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A CRITICAL REVIEW OF THE EXISTING METHODOLOGIES FOR THE ESTIMATION OF THE VALUE OF UNDERGROUND SPACE

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Abstract: Ever since 2020, more than 50% of the world's population has been concentrated in large urban centers. Coupled with the rapidly growing global population, this shift has exacerbated major issues and challenges within modern cities. These problems span environmental, social, transportation, and energy-related concerns that must be addressed to ensure the sustainable development of emerging "mega-cities." One sustainable solution that has gained prominence over the past 30 years is the utilization of Urban Underground Space (UUS). Countries like Singapore and Japan, and cities such as Montreal and Paris, have consistently developed their underground spaces to create metro lines, underground parking lots, and roads to cope with these modern challenges. However, in many other parts of the world, underground projects remain unrealized, often stalled at the decision-making stage. The primary reason for this stagnation is the unfavorable comparison between underground structures and their above-ground counterparts, primarily due to the significantly higher capital costs associated with underground development. However, it is misleading to compare an underground project with an above-ground facility of the same utility and base the decision solely on construction cost estimates. UUS possesses a "hidden" value, often referred to as the indirect value, which represents the monetary value of the indirect benefits that arise from UUS development. This indirect value is frequently overlooked during the decision-making process because it is challenging to quantify in monetary terms. However, if systematically integrated into the decision-making process, the indirect value could allow underground facilities to compete directly with above-ground solutions, making them more attractive investments. Together, the indirect value and direct value constitute the real value of UUS. Consequently, the scope of the current study is to gather and critically evaluate all existing methodologies for estimating the real value, direct value, or indirect value, including losses that may arise from UUS development. To ensure comprehensive coverage of all available techniques, the study utilized the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. The existing methodologies were thoroughly presented, highlighting their strengths and weaknesses, and proposing ways to improve them in the future.

Keywords: Urban Underground Space (UUS), Underground Space Value, Indirect Benefits of UUS, Valuation of Underground Space Benefits, Economics of Underground Space.

1. INTRODUCTION

Urbanization is a well-established worldwide trend that is continually increasing. According to data from the World Bank Group, in 1960, 34% of the world's population lived in urban centers (World Bank Group, Urban Development, 2024). By 2020, this percentage had risen by 22%, with 56% of the world's population residing in large urban areas (World Bank Group, Urban Development, 2024). Coupled with the fact that the global population has increased by more than 159% during this 60-year span, the overall result is a troubling increase in population density in modern cities. As urban areas continuously expand in size, population, and complexity, people, services, and industries compete for the decreasing available urban surface space (Mavrikos and Kaliampakos, 2021). Given the limited availability of surface space, the utilization of subsurface areas has become a necessity in modern urban planning (Papadomarkakis, 2025). The third dimension of a city has constantly proven that it can provide sustainable solutions to all the modern challenges urban centers face.

The primary criticism that most underground projects face, compared to their surface counterparts, is their increased construction cost. Ultimately, this factor often becomes the deciding one (Kaliampakos et al., 2016). Despite the numerous advantages of utilizing underground space, which have been highlighted by many

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researchers over the years (e.g. Barker and Jansson, 1982; Godard and Sterling, 1995; Tareau, 1995; ITA WG15, 1998; ITA WG13, 2004), underground projects are frequently avoided due to their higher capital costs relative to surface solutions. The main reason for this significant capital cost gap is that some of the benefits, particularly environmental ones, provided by underground projects cannot be easily quantified in monetary terms. Comparisons between surface and underground alternatives typically focus solely on construction costs, neglecting the substantial environmental contributions of underground projects. Consequently, the higher initial construction cost of underground structures often makes them a less favorable option (Mavrikos and Kaliampakos, 2021). To ensure the future growth of urban underground space utilization, two critical parameters must be secured (Kaliampakos and Benardos, 2008; Bobylev, 2009; Kaliampakos et al., 2016; Qiao et al., 2017; Mavrikos and Kaliampakos, 2021):

- The creation of a systematic methodology that can estimate the value of underground space, since nowadays it has a zero assigned value, and also
- Incorporate in the estimation process the major environmental benefits of underground projects, something that is often overlooked, because it is difficult to express in monetary terms.

