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An Investment Decision Model for Underground Urban Utility Tunnel Based on MIVES and Real Option Theory from a Sustainable Perspective

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Abstract: Although the importance of urbanization, urban renewal and sustainable development have been increasingly recognized, with the accelerating process of urbanization, the urban above-ground space is no longer sufficient for the process of urbanization, and downward development of the city has become inevitable. Underground Urban Utility Tunnel (UUUT) is an effective measure to promote the sustainable development of urban underground space (UUS). However, decision makers still cannot fully consider the economic, social, environmental and technological factors, as well as the future risks of the project and the value of flexibility in management. In this paper, an investment decision model for UUUT is proposed that combines the Integrated Value Model for Sustainable Assessment (MIVES) and the real option theory, which comprehensively considers the social, economic, environmental and technological impacts, and assists the government in carrying out the investment decision analysis of UUUT from a sustainability perspective by applying the real option theory to the economic evaluation process. The primary process of this study can be divided into four steps. (1) establishment of the investment decision index system for UUUT; (2) determination of the quantitative criteria for each indicator; (3) calculation of the feasibility of UUUT; and (4) a case study to demonstrate the feasibility of the proposed model, as well as the achieved results. The proposed investment decision model can be used as an auxiliary tool in the early planning stage of UUUT, and also for the comparison and selection of different options for UUUT.

Keywords: sustainable urban development; UUUT; investment decision models; MIVES; real option theory

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1. Introduction

As urbanization continues to accelerate, urban sustainability has become an important issue in urban development. Today, more than half of the world's population is concentrated in cities, and in many cities' population growth has outpaced infrastructure development. The urban above-ground space is no longer sufficient to meet the needs of the urban population [1]. Therefore, urban underground space (UUS) should be considered in urban planning to improve urban sustainability [2,3]. UUS is an important non-renewable resource and the way underground space is used affects the sustainability of cities, but currently UUS is often demand-driven and exploited in a relatively arbitrary manner [4].

Urban municipal pipelines are a type of urban underground infrastructure that occupy the underground space resources of the city. In order to meet the needs of the population and the growth of the city, early municipal pipelines (e.g., water and drainage pipes, power cables) were often randomly buried shallowly under roads and independent of each other. However, aging pipelines need to be renewed or maintained [5], requiring repeated road excavation, which is costly to maintain and disruptive to traffic, especially since frequent road excavation leads to serious social impacts when the maintenance of various municipal pipelines is not synchronized [6].

UUUT is a sustainable solution that integrates the pipelines of various urban utilities such as electricity, communication, gas, heating, water supply and drainage, and places them in an underground tunnel space with special access ports, lifting ports and monitoring systems [7,8]. By integrating all kinds of pipelines in one, the UUUT facilitates maintenance, reduces road excavation and reduces traffic congestion. The UUUT also provides good protection for municipal pipelines and can extend their service life. More importantly, UUUT integrates underground pipelines together, effectively saving the resources of UUS and promoting the intensive and efficient use of urban underground space, which is conducive to the sustainable development of the city. However, not all UUUT projects should be built, and any infrastructure construction must consider its sustainability at the planning and design stage [9,10].

The purpose of this paper is to quantitatively consider the social, economic, environmental and technical impacts of UUUT and to provide a systematic analytical framework for the government to analyze the constructability of UUUT from a sustainability perspective at the pre-planning stage. MIVES, an integrated sustainability evaluation model, is a multi-objective decision making method that includes a value function and provides a quantitative methodological framework that considers multiple variables simultaneously, which has been applied in different domains [11]. In addition, traditional economic value calculation methods, such as the net present value (NPV) method, do not take into account the uncertainty of the project and the elastic value of management [12]. In this paper, we incorporate the real options theory approach into the MIVES to model the decision making from a sustainability perspective for a UUUT project [13]. The remaining sections of this paper are arranged as follows: Section 2 summarizes the related research on the indicators influencing the investment decision of UUUT and methodology for economic value analysis of investment projects; Section 3 provides a brief introduction to the methodology of this paper; the development of the UUUT investment decision model and the calculation of the option value are presented in Section 4; Section 5 shows how the model can be applied through a case study, and Section 6 concludes the paper.

2. Literature Review

2.1. Urban Regeneration and Sustainable Development

Urban regeneration has been viewed as a sensible strategy for enhancing environmental quality and raising land values [14]; addressing the issue of urban decay problem; and achieving numerous socioeconomic goals [15]; and boosting already-existing social networks, improving inclusion of vulnerable groups, and reducing negative effects on the environment [16]. Since environmentally sustainable development has become a key component of urban policy since the early 1990s [17], it has been acknowledged that urban regeneration and sustainability should be coupled because sustainable development and urban renewal are similar in terms of social, economic, and environmental sustainability [18].

Regardless of the conception of sustainability used, the agreement seems to be that sustainable development includes three pillars: social, economic, and environmental. Urban regeneration is so intimately related to this strategy, which has proven increasingly popular in most contexts for establishing a more sustainable society [18]. However, rather than focusing on environmental or social regeneration, most urban regeneration strategies have tended to emphasize economic regeneration [17]. Thus, it is critical to achieve effective and efficient sustainable urban regeneration practice. Zheng et al. [18] presents a critical review of studies on sustainable urban renewal as a research road map.

2.2. Investment Decision-Making Methodology for UUUT

Public infrastructure investment decisions, including those related to UUUTs, need to be evaluated and analyzed from social, economic, and environmental perspectives due to the positive externalities associated with them. Mezher et al. [11] proposed a decision-making approach using a weighted average multi-criteria analytical model and designed a decision support system to assist senior decision-makers in the public sector with planning the implementation of public investment projects. Girgis et al. [19] propose a decision model for public projects based on a risk and multi-criteria decision-making approach for developing countries. The integrated value model for sustainable assessment (MIVES) combines Multi-Criteria Decision Making (MCDM) and Multi-Attribute Utility Theory (MAUT) [20], which can be used for investment decisions in public infrastructure and assess sustainability by analyzing the social, environmental and economic impacts [21], and to the assessment of road condition classification [21].

For underground urban utility tunnel, Canto-Perello combines SWOT and AHP methods to make decisions in terms of strengths, weaknesses, opportunities and threats, arguing that UUUTs are easier to inspect and carry out preventive maintenance, can reduce traffic disruptions, improve the image of the community, and increase the sustainability of the underground space, but the underground transportation network coordination is a threat to the decision making of UUUT [22].

