changes bring to tourist destinations [134]. The SRCM calculates the externality development value of underground space by using the cost paid or the economic losses borne by citizens in obtaining underground space services [135]. The CVM directly investigates citizens' willingness to pay for underground space services and the cost of the investigation is relatively high. Therefore, scholars often use the transfer of benefits (BTM) method to transfer the value assessment results of the studied area (research site) to the study area (decision-making site) so as to obtain the value of the decision-making site, reducing the time and the cost of investigation. Based on this method, the cost of underground facilities can be estimated by using the costs of equivalent facilities above the ground, but the monetization of the advantage of underground facilities relative to aboveground space should also be considered [136,137]. Among these methods, the SRCM is the latest and most widely used method. It can provide an evaluation framework for the external value of UUS based on the perspective of urban resilience or sustainable development [78,108,138,139].

For UG residences, their environmental value is derived from energy conservation. Benardos et al. used environmental system simulation software to calculate and compare the energy consumption of overground and underground residences. For UG industry, the environmental value of geothermal energy extraction is of great concern, and the evaluation content includes both positive and negative values. Initially, researchers only focused on positive values because the utilization of geothermal energy has indeed brought many benefits [140]. As its negative impacts become increasingly apparent, such as water pollution and air pollution, scholars have begun to evaluate its negative value using both qualitative and quantitative methods. Qualitative evaluation mainly analyzes the impact of geothermal energy development on various aspects of the environment, such as groundwater, which has a certain degree of subjectivity [141–143]. Quantitative evaluation combines other data for analysis, such as using underground, surface, and atmospheric environmental risk data or market survey data on user willingness to pay [103,144]. This method has high data requirements and is complex to perform, requiring further research. However, overall, it provides a good research demonstration.

There is essentially no relevant research on the evaluation of the external value of UG commerce and UG defense.

3.3.3. Potential Valuation Method

The assessment of the potential value of UUS serves as a foundation for the scientific planning and orderly utilization of underground space resources. It considers factors such as the carrying capacity, geological suitability, and overall quality to ensure the optimal utilization of underground spaces. The process of evaluating the potential value involves selecting evaluation indicators, assigning indicator weights, and conducting a comprehensive evaluation. The indicators of the carrying capacity should reflect the matching between the underground space resources and the environment. The indicators of geological suitability focus on the regional geology, hydrogeology, and engineering geology. Meanwhile, the comprehensive quality evaluation index should consider both the geological conditions and socioeconomic situation. The earliest methods used to assign indicator weights were the expert scoring method and Analytic Hierarchy Process (AHP), which simplify complex decision-making problems into an ordered hierarchical structure [145]. However, these two methods require a large amount of historical data and have strong subjectivity. On the other hand, the entropy weight method can effectively reduce the influence of subjective factors by starting with the amount of information between indicators. However, this method tends to overlook the impact of indicator parameter variability on the overall weights of indicators. This issue can be addressed by introducing the concept of variable weights [146]. The trapezoidal fuzzy number weighting method reflects the uncertainty in expert evaluation and does not require historical data. It is also simple to operate [147]. These methods, combined with traditional subjective weighting methods, are applied to assign indicator weights. In terms of comprehensive evaluation, fuzzy comprehensive evaluation and the multi-objective linear weighted function method are the traditional methods. The fuzzy comprehensive evaluation method has wide applicability but is not able to handle interdependence relationships. The multi-objective linear weighted function method is subjective and computationally intensive. The combination of traditional methods with the Analytic Hierarchy Process or digital technologies can address these issues [64]. Such methods include the fuzzy AHP, GIS fuzzy comprehensive evaluation, the multi-level Grey Evaluation, etc. [148,149]. In addition, with the development of artificial intelligence, algorithms such as the Harmony Search Algorithm (HAS), Artificial Bee Colony Algorithm (ABC), and Self-Organizing Map (SOM) have been applied in geological hazard risk or geological quality assessment. They have the potential to improve the valuation models [150–152]. In the future, computer technology can be introduced on this basis to address the limitations of the existing evaluation models.