It is imperative to consider the environmental benefits of underground projects during the decision-making process, a factor that can make these projects directly competitive with their surface counterparts. Consequently, the aim of this study is to critically review the existing methodologies proposed for estimating the value of underground space using the established Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. Methodologies will be collected from the Scopus search engine and previous conference proceedings, using specific keywords and phrases. This approach will allow the current literature on the subject to be gathered and organized, providing a comprehensive overview. The study will also discuss the strengths and weaknesses of each proposed method, paving the way for future researchers to develop better methodologies or improve existing ones. This critical collection can be of great significance to both future researchers and urban planners. Researchers can use this work as a foundation for future attempts to create new methodologies or improve existing ones. Urban planners, on the other hand, will benefit from a comprehensive database of existing methodologies for estimating the value of UUS, enabling them to choose the most appropriate technique based on the size and type of the underground project. This approach ensures that UUS is evaluated and utilized in a way that maximizes its potential for sustainable urban development.

2. METHODOLOGY

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement, published in 2009 (hereafter referred to as PRISMA 2009) (Moher et al., 2009; Page et al., 2021), is a reporting guideline created to improve the quality of systematic and critical review reporting (Moher et al., 2007; Page et al., 2021). The PRISMA 2009 statement consisted of a checklist with 27 items recommended for reporting in systematic reviews, accompanied by an "explanation and elaboration" paper (Liberati et al., 2009; Page et al., 2021) that offered further guidance for each item and included examples of proper reporting. A need for an updated version of the PRISMA 2009 statement became evident, as the terminology had greatly evolved since 2009 and the publishing landscape had significantly changed. Consequently, the newly proposed 2020 PRISMA statement replaced the 2009 version (Page et al., 2021). The 2020 PRISMA statement checklist includes seven sections with 27 items, some of which include sub-items (Page et al., 2021). The general steps of the PRISMA 2020 method are summarized as follows:

- The identification and gathering stage. In the initial stage, relevant articles are identified using specific keywords and phrases in an electronic search engine. The diverse keywords used include "underground space value," "economics of underground space," "estimation of the value of underground space," "economic evaluation of underground spaces," "economic benefits of underground development," "cost-benefit analysis of underground spaces," and "valuation methods for underground space," thereby ensuring comprehensive coverage. The primary database utilized was Scopus. Additionally, articles were sourced from previous conference proceedings of the World Tunnel Congress (WTC) and the Associated Research Centers for the Urban Underground Space (ACUUS), an organization that has been advocating for the utilization of urban underground space for over 30 years. Upon completion of the gathering process, duplicate articles are excluded from the review.
- The screening stage. In the second stage, the retrieved articles are closely evaluated to determine their relevance to the topic of underground space valuation methodologies. Articles that do not propose original methodologies and merely repeat existing ones are excluded to focus on innovative contributions.

- The eligibility stage. In the third stage, the articles deemed relevant from the screening stage are further assessed for eligibility. Articles that do not directly estimate the value of underground space in monetary terms are excluded. The reasons for exclusion are thoroughly documented, acknowledging that excluded articles might be relevant for other reviews but are omitted based on the authors' specific criteria for this study.
- The inclusion and presentation stage. In the final stage, the remaining articles are presented as the current existing methodologies for valuing underground space. Each methodology is analyzed, highlighting its strengths and weaknesses. This analysis provides a foundation for future research and helps urban planners choose the most suitable methods for their projects.

This structured approach ensures a thorough review and critical assessment of the methodologies used to estimate the value of underground space.

3. RESULTS

3.1. Identification and gathering stage

As previously mentioned, the database of Scopus and conference proceedings from the World Tunnel Congress (WTC) and the Associated Research Centers for the Urban Underground Space (ACUUS) were utilized to gather the current literature on the methodologies for estimating the value of underground space. Using the following keywords in the Scopus search engine: "underground space value", "economics of underground space", "economic evaluation of underground spaces", "economic benefits of underground development", "cost-benefit analysis of underground spaces", and "valuation methods for underground space", a total of 81 articles were gathered. Additionally, 2 articles were obtained from previous WTC conference proceedings, and 58 articles were sourced from previous ACUUS conference proceedings. In total, 141 articles were collected. Of the 81 articles collected from Scopus, eight were excluded due to duplication, resulting in a total of 133 articles advancing to the screening stage.