2.3. Economic Value Evaluation of Investment Projects

The analysis of the economic value of an investment project is crucial to the investment decision of the project. Research has shown that the method of calculating the economic value of investment projects can be divided into three stages [23]: (1) The first stage is the traditional Net Present Value (NPV) or Internal Rate of Return (IRR) method of calculating the economic value [24], which analyzes the economic value of the project by discounting the future benefits and costs to present value according to the basic rate of return. (2) The second stage is to add Uncertainty Analysis to the traditional economic value calculation method [25], such as the Decision Tree Method and [26]. (3) In the third stage, financial options are used to make real investment decisions resulting in the real option method, which considers the uncertainty of the project to be directly proportional to the option value.

2.4. Research Gap

Despite the discussion on the importance of social, economic, and environmental factors in urban regeneration and sustainable development, and the recognition of Underground Urban Utility Tunnel (UUUT) as an effective measure to promote the sustainable development of urban underground space (UUS), the comprehensive consideration of economic, social, environmental, and technological factors, especially in relation to underground space, has not been adequately addressed. As one of the major public infrastructures in the city, the UUUT occupies the underground space, which is a non-renewable urban resource, the sustainability of the UUUT needs to be considered in the planning and design phase [20]. Existing studies on the decision-making of underground urban utility tunnel have considered the impact factors from economic, social, environmental, and technical aspects. However, they have not quantitatively considered these factors simultaneously. In addition, the traditional Net Present Value (NPV) method is usually used to calculate the economic value of UUUT, which cannot take into account the uncertainty of the project and the value of management flexibility [27], therefore, a more scientific and rational way to calculate the economic value of UUUT is needed.

This paper introduces MIVES into the early decision-making of underground urban utility tunnel to quantitatively consider the economic, social, environmental, and technical aspects of decision-making.

3. Research Methodology

This paper develops an investment decision model based on MIVES, a comprehensive evaluation framework for sustainable development, and incorporates real option theory into the framework to calculate the economic value of UUUT. The flowchart depicted in Figure 1 outlines the four main stages of this paper's workflow: (1) establishment of the investment decision index system for UUUT; (2) determination of the quantitative criteria for each indicator; (3) calculation of the feasibility of UUUT; and (4) a case study to demonstrate the feasibility of the proposed model.

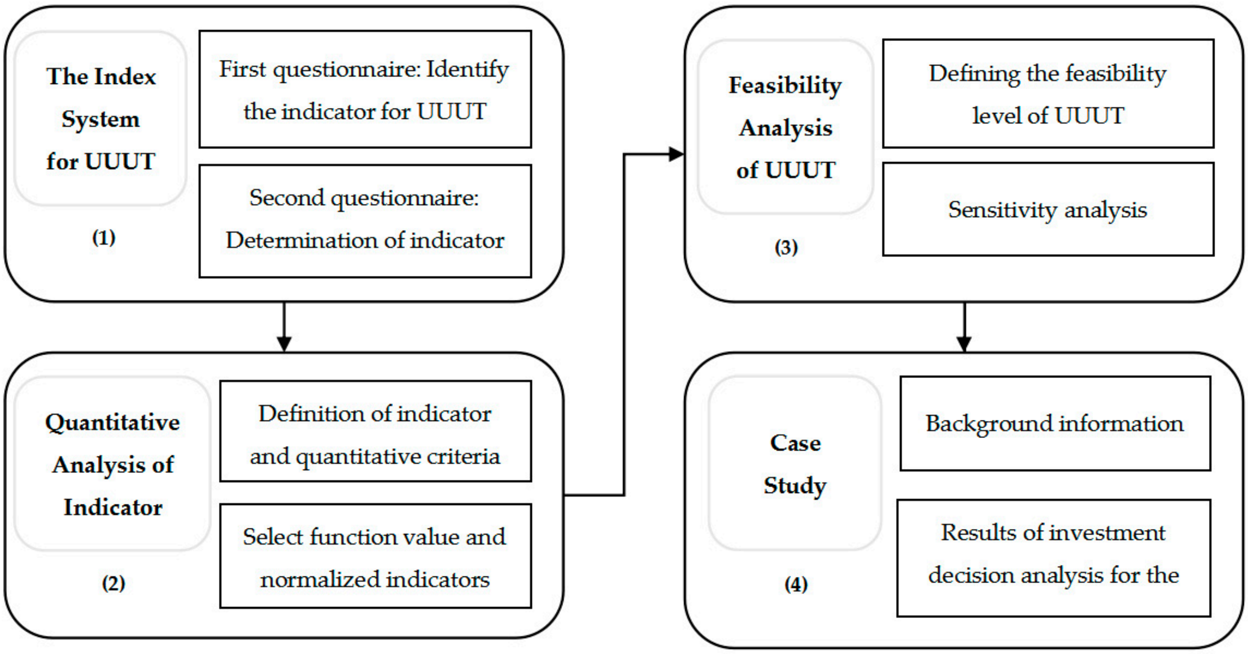

Figure 1. The Workflow of Paper.

The first stage initially identifies the indicators affecting the UUUT through literature review and expert interviews, followed by a two-stage questionnaire approach to screen the indicators (Ishikawa, et al., 1993) [28]. At stage 2, the indicators are defined and their calculation methods are specified, followed by the normalization of indicators using the value function method [29]. The process involved screening the indicators using the Delphi method and determining the weight of the indicators using the Analytic Hierarchy Process (AHP) method. The fixed weights applied to each indicator. In addition, at this stage, the economic evaluation of UUUT considers the uncertainty of the project's future and calculates the option value instead of the net present value (NPV). The third stage defines the constructability rating of a UUUT project and calculates the constructability score based on the developed investment decision model. It should be noted that the ability of an investment project to bear risk needs to be considered. Also, sensitivity analysis, a widely used method for uncertainty analysis in investment project evaluation [30] is applied. Finally, this paper validates the proposed investment decision model with a case study.

4. Investment Decision Model for UUUT

When making investment decisions for UUUT, government departments need to consider a wide range of indicators that influence the project. UUUTs are public infrastructure, and sustainability is key to investment decisions. Economic, social and environmental impacts are often considered to assess the sustainability of public infrastructure [20]. The technical feasibility of construction and implementation should also be considered for an UUUT project [21]. Therefore, the decision model includes economic, social, environmental and technical aspects to comprehensively examine the feasibility of UUUT.