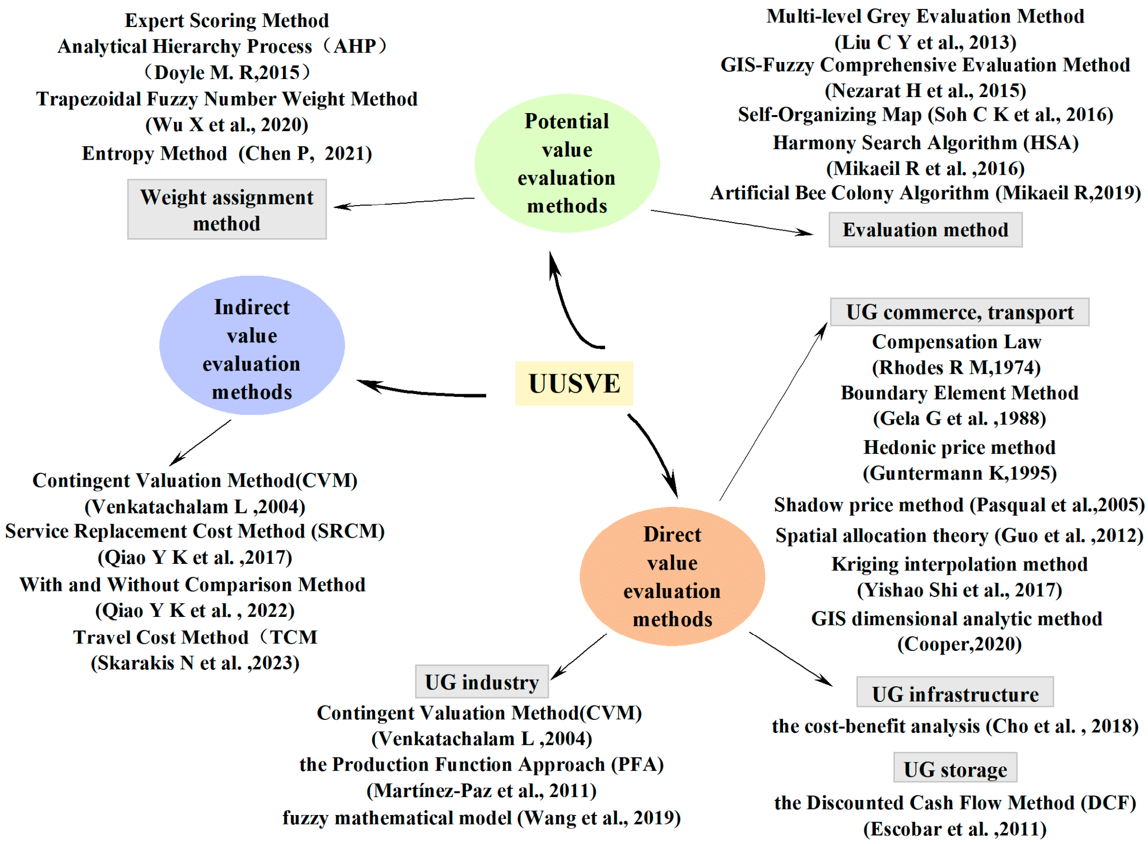

Figure 8. Current status of UUSVE.

4. Development Trends of UUSVE

After examining the current status of UUSVE and integrating the requirements of future urban development, it is anticipated that the following trends will emerge.

4.1. The Evaluation Scope Will Be Extended to Multiple Scenarios and Domains

The abundant resources and enormous development potential of underground spaces are gradually attracting attention in urban construction, giving rise to various methods of utilizing underground space. The research on UUSVE should not only consider real estate development scenarios, but also expand to government management scenarios. With the prominent environmental advantages of UUS, UG storage and MUTs will become important uses of underground space in the future [69,153]. Evaluating the operational efficiency of these systems can meet the needs of the government in ensuring the efficient operation of urban facilities. Furthermore, the recycling of groundwater, the extraction of geothermal energy, and the utilization of geological materials support the transition of underground spaces towards a greener, more ecological, and more sustainable development model [63]. Therefore, the scope of UUSVE will involve more fields in the future, including ecology, energy engineering, geology, etc., to fully realize UUSV. Overall, UUSVE will keep pace with the changes in UUS utilization orientation, appropriately expand the scope of application, and meet the demands of practical assessments.