3.2. Screening stage

In this stage, the 133 articles collected from the previous stage were meticulously examined to determine their relevance to the subject of estimating the value of underground space. At this juncture, it is essential to clarify the key concepts upon which the exclusion criteria were based. Generally, Urban Underground Space (UUS) encompasses both real and potential values. The real value comprises the direct and indirect values of UUS. The direct value refers to the economic benefits, such as the increase in surface land value following the construction of a metro station nearby. The indirect value, often overlooked in the decision-making process for underground projects, encompasses environmental and social benefits quantified in monetary terms. Examples include reductions in noise pollution, decreases in CO_2 emissions, and overall improvements in living standards. Conversely, the potential value represents the comprehensive benefits that could be derived from untapped underground resources, such as underground space, groundwater, geomaterials, and geothermal energy. At this stage, articles that estimate any of the aforementioned values of underground space were considered relevant and accepted. However, articles that did not propose new methodologies and merely reiterated existing ones were excluded for lacking original contributions. Overall, 110 articles were excluded for not being pertinent to the subject matter. The remaining 23 articles, 17 from Scopus and 6 from previous ACUUS conference proceedings, were forwarded to the eligibility stage.

3.3. Eligibility stage

In the eligibility stage, the 23 articles identified in the previous phase underwent a final examination process. During this stage, articles proposing new methodologies for estimating the potential value of Urban Underground Space (UUS) were excluded, as the primary focus of this study is to critically review existing methodologies for assessing the real value of UUS. Consequently, the final selection includes only those articles that present new and original methodologies for estimating the real value of UUS or the losses associated with its development. Additionally, in some instances, authors have published fragments of a larger methodology, later followed by a complete version of the method. In such cases, the final and complete work is retained, while the preliminary fragments are excluded. Overall, 13 articles were excluded at this stage, with the final 10 moving to the inclusion and presentation stage.

3.4. Inclusion and presentation stage

In this final stage, the remaining 10 articles are identified as the existing methodologies for estimating the real, direct, or indirect value and losses of Urban Underground Space (UUS). In Table 1 below, these 10 articles are presented, including their source of retrieval, reference, and the specific type of UUS value they estimate (whether real, direct, or indirect).

Table 1. *A summary of the 10 articles that can estimate the real, direct, or indirect value and/or losses of UUS.*

Title	UUS Value	Source	Reference
The Importance of Urban Underground Land Value in Project Evaluation: A Case Study of Barcelona's Utility Tunnel	Direct Value	Scopus	Riera and Pasqual (1992)
Underground Land Values	Real Value	Scopus	Pasqual and Riera (2005)
Urban Underground Space Value: Case Study of Kaisheng Square Planning in Lanzhou City	Direct Value	2009 ACUUS International Conference Proceedings	Zhu et al. (2009)
Monetary Valuation of Urban Underground Space: A Critical Issue for the Decision-Making of Urban Underground Space Development	Real Value	Scopus	Qiao et al. (2017)
Valuing External Benefits of Underground Rail Transit in Monetary Terms: A Practical Method Applied to Changzhou City	Indirect Value	Scopus	Qiao et al. (2019a)
Socio-Environmental Costs of Underground Space Use for Urban Sustainability	Indirect Losses	Scopus	Qiao et al. (2019b)
Monetary Evaluation Method of Comprehensive Benefits of Complex Underground Roads for Motor Vehicles Orienting Urban Sustainable Development	Real Value	Scopus	Ma and Peng (2021)
An Integrated Methodology for Estimating the Value of Underground Space	Real Value	Scopus	Mavrikos and Kaliampakos (2021)
Measuring the Monetary Value of Environmental Externalities Derived from Urban Underground Facilities: Towards a Better Understanding of Sustainable Underground Spaces	Indirect Value and Losses	Scopus	Dong et al. (2021)
Rethinking Underground Land Value and Pricing: A Sustainability Perspective	Real Value	Scopus	Qiao et al. (2022c)

4. DISCUSSION

4.1. Early attempts for estimating the value of UUS (early 1990s to late 2000s)

In their initial attempt to estimate the direct value of Urban Underground Space (UUS), Riera and Pasqual (1992) implemented a market-oriented approach. The authors proposed that when parameters such as the construction cost of the underground facility (c), its selling price (p), and the rate of return on this particular investment (b) are known, the direct value of the underground space (u) can be calculated using the following formula:

$$u = \left(\frac{p}{1+b}\right) - c \qquad (1)$$

After presenting this straightforward equation, they applied it to estimate the direct value of an underground parking facility in central Barcelona. Their findings revealed that the value of the underground space in this particular case was $6.518 per parking spot or $113,3 per cubic meter (based on 1990 prices), assuming that a standard parking space occupies 57,5 cubic meters (Riera and Pasqual, 1992).