MIVES was first used for the sustainability of industrial buildings [31], and is a method that allows for the simultaneous analysis of multiple influences. MIVES combines, Multi-Criteria Decision Making (MCDM) and Multi-Attribute Utility Theory (MAUT) with Value Functions (VF) and Analytic Hierarchy Process (AHP), which has been widely used for sustainability evaluation and comparative evaluation of similar projects. In addition, traditional methods such as the NPV method are often used by government departments to analyze the economic viability of utility tunnel projects, which reveals the shortcomings of failing to fully consider project risks and the value of project management flexibility [12]. The real option theory is a way to compensate for these shortcomings. Therefore, in this paper, the investment decision model for UUUT is established based on MIVES and real option theory.

4.1. Establishment Investment Decision-Making Index System of UUUT

Urban infrastructure projects need to consider their sustainability at the planning and design stage, which is generally assessed in terms of social, economic and environmental impacts [20]. Based on a review of studies related to utility tunnel, the addition of technical feasibility indicators in conjunction with expert opinion, a total of 24 impact indicators were obtained. However, not all the influencing indicators should be included in the evaluation system, therefore, this paper uses the fuzzy Delphi method to screen the indicators, which is a method to integrate multiple expert opinions to reach a consensus [28]. This research distributed a total of five questionnaires to experts with more than five year work experience, including three from personnel involved in the construction of urban utility tunnel, and two from university staff with professional expertise. All five questionnaires were retrieved, resulting in a 100% recovery rate. By distributing the first stage expert questionnaires and integrating expert opinions, the screening resulted in a total of 16 evaluation indicators is shown in Table 1.

Table 1. The Investment Decision-Making Index System for UUUT.

Target	Criteria	Indicator	Criteria Weight	Indicators Weight	Reference for Indicator
Priority Index for Utility Tunnel	Economic criteria	Project Economic Benefit (PEB)	0.4033	0.3234	[32]
		Annual Unit Cost (AUC)		0.1838	[21]
		Annual Maintenance Cost (AMC)		0.1946	[21]
		Possibility of Obtaining External Funding (POEF)		0.2982	[21]
	Social criteria	Service quality Improvement (SQI)	0.2446	0.1120	[21]
		Service capacity Improvement (SCI)		0.1639	[21]
		Employment creation (CE)		0.1300	[21]
		Social acceptability (SA)		0.1562	[21]
		Functional urban areas (FUAs)		0.3369	[33]
		Urban population density (UPD)		0.1010	[34]
	Environmental criteria	Environmental contribution index horizontal (ECIH)	0.1134	1.0000	[21]
	Technical criterion	Availability of underground space (AoUS)	0.2387	0.0641	[33]
		Underground Traffic Complexity (UTC)		0.2929	[35]
		Pipeline type requirements (PTR)		0.3368	[36]
		Pipeline quantity requirements (PQR)		0.2149	[36]
		Road width (RW)		0.0913	[37]

In this paper, the AHP method is used to determine the weights of each level of the UUUT decision index system, which adopts the nine-scale method to compare the importance of two indicators, construct a judgment matrix, and then calculate the weights of each level. In this paper, we calculate the weights of each level of the UUUT investment decision indicator system according to the general steps of the AHP. The calculation results are given in Table 1.

After the screening of indicators and the calculation of weights, we obtain the investment decision model of UUUT based on MIVES and real option theory, as shown in Figure 2.