4.2. Economic Value Evaluation Will Attempt to Incorporate Automatic Evaluation

From the existing results of economic value assessments, the main objects of such assessment for UUS are the prices of UG land use rights and UG water resources. The purpose of the assessment is to determine the value of UG resources and regulate their utilization. Traditional overground resource assessment methods can, to some extent, still be used, but there are many cases in which they are not applicable, creating obstacles in the valuation process [114]. The development of 3D cadaster and UG resource databases provides solutions to these issues. In 1998, the FIG 7.1 working group published the document "Cadastre 2014" [154], which encouraged the introduction of the dimension of underground space into cadasters. Countries such as the Netherlands, China, Australia, Sweden, and Israel, have attempted to establish 3D cadaster databases, incorporating UG land's physical attributes and legal objects into land management systems [155–161]. This integration of information on overground, surface, and UG land resources provides a basis for the identification of UG asset rights, facilitating the acquisition of more comprehensive and reliable UG land resource data.

Moreover, UG water resource databases are relatively well established in many countries. For example, the United States' National Water Information System provides groundwater data for all states, and China's Water Resources and Environmental Geology Confidence Platform includes 10,168 national-level groundwater monitoring stations [162]. With the support of such rich data resources, future economic value assessments of underground spaces may no longer simply involve the straightforward application of traditional direct assessment methods. Instead, building on existing assessment methods and practical experience, there may be attempts to establish automated valuation models. These models would input the necessary data to calculate corresponding underground resource prices, enhancing the assessment efficiency and accuracy, and better supporting decision making regarding the development and utilization of underground space resources.

4.3. Indirect Value Evaluation Will Tend towards Integration

As the importance of UUS continues to be highlighted, the assessment of their indirect value becomes increasingly important. In the future, indirect value assessment will tend towards comprehensiveness, i.e., the comprehensive evaluation of the indirect value of UUS. For urban managers, if the social order is chaotic, the environment is poor, and the disaster prevention capabilities are weak, the economic functions cannot be maximized. Therefore, there is a need for a holistic understanding of indirect value, which requires the consideration of both the positive and negative impacts of underground space development [163,164]. Furthermore, with the continuing implementation of the ecological civilization concept, future assessments will pay more attention to the sustainable development of UUS. This not only means increasing the consideration of environmental protection and ecological balance in the assessment process but also emphasizes the need to focus more on long-term benefits and overall efficiency in urban planning and underground space development, avoiding short-sightedness and excessive exploitation [38].

4.4. Potential Value Evaluation Will Move towards Diversification and Intelligence

UUS is a complex and multifunctional system that includes functions such as commercial activities, transportation, infrastructure, and various types of resources, including underground space, groundwater, geological materials, and geothermal energy [39]. Therefore, a diversified assessment will comprehensively consider the underground space resources and their interactions and impacts [46]. Intelligence is reflected in the efficient and accurate assessment of underground space resources through advanced technologies such as big data and artificial intelligence [165,166]. By collecting and analyzing a large amount of underground space data, including geological structures, spatial layouts, and usage conditions, suitable assessment models can be established to quantitatively analyze the potential value of underground space. Intelligent assessment can not only improve the efficiency and accuracy of assessments but also enable the dynamic monitoring and forecasting of underground space resources, providing more timely and effective support for decision-making [167].

5. Conclusions and Suggestions

In summary, significant progress has been made in UUSVE work, and many important research results have been achieved. This paper focuses on the evaluation methods of various types of UUSV, reviews the relevant literature, and draws the following conclusions.

First, UUSV is composed of economic value, social value, environmental value, disaster prevention value, and potential value. Among them, economic value is the direct value of underground space development, while social, environmental, and disaster prevention values are types of indirect value. Direct value and indirect value together constitute the actual value, which, along with potential value, forms the value of an urban underground space. The uses of UUS include UG commerce, residences, transportation, storage, industry, infrastructure, and defense. The assessment objects encompass the prices of underground space usage rights, the underground space environment, and the carrying capacity, among others. However, existing research results on the evaluation of usage rights prices and indirect value for UG commerce and residences do not meet the needs of practical implementation. Additionally, there is a lack of evaluation of the economic value and indirect value of UG defense.