The two researchers enriched their previous work when they proposed a purely theoretical economic approach. Specifically, Pasqual and Riera (2005) introduced a simplified economic model that applied an optimization algorithm using Lagrange multipliers to maximize a utility function. This approach generated a mathematical expression that quantifies the social value of underground space, and the associated externalities linked to its utilization. Finally, they concluded that the socially optimal price for using a certain amount of underground space has two components: the first represents the value of property rights, which includes the scarcity of underground land and the rising cost of access, and the second reflects the marginal productivity of the underground space and the externalities it produces (Pasqual and Riera, 2005). They also emphasized that the market typically overlooks these externalities, leading to suboptimal use of underground space for society unless some forms of corrective measures are implemented.

While these two efforts were significant first steps in evaluating the value of underground space, they do have some limitations. Firstly, the original method assumes the existence of a competitive market for buying and selling underground spaces, which is necessary to determine parameters like market prices and the rate of return, a market that does not exist in reality. Secondly, the first methodology overlooks the indirect benefits derived from utilizing underground space, failing to account for its indirect value. Although the later approach made a major advancement by incorporating social benefits into the estimation process, it is not easily applicable to real-world underground projects. The method demands a significant amount of input data, which is not always available, and the overall procedure can become somewhat complex, particularly when applied by individuals without a strong economic background.

Another important step forward was made by Zhu et al. (2009) when they utilized a cost-benefit analysis to calculate the direct value of UUS. In their study, they applied this method to compare three different development scenarios for UUS in Kaisheng Square. The first scenario proposed two underground floors, one for commercial use and one for parking. The second scenario added a third floor, one for commercial use, with the other two floors designated for parking. The third scenario suggested creating two floors solely for parking. The authors first estimated the construction costs for each scenario, including excavation and other related expenses. They also calculated the annual operating costs once the facility became operational, such as electricity, equipment depreciation, building depreciation, and rental income taxes. By summing the annual operating costs and construction costs, they derived the total cost of each scenario. As for the benefits, they estimated the commercial rental income and parking income, which, when combined, gave the total annual income for each scenario. To assess the financial feasibility, they calculated the annual net income by subtracting the total costs from the total annual income, and they determined the payback period by dividing the construction costs by the annual net income.

The results of the analysis indicated that the first scenario was the best development option, with a net annual income of $153{,}704 \times 10^4$ RMB Yuan/year (based on 2009 prices) (Zhu et al., 2009), while the other two scenarios had negative net annual incomes. The payback period for the first scenario was 9 years (Zhu et al., 2009), shorter than the standard 12-year period typically expected in China. This methodology was a significant advancement, as it allowed for the estimation of the direct value of UUS through a straightforward cost-benefit analysis. It also enabled the comparison of different development scenarios, aiding in the creation of optimal facilities that maximize direct value. However, this method, like others before it, did not include the social and environmental benefits that come from the sustainable development of UUS. The analysis only considered commercial rental and parking income. If the social and environmental benefits had been included in the total annual income calculation, the annual net income would have been higher, further reducing the payback period for the project and making it an even more attractive investment.

4.2. Attempts of the previous decade for estimating the value of UUS (late 2010s)

Almost a decade later another attempt for estimating the real value of Urban Underground Space (UUS) was introduced by Qiao et al. (2017). Specifically, the authors proposed a modified Service Replacement Cost Method (SRCM), which values UUS by assessing the cost society would face if the urban services provided by UUS were to be replaced by alternative methods. Before conducting the monetary evaluation, it was noted by the authors how crucial it was to identify the urban services provided by UUS, allowing the replacement cost to be calculated based on each type of service. These services were initially categorized by their value, meaning internal or external, and further subdivided according to the type of benefit they offered, such as direct, social, or environmental benefits. Ultimately, UUS services were used as valuation indicators within the SRCM framework. The proposed SRCM can be divided into seven straightforward steps which are extensively analyzed in the original study of Qiao et al. (2017). When introducing the SRCM framework, the authors presented equations to estimate the monetary values of all UUS services. In order to demonstrate their method's effectiveness, they applied it in Changzhou, China, where the real value of UUS was calculated. The total value of UUS services was approximately 276,8 billion yuan, averaging 7,3 billion yuan annually (around 1.156 million USD based on 2012 prices) over a valuation period of 38 years, accounting for more than 1,8% of Changzhou's 2012 GDP (Qiao et al., 2017).

The latter methodology represents a significant advancement in estimating the real value of UUS and marks the second major attempt in this field. While the technique is well-structured and comprehensive, particularly in considering the often-overlooked indirect value, it does have some notable limitations, as acknowledged by the researchers themselves. Particularly, The SRCM relies on a comprehensive classification and identification process that covers all UUS services from underground facilities. Although the authors made considerable efforts to encompass a wide range of services, a systematic identification and classification process is necessary for the method's application across all types of UUS facilities. Additionally, the SRCM requires extensive input data, much of which may be unavailable or even nonexistent, raising concerns about the method's applicability in other regions, particularly in Europe, where such specialized data is challenging to obtain.