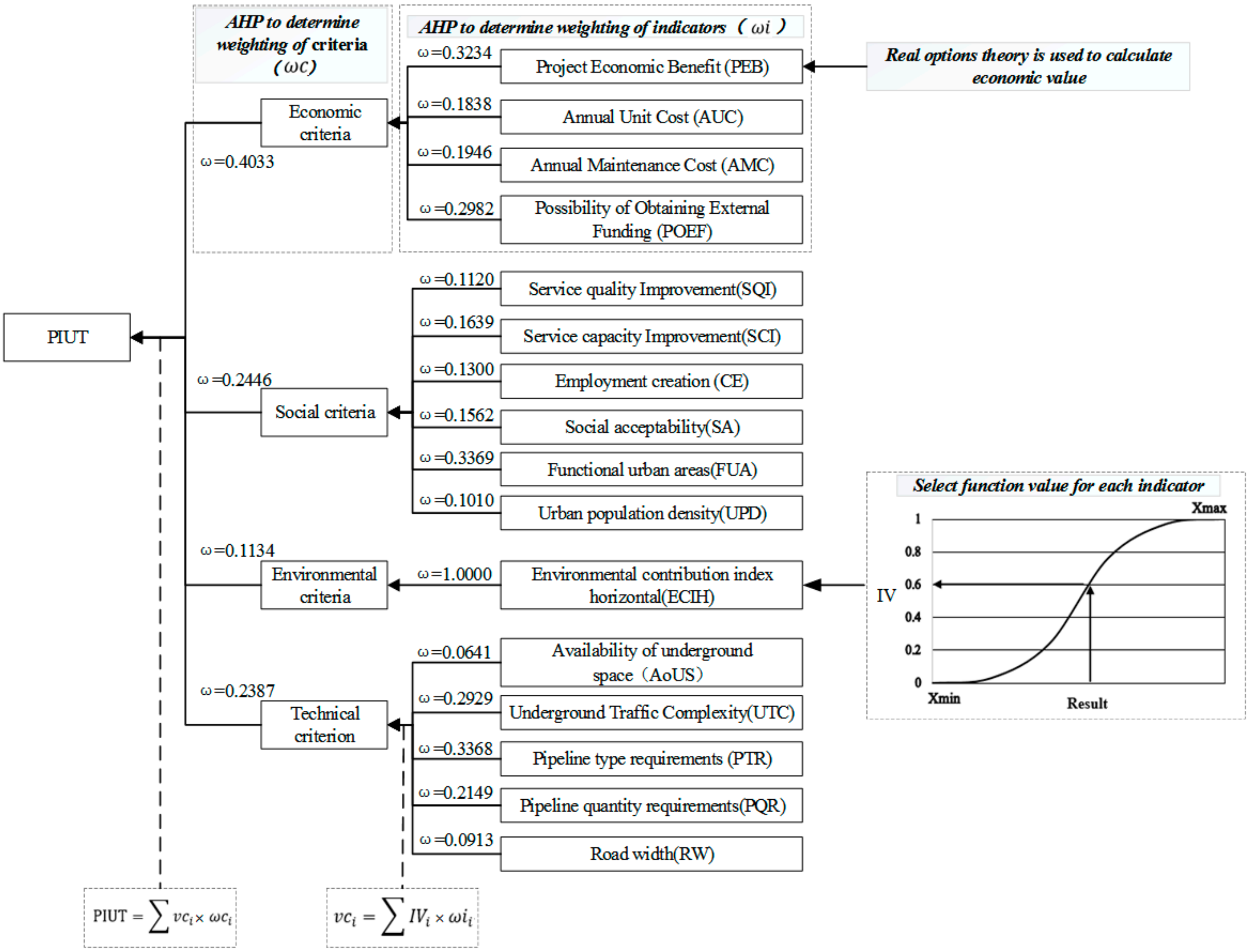

Figure 2. Investment Decision Model Framework for UUUT from a Sustainable Perspective.

While, vc_i, IV_i represent the score value corresponding to each level, which is calculated according to the calculation rules corresponding to each index; wc_i, wi_i represent the weight of each index, which is determined by the AHP method, and PIUT (Prioritization Index for Utility Tunnel) represents the final feasibility result of the construction of the UUUT project.

4.2. Calculation Modalities for Determining the Indicators

From a sustainability point of view, investment decisions in UUUT are influenced by four aspects: economic, social, environmental and technological, and a method for quantifying each indicator needs to be defined [29].

4.2.1. Economic Assessment of UUUT

Using the analytic hierarchy process (AHP), four indicators were selected as the most heavily weighted indicators to evaluate the economics of UUUT, which are Project Economic Benefit (PEB), Annual Unit Cost (AUC), Annual Maintenance Cost (AMC), and Possibility of Obtaining External Funding (POEF) [21].

(1) Project Economic Benefit (PEB)-Based on Real Option Value

Project Economic Benefit (PEB) is mainly used to measure the future revenue of the project [38]. As quasi-operational construction projects, UUUT have significant externalities and can generate cash income from utility tunnel entry fees, lease fees, maintenance fees and financial subsidies. In most cases, investors ignore the value of management flexibility and the uncertainty of the project when evaluating the economic benefits of a UUUT project. The real option approach is based on risk uncertainty and recalculates the return of an investment project by considering the possible beneficial value of the uncertainty risk. Therefore, it is more accurate and realistic to calculate the economic benefits of a UUUT project based on the real options theory.

Pricing in real options theory is derived from financial options theory. Dynamic planning, simulation and partial differential equation methods are usually used to calculate the option value [39]. The partial differential equation method is a pricing method for continuous time, and the Black-Scholes (B-S) model proposed by Merton is the most basic pricing model [5]. In this paper, we refer to the B-S model and the study by Antonio L to use partial differential equation for option value calculation. This paper determines the actual value of the project from the perspective of expansion options. The following calculations are based on the calculation of expansion options, but the calculation of deferred options is also applicable [40].

Definition C is the value of the expansion option for the utility tunnel project, then where:

$$C(V,t) = VN(d_1) - Ie^{-r(T-t)}N(d_2) \tag{1}$$

$$d_1 = \frac{\ln\frac{V}{I} + \left(r + \frac{1}{2}\sigma^2\right)(T-t)}{\sigma\sqrt{T-t}} \tag{2}$$

$$d_2 = \frac{\ln\frac{V}{I} + \left(r - \frac{1}{2}\sigma^2\right)(T-t)}{\sigma\sqrt{T-t}} \tag{3}$$

where I is the discounted value of the project company's construction period cost, and V is the net present value of the total revenue of the utility tunnel project in the operational phase, and r is the risk-free interest rate.

Using option theory, the calculation of the net present value of the original traditional investment decision is converted into the calculation of the current option value, which is more in line with the actual situation. Using ENPV to represent the extended net present value of the utility tunnel project, the formula is:
where:

$$ENPV = NPV + C(V_t, t) \tag{4}$$

$$NPV = V - I \tag{5}$$

$$V = \sum_{i=t}^{i=T_C} \frac{CI_i - CO_i}{(1+r)^i} \tag{6}$$

$$I = \sum_{i=0}^{i=t-1} \frac{I_i}{(1+r_f)^i} \tag{7}$$

NPV is the net present value of the project, V is the net present value of the project's operation period, and I is the net present value of the investment cost of the project.

Then,

$$PEB = ENPV/Cost \times 100\% \tag{8}$$

PEB is divided into 5 levels based on percentage, See Table 2 for details.

(2) Annual Unit Cost (AUC)

Annual Unit Cost (AUC) is defined as the ratio of the total project cost to the expected lifecycle, which is a key factor in the economic impact indicators [41]. The main consideration is the cost of the project's annual input. The AUC is divided into five tiers based on

1 million USD/year, 2 million USD/year, 3 million USD/year, and 4 million USD/year [21]. Table 2 gives the score corresponding to the AUC for each tier.

$$\text{AUC} = \text{Total cost}/\text{Expected life cycle} \tag{9}$$

Table 2. Indicators for evaluating economic criteria.

Criteria	Indicators	Taxonomic Standards		Points
Economic criteria	PEB	Calculation of the proportion according to Equation (8)		
		80% < C4		5
		60% < C4 ≤ 80%		4
		40% < C4 ≤ 60%		3
		20% < C4 ≤ 40%		2
		C4 ≤ 20%		1
	AUC	Calculation of the AUC according to Equation (9)		
		<1 million/year		5
		1 million/year–2 million/year		4
		2 million/year–3 million/year		3
		3 million/year–4 million/year		2
		>4 million/year		1
	AMC	Very high		5
		High		4
		Medium		3
		Low		2
		Very low		1
	POEF	p	PrF	
		Very high	>80%	5
		High	60–80%	4
		Medium	40–60%	3
		Low	10–40%	2
		Very low	<10%	1

(3) Annual Maintenance Cost (AMC)

Annual Maintenance Cost (AMC) is a qualitative indicator of the cost of annual maintenance work on a project [42], quantified in five levels based on the difficulty of the annual maintenance work on the project, as shown in Table 2.