Second, there is still a significant research gap regarding the evaluation of the economic value of UUS. Regarding the valuation of UUS use rights, both traditional and improved assessment methods lack sufficient scientific rigor and universality. They encounter obstacles whenever there are changes in commercial or residential projects, thus requiring further research. In terms of evaluating the economic value of UG storage and UG infrastructure, the methods proposed in the current research are limited, lacking multiple options for selection and comparison, making it difficult to scientifically assess their accuracy. With the support of 3D cadastral mapping, various UG resource databases, and artificial intelligence technology, the economic value assessment of UUS is expected to transition towards automated valuation. In comparison, there are multiple choices and strong universality in the indirect value assessment methods for UUS, which have been proven to be effective and applicable in many studies. Furthermore, the indirect value of UUS is closely related to urban sustainable development. Indirect value assessment, as a decision-making tool supporting urban sustainable development, is gradually moving towards integration.

Third, the evaluation of potential value is a current and future research focus; it mainly includes weight assignment and evaluation model construction. The AHP and expert scoring method are traditional weight assignment methods, while the entropy weight method and trapezoidal fuzzy number weighting method have been proposed to improve upon the traditional methods. The fuzzy comprehensive evaluation model and multi-objective linear weighted function model are traditional value evaluation models, while the hierarchical fuzzy evaluation model, GIS fuzzy comprehensive evaluation model, and multi-level grey evaluation model are improved evaluation models. With the rapid development of big data and artificial intelligence technologies, an increasing number of studies are combining geographic information technology with information technology to utilize geographic information processing software, artificial intelligence, machine learning, etc., for the evaluation of the potential value of urban underground space.

Previous researchers have made significant contributions to the study of UUSVE. However, in the digital and information age, traditional assessment methods should be updated, expanded to other popular fields, and developed towards multidisciplinary applications. In the future, the focus of this field will include the following aspects.

First, it is necessary to strengthen the research on the shortcomings of UUSVE, enhancing the valuation methods for UUS use rights, such as those for UG commerce, residences, and transportation. By analyzing a large number of existing cases of UUS use rights valuation and combining relevant literature research, suitable methods for UUS use rights valuation can be explored. Issuing standardized documents and usage guidelines for valuation methods can promote the standardization of such assessment methods. Moreover, the assessment of indirect value for UG commerce and defense is equally important. Otherwise, situations may arise in which some defense facilities are considered to have no economic value and are left idle. Academic research support is needed to promote their utilization.

Second, it is necessary to build an evaluation index library and a case library. Electronic resource sharing, as a product of the information age, is also applicable to the UUSVE field. In the assessment of indirect value and potential value, the selection of indicators and the calculation of weights are often involved. Due to the influence of subjective factors, different researchers may choose different indicators for the same study area, leading to the poor comparability of results from different studies. If corresponding index libraries and corresponding weight data by region and type are established, researchers from different periods can refer to them, which would be beneficial in improving the reference value of the research results. Moreover, in economic value assessment, a reference basis for evaluators can be obtained by collecting, organizing, and classifying basic data, evaluation methods, evaluation results, etc., and establishing a case library by region and type. This will enhance the scientific validity of the evaluation results.

Finally, it is necessary to emphasize interdisciplinary collaboration, particularly focusing on the application of machine learning. In recent years, machine learning has been rapidly developed and combined with various disciplines to produce a wealth of innovative results. The application of machine learning to UUSVE poses certain challenges, primarily due to the expertise of researchers, the adaptability of models, and difficulties in data acquisition. Given that data related to indirect value and potential value indicators exhibit the characteristics of big data, machine learning holds significant research potential. However, the level of data acquisition required for economic value assessment is relatively low and its application is not yet well established. In the future, attention should be paid to the application of machine learning in assessing the potential value and indirect value of UUS. Simultaneously, robust data resource support for the application of machine learning can be provided by accelerating the public availability of UUS information, leveraging technologies such as the Internet of Things and artificial intelligence to build a massive, multi-source heterogeneous data platform for underground spaces.

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