Qiao et al. (2019a) expanded upon their previous work on the Service Replacement Cost Method (SRCM) by refining it into a more concise three-step process, enhancing its ability to translate the indirect benefits of an underground rail transit system into monetary terms, by deepening its theoretical framework using marginal value theory for non-market goods. Specifically, they argued that the core economic principles of the SRCM framework were rooted in the concept of marginal value. Since the external benefits of underground rail transit reflect a use value rather than an exchange value, they cannot be directly expressed in monetary terms in the real-world market. However, by considering the marginal benefit, the impact of the external benefit provided by underground rail transit on a unit scale can be measured by assessing its influence on social welfare. In this context, the costs people incur or the monetary losses they suffer, known as replacement costs, can be viewed as the unit value (Qiao et al., 2019a). The updated SRCM framework was divided into three steps, that are thoroughly presented and consequently explained by Qiao et al. (2019a). Finally, the modified SRCM was applied to the Changzhou underground rail transit system in order to estimate its indirect value. The annual total indirect value of the transit services were approximately 11,5 billion yuan (about 1.769 million US dollars based on 2016 prices), accounting for nearly 2,0% of Changzhou's GDP in 2016 (Qiao et al., 2019a).

This modification marked a significant improvement over the original SRCM by better incorporating the indirect benefits of UUS, specifically those of underground rail transit systems, using the concept of marginal value. The framework was also made more robust by reducing the original seven steps to just three. Moreover, while the original methodology required a separate formula for calculating the replacement cost value of each listed service, the reformed approach allows the values of all services to be calculated using a single equation, again making the overall process more straightforward. However, some of the challenges present in the original method remain unaddressed. First, the SRCM still relies on a comprehensive classification and identification process for all services provided by UUS facilities. While the authors made considerable efforts to cover a broad range of services, a systematic approach for identifying and classifying is necessary for applying this method across various types of UUS facilities, and not just underground rail transit systems. Additionally, although the input data requirements were somewhat reduced due to the simplified formula, the method still demands a significant amount of input data, much of which may be unavailable or even nonexistent. This issue, as noted by the researchers themselves, raises concerns about the applicability of the SRCM in other regions and countries.

Less than a year later, Qiao et al. (2019b) expanded their research by assessing the socio-environmental losses caused by the development of UUS in monetary terms, from the perspective of urban sustainability. They used the service replacement cost method (SRCM), which they had introduced in their previous work. Initially, the authors identified and categorized these socio-environmental losses by examining the interactions between UUS and urban sustainability. To do this, they referenced the seventeen Sustainable Development Goals (SDGs) provided by the United Nations (UN). They also listed the main losses associated with UUS development, such as the reduction of physical underground space, loss of geomaterials, groundwater contamination, and the loss of geothermal energy. These compromised underground assets were then paired with their respective SDG contributions to urban sustainability (Qiao et al., 2019b). As for the SRCM, it was assumed that the costs would be at least equivalent to the amount of money required to restore the damaged underground assets to their original state, i.e., the condition of the underground environment before UUS development. The SRCM involved six steps, for a comprehensive explanation of these steps the author suggests reading the original manuscript of Qiao et al. (2019b).

Once again, the city of Changzhou, China, was chosen as a case study to apply the SRCM methodology to calculate the indirect losses from UUS development. The findings revealed that the total socio-environmental costs of UUS development in Changzhou amounted to approximately USD 719,76 million (Qiao et al., 2019b). When these costs were compared with the total external benefits, which were close to USD 36,16 billion, it was found that the socio-environmental costs could exceed 1,99% of the external benefits derived from UUS development (Qiao et al., 2019b). Overall, this study marks a significant milestone as it is the first to examine the indirect losses resulting from the development of Urban Underground Space (UUS), a previously unexplored area of research. By recognizing that the development of a city's third dimension can produce not only benefits but also losses, this research takes a major step forward in providing a more comprehensive estimation of UUS's real value. The methodology employed, a modified version of the Service Replacement Cost Method (SRCM) developed by the authors in their earlier work, was adapted to focus on capturing losses rather than advantages. However, the approach has several critical limitations regarding its general applicability. The estimation of costs is heavily dependent on two key parameters: the magnitude of losses and the probability of their occurrence. These parameters are highly contingent on the local conditions of the case study and can be difficult, if not impossible, to predict accurately. As a result, their estimation is largely subjective, varying significantly depending on the user's judgment, which can lead to considerable differences in outcomes. This subjectivity means that the method may produce inconsistent results across different case studies, as each location would need to establish its own values for these parameters. Consequently, the method fails to provide a systematic approach for estimating indirect losses that are both easily applicable and highly efficient across various contexts. Moreover, the fact that underground space is a non-renewable resource further complicates the replacement cost approach. The underground environment can never be fully restored to its original state once altered by engineering structures and construction materials used for UUS development, raising questions about the accuracy of using replacement costs to assess socio-environmental losses. Finally, as highlighted in the authors' previous works, the SRCM's reliance on extensive input data, particularly for aspects like geothermal energy and groundwater, poses a significant challenge. This data is often difficult to obtain or even nonexistent, further restricting the method's applicability in different case studies.