(4) Possibility of Obtaining External Funding (POEF)

The Possibility of Obtaining External Funding (POEF) is the product of the proportion of external obtain to finance and the probability [43], and is classified into five levels. See Table 2 for details.

$$\text{POEF} = \text{PrF} \times \text{p} \tag{10}$$

4.2.2. Social Assessment for UUUT

The influence of the social dimension on the investment decision of UUUT is reflected in the direct or indirect role of the direct users and maintainers. We measure this in terms of the six dimensions of Improved Service Quality (SQI), Improved Service Capacity(SCI), Employment Creation (EC), Social Acceptability (SA), Functional Urban Areas (FUAs) and Urban Population Density (UPD) resulting from investment projects [21].

(1) Service Quality Improvement (SQI)

Investment projects are all aimed at improving service quality and enhancing service capacity. SQI is evaluated in terms of the project's safety performance, project accessibility, cultural and educational access, public health and social security, and social cohesion. The project's SQI score is determined by the cumulative value.

(2) Service Capacity Improvement (SCI)

The more residents a utility project can serve, the greater the social benefits it will provide, and the project's Service Capacity Improvement score is based on the incremental user level.

User increment levels are divided into 5 levels according to 5 degrees of very high, high, medium, low, and very low, corresponding to 5 scores as shown in Table 3.

(3) Employment Creation (EC)

Jobs are created at all stages of the project, but the stability of jobs created at different stages varies, with job stability at the construction stage being lower than at the operation stage. In addition, the number of jobs created directly by the UUUT is less than the number of jobs created indirectly, therefore, we calculate the project's employment creation capacity according to a ratio of 1:1:3 (Employment Creation capacity at the project construction stage [44]: Direct employment creation capacity at the utilization stage: Indirect employment creation capacity at the utilization stage), and the calculation metric is shown in (11), the values of CSE, UDE and UIE are shown in Table 3.

$$\mathrm{EC} = \rho 1 \times \mathrm{CSE} + \rho 2 \times \mathrm{UDE} + \rho 3 \times \mathrm{UIE} \tag{11}$$

(4) Social Acceptability (SA)

Public infrastructure projects cannot be considered 'sustainable' in the full sense if they are not acceptable to people as places to live, work and interact [45]. Utility tunnel are public infrastructure projects whose ultimate beneficiaries and users are the public, therefore, SA is one of the indicators that influence decisions. We have classified the SA into 5 levels and the corresponding scores are shown in Table 3.

(5) Functional Urban Areas (FUAs)

The city will continue to plan and build functional areas as the economy grows. The construction of UUUT must be in line with the city's future development plan. The more important the city's functional areas are, the higher the requirements for the city's image, and the higher the buildability of the UUUT.

(6) Urban Population Density (UPD)

Utility tunnel ultimately serve the urban population, therefore, population density has an impact on the investment decision for UUUT. We use the urban population density indicator [46] to measure the impact of population.

4.2.3. Environmental Assessment for UUUT

The environmental impact of public infrastructure projects needs to be evaluated. The environmental impact of UUUT is measured by the environmental contribution level index. The environmental contribution of a utility tunnel can improve the urban environment in many aspects, such as the appearance of the city, air quality and sound quality, which can be analyzed from seven aspects: (1) waste management, (2) energy efficiency, (3) water efficiency, (4) air quality, (5) sound quality, (6) biodiversity city, and (7) urban landscape [21]. The indicators for each aspect are set on a scale of five very low to very high, corresponding to a score of 1 to 5, as shown in Table 4, and the environmental contribution level score for utility tunnel is calculated by Equation (12).

$$\mathrm{ECIH} = \sum_{\mathrm{i}=1}^{7} es_i \tag{12}$$

Table 3. Indicators for evaluating social criteria.

Criteria	Indicators	Taxonomic Standards	Points
Social criteria	SQI	The project's safety performance, project accessibility, cultural and educational access, public health and social security, and social cohesion	
		Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1
	SCI	Incremental user level	
		Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1
	EC	CSE, UDE and UIE	
		Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1
	SA	Social acceptability	
		Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1
	FUAs	Importance of functional urban areas	
		Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1
	UPD	Urban population density	
		>1000 people/km^2	5
		201–1000 people/km^2	4
		101–200 people/km^2	3
		2–100 people/km^2	2
		0–1 person/km^2	1

Table 4. Indicators for evaluating environmental criteria.

Criteria	Indicators	Taxonomic Standards	Points
Environmental criteria	ECIH	*es* of (1) waste management, (2) energy efficiency, (3) water efficiency, (4) air quality, (5) sound quality, (6) biodiversity city, and (7) urban landscape	
		Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1

4.2.4. Assessment of the Technical Feasibility for UUUT

(1) Availability of Underground Space (AoUS)

Not all UUS can be developed, it is influenced by geological conditions, topography, surface architecture and technology and economy [3]. The lower the Availability of the Underground Space, the less suitable it is for the construction of UUUT. We classify the availability of underground space into 5 levels, and the higher the availability, the higher the score.

(2) Underground Traffic Complexity (UTC)

With the dramatic increase in urban population, the construction of subways and underground businesses has accelerated, and the underground transportation system has become increasingly complex. Therefore, we introduce the complexity of underground traffic to characterize the impact of underground traffic on the construction of UUUT, and classify the complexity into five levels.

(3) Pipeline Type Requirements (PTR)

A utility tunnel is a collection of multiple types of pipelines that can accommodate power cables, communication cables, gas lines, heating lines and water supply lines. In general, the more types of pipelines a utility tunnel can accommodate, the higher the need for construction, therefore, it is divided into five levels according to the number of types of pipelines to be accommodated.

(4) Pipeline Quantity Requirements (PQR)

Similarly, the number of pipeline accommodations is also one of the indicators influencing the construction of UUUT, therefore, the PQR is divided into five levels based on the number of proposed accommodations.

(5) Road Width (RW)

The construction of a utility tunnel can have an impact on road traffic. We have chosen the road width indicator to reflect this impact. The wider the road, the easier it is to construct a utility tunnel. Road widths are divided into 5 classes, with road widths of 1–9 m get 1 point, and greater than 36 m get 5 points (Table 5).

Table 5. Indicators for evaluating technical criteria.