4.3. More recent attempts for estimating the value of UUS (early 2020s)

Ma and Peng (2021) made a significant recent contribution by identifying nine sustainability-oriented benefits of complex underground roads and then estimated their monetary value. The researchers divided these benefits into two main categories. The first category, the intrinsic benefits (or direct benefits) that stemmed from the fundamental functions of the newly planned roads, primarily through increased traffic supply (Ma and Peng, 2021). The second category, the specific benefits (or indirect benefits) that were unique to complex underground roads and included the mitigation of adverse effects typically caused by aboveground arteries or expressways (Ma and Peng, 2021). In order to properly identify these nine sustainability-oriented benefits systematically, the authors employed a comparison-based approach. They used the "with-without comparison principle" to identify intrinsic benefits by assessing the differences between scenarios where the new transport infrastructure would be built versus scenarios where it would not. While for the specific benefits, they adopted the "aboveground-underground comparison principle," which focused on comparing the impacts on urban sustainability when a new road was built underground versus aboveground. This method considered scenarios with similar route selections, portal arrangements, and traffic volumes, allowing for a clear comparison of the sustainability impacts between underground and aboveground road placements.

Via the usage of the two aforementioned comparison principles, the researchers identified nine sustainability-oriented benefits associated with complex underground roads. These benefits included reducing carbon dioxide emissions, saving transportation time for passengers and cargo, lowering traffic accident risks, and reducing air and noise pollution, among others (Ma and Peng, 2021). To estimate the monetary value of these benefits, the General Substitute Cost Method (GSCM) was applied. This method is derived from substitute cost methods used in ecosystem valuations, which are based on the idea that environmental benefits provided by ecosystems can be monetarily assessed by calculating the costs of reproducing these benefits through alternative means. Each of the nine identified benefits was matched with a corresponding general substitute cost, allowing for a systematic valuation. The monetary value of each benefit was calculated using a specific equation tailored to that particular benefit. The authors applied their newly developed equations to the Bund Tunnel in Shanghai, estimating its total value at approximately 54,672 billion yuan (about 8,167 billion USD based on 2020 prices) over a 100-year period (Ma and Peng, 2021). Specifically, the intrinsic (direct) benefits accounted for 54,2% (or CNY 29,64 billion), while the specific (indirect) sustainability benefits unique to complex underground roads accounted for 45,8% (or CNY 25,03 billion) (Ma and Peng, 2021).

This study represents one of the most comprehensive efforts to estimate the real value of complex underground roads, introducing a systematic approach for identifying both direct and indirect benefits of underground facilities. However, the methodology has some significant drawbacks. First, the entire approach is tailored specifically for underground roads, limiting its applicability to other types of underground structures. Even if other facilities share similar benefits with underground roads, the equations used cannot be applied due to the specific data required, further narrowing the method's utility. Second, as with other methods that employ the replacement cost approach, obtaining the necessary input data can be challenging in many countries. Relevant studies are often scarce, and public documents containing the required information are not easily accessible.

Mavrikos and Kaliampakos (2021) made a significant and influential contribution by proposing a systematic methodology for estimating the real value of Urban Underground Space (UUS). The researchers emphasized the critical importance of including the monetary value of the indirect benefits of underground structures in the estimation process. To address this issue, the authors suggested employing environmental economics to quantify the indirect advantages of UUS, thereby enabling it to more effectively compete with above-surface options. Their methodology can be summarized in 8 key steps, which involve estimating the direct value of an underground structure with the replacement cost method and the real estate income approach, while the indirect value is evaluated using the Benefit Transfer (BT) method, an environmental economics technique. Finally, by combining the direct and indirect values obtained through these methods, they were able to estimate the real value of UUS. The researchers applied their proposed methodology to an underground storage facility in the Attica region of Greece. The final estimated values are 1.022,49€ /m^2 for the replacement cost approach and 1.001,61€/m^2 for the income approach (Mavrikos and Kaliampakos, 2021). The two values differ by only 2,1%, confirming the correct implementation of the valuation approaches. It should be noted that the total cost for constructing an underground storage facility in the examined case was approximately 190€/m^2 (including excavation and improvements), while the value of the underground space was over five times greater (Mavrikos and Kaliampakos, 2021).

The proposed methodology stands out as one of the most comprehensive and systematic approaches for estimating the real value of Urban Underground Space (UUS). It employs the service replacement cost method and the income approach method, both well-established real estate valuation techniques, to calculate the direct value of underground structures. Notably, this methodology is among the few that fully incorporate the indirect value of underground facilities, an aspect often overlooked in other approaches. However, the authors themselves acknowledge a few limitations that could be addressed to further enhance the technique. First, the Benefit Transfer (BT) method, which is used to estimate the indirect value, requires a substantial amount of primary environmental studies. This reliance can limit the methodology's applicability, depending on the availability of such studies. Therefore, expanding the database on the monetization of benefits and advantages of underground structures compared to surface alternatives is crucial. This expansion would improve the accuracy of estimations and reduce uncertainties associated with the BT method, thereby strengthening the overall approach. Additionally, the methodology's results are highly land-use specific. When applied on a larger scale, with multiple potential land-use scenarios, the technique must be repeated for each scenario, making the process time-consuming and labor-intensive. Finally, while the methodology does account for the depth of the underground facility, this factor is not sufficiently emphasized in the final results. Given the increasing importance of three-dimensional urban planning, better integration of depth considerations into the final valuation would be a significant improvement.

A few months later Dong et al. (2021) made a significant advancement by substantially modifying the service replacement cost method (SRCM) to estimate the monetary value of environmental externalities resulting from the development of Urban Underground Space (UUS). This approach encompasses both the benefits and losses associated with underground facilities. The researchers began by identifying key environmental contributions and detriments linked to UUS, such as air and noise pollution reduction, greenhouse gas emission mitigation, groundwater disturbance, and waste from excavated geomaterials. They then introduced a new framework for applying the SRCM, which is structured into three primary steps, that are extensively showcased in their original work (read Dong et al., 2021). After introducing the general framework for the restoration cost method, the researchers presented formulas for calculating the monetary values of specific environmental externalities associated with the construction of various underground facilities. These included structures like underground buildings, transportation facilities, roads, and parking lots. The technique was then applied to several underground facilities in China, such as the Changzhou pedestrian underpass and Shanghai's Metro Line 10. The results demonstrated that the benefits of such facilities significantly outweigh the losses, and that the monetary value of the environmental externalities from underground structures are significantly higher in relation to their construction costs.

The newly proposed method represents a significant advancement in evaluating the indirect value of UUS, as it is the first to fully incorporate the losses resulting from UUS development, offering a comprehensive technique for estimating the indirect value of underground structures. However, a notable limitation of this method is that the formulas introduced are highly specific to the types of underground structures being evaluated, making it difficult to adapt them for a broader range of facilities. This specificity limits the method's applicability to other types of UUS, as the formulas are tailored to the structures mentioned by the authors. Additionally, the input data required for these equations is often difficult, if not impossible, to obtain in many countries, raising concerns about the method's general applicability. Moreover, the authors did not provide a systematic approach for determining and categorizing the environmental benefits and losses associated with different underground structures. While they covered a broad spectrum of indirect benefits and losses, their choices were limited to the facilities they evaluated.

One year later, Qiao et al. (2022c) presented their final and most recent work, building on their earlier research. In this study, they applied the service replacement cost method, previously detailed in their studies (Qiao et al., 2017; Qiao et al., 2019a; Qiao et al., 2019b), to estimate both the indirect value of UUS, encompassing both benefits and losses, as well as the direct value of UUS by using policy approaches employed by countries such as China, Germany, and Japan. By refining their earlier work and incorporating a new approach to estimate the direct value, they developed a comprehensive method for calculating the real value of UUS. The results of this method were visualized using Geographic Information System (GIS) technology. A key distinction from their previous work is the researchers' acknowledgment that most existing techniques for monetarily evaluating the value of UUS are market-oriented and lack a sustainability perspective, which they integrated into their latest study. Furthermore, the authors pointed out that underground projects are generally undertaken by either private developers or the government, each with different objectives, private developers focus on profit, while the government emphasizes long-term sustainability for society. This difference in perspective underscores the importance of considering both external benefits and costs, along with business revenues from underground land development, in determining the sustainability-oriented underground land price (Qiao et al., 2022c). In order to monetize the indirect benefits and costs, the researchers relied on their service replacement cost method, which they had thoroughly developed and explained in their previous works (read Qiao et al., 2017; Qiao et al., 2019a; Qiao et al., 2019b). Finally, for valuing the land price (direct value) they employed policies from countries like China, Germany, and Japan as a basis for their calculations. The researchers applied their newly developed method to calculate the real value of UUS in Shinan District, Qingdao, China, as a case study. The results were then visualized using Geographic Information System (GIS) technology. The findings indicated that, in most of the underground spaces examined in the region, environmental benefits significantly outweighed environmental costs (Qiao et al., 2022c). Moreover, when the direct value of the underground structures was also considered, their overall value proved to be very high (Qiao et al., 2022c).