Criteria	Indicators	Taxonomic Standards	Points
Technical criteria	AoUS	Availability of underground space	
		Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1

Table 5. *Cont.*

Criteria	Indicators	Taxonomic Standards	Points
Technical criteria	UTC	Extent of conflict with underground transportation systems	
		Very high	1
		High	2
		Medium	3
		Low	4
		Very low	5
	PTR	Types of pipelines that can be accommodated in utility tunnel	
		5	5
		4	4
		3	3
		5	2
		1	1
	PQR	Number of pipelines that can be accommodated in utility tunnel	
		Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1
	RW	Road width	
		>36 m	5
		28–36 m	4
		19–27 m	3
		10–18 m	2
		1–9 m	1

4.2.5. Determination of the Value Function for Each Indicator

In the decision-making system established in this paper, there are both qualitative and quantitative indicators, using different units and ratios depending on their meaning. Therefore, a value function is needed to standardize the indicators and to be able to represent the satisfaction of the decision maker. The value function is a single mathematical function that converts the qualitative and quantitative variables of the indicator and their different units and scales into a single scale from 0 to 1. This study utilizes previous research [47] as its value function and the value function is determined based on the decision maker satisfaction into Incremental functions (I) and Decreasing functions (D), and classified into Linear (LR), Concave (CE), Con-vex (CX), or S-shaped (S) according to the increasing or decreasing trend of satisfaction. Table 6 gives the value function types for each indicator of the decision model developed in this paper [5].

Table 6. Value function and parameters for each indicator.

Indicator	Xmin	Xmax	Fi	Ci	Ki	Bi	Shape
Project Economic Benefit (PEB)	1.0	5.0	0.8	2.0	0.8	1.33	I-LR
Annual Unit Cost (AUC)	1.0	5.0	2.5	2.5	0.5	1.25	D-S
Annual Maintenance Cost (AMC)	1.0	5.0	1.0	5.0	3.0	1.10	I-CE
Possibility of Obtaining External Funding (POEF)	1.0	25.0	2.0	12.0	1.0	1.02	I-S
Service quality Improvement (SQI)	4.0	20.0	2.0	10.0	1.0	1.08	I-S
Service capacity Improvement (SCI)	1.0	5.0	1.0	4.0	2.0	1.16	I-CE
Employment creation (CE)	1.0	5.0	1.5	5.0	1.0	1.96	I-CX
Social acceptability (SA)	1.0	5.0	1.0	2.5	1.0	1.25	I-LR
Functional urban areas (FUAs)	1.0	5.0	2	2.5	0.5	1.39	I-LR
Urban population density (UPD)	1.0	5.0	0.8	2.0	0.8	1.33	I-LR
Environmental contribution index horizontal (ECIH)	5.0	25.0	2.0	20.0	2.0	1.16	I-S
Availability of underground space (AoUS)	1.0	5.0	1.0	2.0	1.0	1.16	I-LR
Underground Traffic Complexity (UTC)	1.0	5.0	3.0	0.2	0.1	1.00	I-LR
Pipeline type requirements (PTR)	1.0	5.0	1.0	2.5	0.5	1.82	I-LR
Pipeline quantity requirements (PQR)	1.0	5.0	2.0	2.0	0.8	1.04	I-LR
Road width (RW)	0.0	5.0	1.0	2.5	1.0	1.16	I-LR

Then the indicator value can be calculated accordance with Equation (13).

$$\mathrm{IV}_i = B_i * [1 - e^{-Ki*(\frac{|X - X_{min_i}|}{C_i})^{F_i}}] \quad (13)$$

where

IV_i is the value of the indicator being evaluated

B_i is a factor that allows the function to remain within the range from 0 to 1. It is assumed that the highest level of satisfaction has a value of 1. This factor is determined by Equation (14).

X_{min_i} is the point of minimum satisfaction, with a value of 0.

X_{max_i} is the point of maximum satisfaction, with a value of 1.

X is the abscissa that generates a value equal to IV_i.

F_i defines approximately the shape of the curve: concave, convex, linear or S-shaped. If $F_i < 1$ the curve is concave; if $F_i > 1$ the curve is convex or S-shaped; if $F_i = 1$ it is linear.

C_i is a parameter that approximately defines the x-value of the point of inflexion for curves with $F_i > 1$.

Ki is a parameter that approximately defines the y-value at the point C_i.

$$B_i = [1 - e^{-Ki*(\frac{|X_{max_i} - X_{min_i}|}{C_i})^{F_i}}]^{-1} \quad (14)$$

4.3. PIUT (Prioritization Index for UUUT)

From a sustainability perspective, decisions on urban underground integrated tunnels are influenced by four aspects: social, economic, environmental and technical. Referred to F. Pardo-Bosch and A. Aguado [48], this research defines the Priority Index for Utility Tunnel (PIUT) to characterize the feasibility and priority of the project, and the PIUT is calculated by multiplying the score of each layer by the weight of each layer, as shown in Equation (14).

$$\mathrm{PIUT}(P_X) = 100 \times \sum \omega c_i \times \omega i_i \times IV(P_X) \quad (15)$$

The symbols in the formula are as follows:
PIUT(P_X) indicates the constructability score of the utility tunnel;
$IV(P_X)$ represents the score of the value function of each indicator;
ωi_i represents the weight of the indicator layer;
ωc_i represents the weight of the criteria layer.

The value of PIUT is in the range of [0,100], and the lower the score, the lower the buildability it has. Based on the PIUT score, decision makers can analyze the buildability of the project or compare different construction options to determine the optimal solution. The buildability of UUUT is classified into five levels, characterizing the level of contribution to project sustainability, as shown in Table 7. Level A indicates that the project is socially, economically, environmentally, and technically beneficial and can be carried out as soon as possible, while level E indicates that the project is poorly sustainable, unsuitable under current conditions, and recommended for rejection. According to Pardo-Bosch and Aguado [49], investment projects may hardly score over 80 due to the highly demanding requirements of a multi-criteria analysis. At the same time, it is unlikely to get projects with an E level score, as those are directly rejected beforehand for its obvious lack of contribution to sustainability.

Table 7. The level of PIUT.

Level A	Level B	Level C	Level D	Level E
$100 \leq$ PIUT ≤ 80	$80 \leq$ PIUT ≤ 60	$60 \leq$ PIUT ≤ 40	$40 \leq$ PIUT ≤ 20	$20 \leq$ PIUT ≤ 0

After considering the social, economic, environmental and technical benefits of a UUUT project, the calculated PIUT can be used to evaluate and make decisions on the sustainability of the proposed project, as well as to compare and select multiple options. In this sustainability perspective, the decision to consider the option benefits of the project is more objective and realistic, and can be used to guide the relevant government departments to make scientific decisions.