In this most recent work, the authors made a significant advancement in estimating the real value of UUS. They achieved this by refining their earlier efforts to calculate the indirect benefits and costs of underground facilities using the service replacement cost method, while also incorporating a more systematic and realistic approach to assessing their overall value. This shift from a primarily market-oriented perspective to a more sustainability-focused approach represents a major step forward. Additionally, it is noteworthy that this study was only the second time that the results of such estimations were visualized using GIS, providing a clearer spatial representation of UUS's real value. The first attempt at visualization occurred earlier that same year in studies by Qiao et al. (2022a) and Qiao et al. (2022b). However, several concerns previously raised about the applicability of the service replacement cost method remain unresolved. Firstly, the method heavily depends on a thorough classification and identification of all services provided by UUS facilities. While the authors made considerable efforts to cover a wide range of services, a more systematic approach to this classification is needed to make the method applicable across different types of UUS facilities. Furthermore, the method requires a substantial amount of input data, much of which may be unavailable or nonexistent in many regions. This limitation, acknowledged by the researchers themselves, casts doubt on the broader applicability of the service replacement cost method in other areas and countries. Despite these challenges, the researchers' integration of sustainability considerations and the use of GIS for visualization mark important progress in the field, even though further refinement and adaptation of the methodology are necessary for wider application.

5. CONCLUSIONS

The incorporation of underground space use has become a necessity in modern urban planning due to the increasing demands and challenges that 21st-century cities face. However, many underground projects are often stalled in the decision-making phase and never materialize. The primary reason is the significantly higher capital cost of underground facilities compared to above-surface alternatives, leading to their frequent neglect. It is crucial to integrate the indirect advantages of underground structures, particularly socio-environmental benefits, into the decision-making process. Doing so can enable underground options to compete directly with, or even surpass, their surface counterparts.

To systematically embed UUS into urban planning and make underground options more favorable, it is essential to estimate the real value of UUS. The real value encompasses both the direct and indirect value of UUS, with the latter often being more challenging to quantify in monetary terms, as it involves non-market goods. This study aimed to gather and review all existing methodologies that have been developed over the years to estimate either the real, direct value or indirect value, or losses from UUS development. To ensure comprehensive coverage, the study followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). Most of the articles were sourced from the Scopus online database using specific keywords and phrases, with additional materials retrieved from conference proceedings of the Associated Research Centers for the Urban Underground Space (ACUUS) and the World Tunnel Congress (WTC).

The study's findings revealed that early attempts to create methodologies for estimating the value of UUS primarily focused on its direct value, neglecting the crucial indirect benefits and their corresponding values. However, over the past 15 years, researchers have increasingly recognized that excluding indirect advantages omits a significant portion of UUS's value. Consequently, methods like the service replacement cost have been carefully modified to account for the indirect benefits of UUS, with some approaches even estimating the indirect losses resulting from inconsistent and reckless UUS development. The most recent methodologies have further advanced by visualizing their estimation results using Geographic Information System (GIS) technology, providing a more comprehensive spatial analysis of UUS's real value.

In summary, this critical review offers valuable insights for both future researchers and urban planners. Researchers can use this collection as a foundation for developing new methodologies or improving existing ones, serving as an organized and comprehensive database. Urban planners, on the other hand, can leverage this information in the decision-making process to identify the most suitable method for their specific projects. This approach promotes sustainable and cost-effective urban development, enabling planners to make informed choices based on thorough research. However, it is crucial that this collection be continuously updated to include the latest methodologies and improvements to existing ones, ensuring it remains a relevant and valuable resource.

6. APPENDIX

To ensure thorough documentation, the 141 articles initially retrieved by the author during the identification and gathering stage can be made available as supplementary material upon request.

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