5. Case Study

5.1. Background of the Case

UUUT has many advantages such as large carrying capacity, high service level, extending the service life of municipal pipelines and saving underground space resources. Therefore, China began to vigorously promote the construction of UUUT. At present, the investment decision of UUUT is still based on the traditional method of decision analysis, lack of sustainable perspective investment comprehensive decision making method, and economic evaluation is still using the NPV method or other traditional methods. In this context, we propose a comprehensive sustainability evaluation model and real option theory method, to evaluate the suitability of the proposed UUUT. This section applies the proposed investment decision model through a case simulation analysis.

The case project is divided into four sections with a total length of 18,788.469 m, with two silos of underground pipeline corridors. Silo A is loaded with 10 kv high-voltage power lines, and silo B is loaded with heating lines, water supply lines, source water lines, and telecommunication lines, with a single pipeline set up for each type of setting. Table 8 shows the background information of the case project.

Table 8. The background information of the case project.

Information	Value	
Urban population	1 million people	
Urban population density	600 persons/km^2	
Number of people served by the project	100,000	
Number of jobs created during construction	100	
Number of jobs created directly at the utilization stage	30	
Number of jobs created indirectly at the utilization stage	200	
Contribution to the environment	Contribution to waste management	Medium
	Contribution to energy efficiency	High
	Contribution to water efficiency	High
	Contribution to air quality	Very low
	Contribution to sound quality	Very low
	Contribution to biodiversity	Very low
	Contribution to the urban landscape	High
Project construction period	2 years	
Project operation period	20 years	
Project construction costs	147,756,001 USD	
Project operating costs	1.06 million USD/year and growing 2% year over year	
Project operating profit	9.93 million USD yuan/year	
Amount of government subsidy	6.66 million USD yuan/year	
Construction of the pipeline involves the average width of the road	32 m	

5.2. Calculation of the Option Value of the Project

The UUUT can collect income from utility tunnel entry fees, rental fee and property fee to realize the return on investment. Taking into account the proportion of the cross-sectional space used by different users.

To simplify the calculation, a fixed price system is adopted for the financial benefit analysis of the project, based on the price in 2019, without considering the price increase factor during the calculation period. With reference to China's UUUT project, a financial benchmark yield of 6% is assumed, and the 5-year treasury bond issuance rate of 4.27% in 2018 is used as the risk-free interest rate. The lower limit of volatility of the stock market of 4% is taken as the volatility calculated in this case.

Based on the above information and assumptions, Table 9 presents a simplified cash flow statement for the project.

Based on Equations (5)–(7), calculate the NPV:

$$V = \sum_{i=t}^{i=T_C} \frac{CI_i - CO_i}{(1+r)^i} = 16,605.31$$

$$I = \sum_{i=0}^{i=t-1} \frac{I_i}{(1+r_f)^i} = 14,357.42$$

$$NPV = V - I = 2247.88$$

Table 9. Simplified cash flow statement (unit: USD).

Year	2019	2020	2021	2022	2023	2024	2025
Construction costs	7387.80	7387.80	0.00	0.00	0.00	0.00	0.00
operating costs	0.00	0.00	105.71	107.82	109.98	112.18	114.42
Government subsidies	0.00	0.00	665.68	665.68	665.68	665.68	665.68
operating profit	0.00	0.00	992.56	992.56	992.56	992.56	992.56
Net cash flow	−7387.80	−7387.80	1552.53	1550.42	1548.26	1546.06	1543.82

Year	2026	2027	2028	2029	2030	2031	2032
Construction costs	0.00	0.00	0.00	0.00	0.00	0.00	0.00
operating costs	116.71	119.04	121.42	123.85	126.33	128.85	131.43
Government subsidies	665.68	665.68	665.68	665.68	665.68	665.68	665.68
operating profit	992.56	992.56	992.56	992.56	992.56	992.56	992.56
Net cash flow	1541.53	1539.20	1536.82	1534.39	1531.91	1529.38	1526.81

Year	2033	2034	2035	2036	2037	2038	2039	2040
Construction costs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
operating costs	134.06	136.74	139.48	142.27	145.11	148.01	150.97	153.99
Government subsidies	665.68	665.68	665.68	665.68	665.68	665.68	665.68	665.68
operating profit	992.56	992.56	992.56	992.56	992.56	992.56	992.56	992.56
Net cash flow	1524.18	1521.50	1518.76	1515.97	1513.13	1510.23	1507.26	1504.25

From the traditional NPV investment decision methodology, the project's NPV is greater than zero and the project is recommended for execution. However, based on the option value perspective, it is not realistic to reflect the economics of the UUUT through NPV alone as the project will be in operation for a long time. In addition, the potential benefits such as the technological growth of employees and the export of brand culture after the implementation of the utility tunnel project should also be considered, so it is more realistic to consider the option value of the project from a expansion option perspective.

According to Equations (1)–(3), the expansion option value of the project is:

$$C(V,t) = VN(d_1) - Ie^{-r(T-t)}N(d_2) = 13{,}799.73$$

5.3. PIUT of the Case

Based on the previous explanation of the indicators, the observations for each indicator were calculated based on the relevant case data in Table 8, and the results are shown in Table 10.

Table 10. Case project scores for each indicator.

Criteria	**Indicator**	**Calculation Method**	**Point**
Economic criteria	Project Economic Benefit (PEB)	ENPV/Cost × 100%	5
	Annual Unit Cost (AUC)	Total cost/Expected life cycle	5
	Annual Maintenance Cost (AMC)	7.26 million yuan/year (Medium)	3
	Possibility of Obtaining External Funding (POEF)	PrF × p	25

Table 10. *Cont.*

Criteria	Indicator	Calculation Method	Point
Social criteria	Service quality Improvement (SQI)	Background information	13
	Service capacity Improvement (SCI)	Background information	3
	Employment creation (CE)	$\rho 1 \times CSE + \rho 2 \times UDE + \rho 3 \times UIE$	4.2
	Social acceptability (SA)	Background information	5
	Functional urban areas (FUAs)	Background information	2
	Urban population density (UPD)	Background information	4
Environmental criteria	Environmental contribution index horizontal (ECIH)	$\sum_{i=1}^{7} es_i$	18
Technical criterion	Availability of underground space (AoUS)	Background information	4
	Underground Traffic Complexity (UTC)	Background information	4
	Pipeline type requirements (PTR)	Background information	5
	Pipeline quantity requirements (PQR)	Background information	4
	Road width (RW)	Background information	4

The indicators have different units and different scopes, and need to be normalized to the value function selected for each of the indicators in the preceding section. Table 11 presents the scores for each indicator after normalization.

Table 11. Indicator value (IV).

Criteria	Indicator	$\mathbf{IV}_i$
Economic criteria	PEB	0.9014
	AUC	0.9824
	AMC	0.3559
	POEF	0.9830
Social criteria	SQI	0.5843
	SCI	0.4391
	CE	0.6328
	SA	0.8653
	FUAs	0.1988
	UPD	0.8412
Environmental criteria	ECIH	0.3865
Technical criterion	AoUS	0.8236
	UTC	1.0000
	PTR	0.9453
	PQR	0.9042
	RW	0.8428

Then:

$$\mathrm{PIUT}(P_X) = 100 \times \sum \omega c_i \times \omega i_i \times IV(P_X)$$

Considering the four indicators of economy, society, environment and technology, the feasibility of case project construction scores 72.07 points, belongs to the B grade project, and is recommended to be carried out. In terms of the weighting of indicators, the economic benefit of the project is still one of the key indicators that investors focus on. In addition, if only the NPV of the project is considered, when the NPV is negative, investors may give up the investment because of the economic value of the project and ignore the added value of the underground integrated pipeline, resulting in investors losing some valuable investment opportunities.

5.4. Results and Discussion

In practical implementation, there may be a requirement to consider the weightings of certain indicators due to policy requirements or real-world constraints. Similarly, there may be a need to de-emphasize certain factors or aspects of the model in order to account for these constraints. This study conducts a sensitivity analysis to examine the sensitivity level of all indicators in the early-stage decision-making process for the construction of urban underground utility tunnels. The impact of changes in the weight of each indicator on project evaluation and selection results is analysed.

In order to analyze the impact of investor preference and uncertainty risk on the investment decision of the UUUT project, economic, social, environmental, and technical indicators were set as maximum weights respectively. In this case, the economic indicators have been given the maximum weighting, so Hypothesis 1 is the original case. Hypothesis 2, 3 and 4 are three scenarios in which the decision maker focuses on the social, environmental and technical impacts of the project, and the weights for each scenario are shown in Table 12.

Table 12. Requirement weights used for sensitivity analysis.

Hypothetical Scenario	Economic Criteria	Social Criteria	Environmental Criteria	Technical Criterion
H1	0.51	0.15	0.26	0.08
H2	0.20	0.40	0.20	0.20
H3	0.20	0.20	0.4	0.20
H4	0.20	0.20	0.20	0.40

In addition, in order to explore the impact of changes in indicator weights on the multiple option comparison, the study added four cases to the original case data, as shown in Table 13.

The results corresponding to each hypothesis are shown in Figure 3.

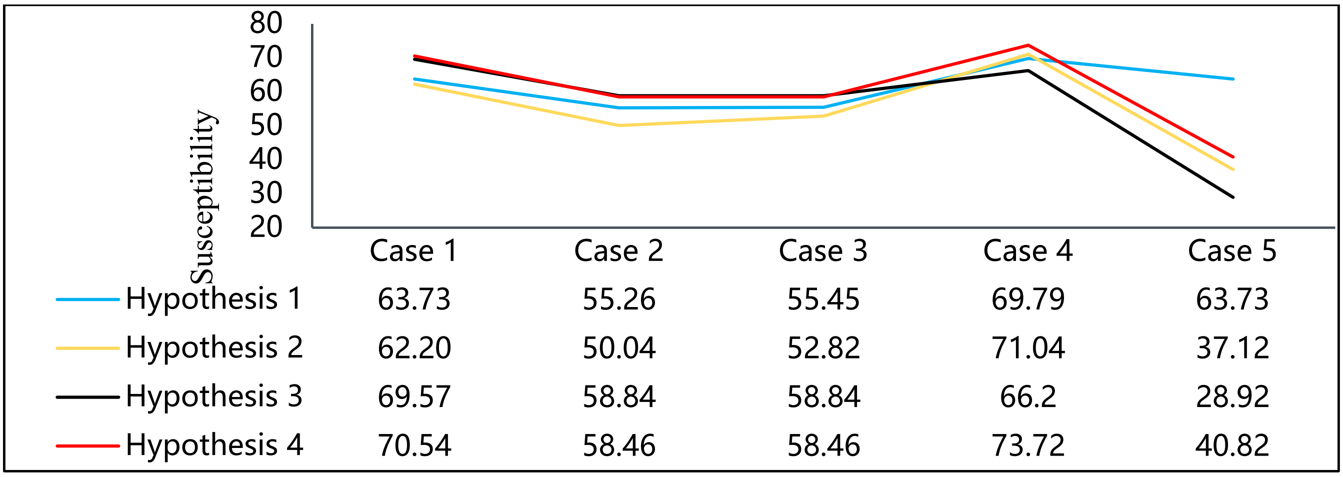

Figure 3. The result of sensitivity analysis.

As shown in Figure 3, the case is rated B under all four assumptions which means that it is recommended regardless of the decision maker's preference for economic, social, environmental and technical aspects. In addition, from the results of the sensitivity analysis, it can be seen that a change in the weighting priority of the influencing indicators will not affect the final results of the competition. Thus from the sensitivity analysis it can be seen that the model allows for the adjustment of the weights of the various influences and can cope with the uncertainty of future use where adjustments to specific influences are required.

Table 13. Basic data of 5 cases for sensitivity analysis.

Indicator	Case 1	Case 2	Case 3	Case 4	Case 5
Project Economic Benefit (PEB)	4612.76	3000	2000	5000	6000
Annual Unit Cost (AUC)	3	2	2	5	4
Annual Maintenance Cost (AMC)	25	20	15	20	5
Possibility of Obtaining External Funding (POEF)	5	4	3	4	2
Service quality Improvement (SQI)	13	10	11	18	8
Service capacity Improvement (SCI)	3	1	2	3	4
Employment creation (CE)	4.2	3.4	2	3	4
Social acceptability (SA)	5	3	1	4	2
Functional urban areas (FUAs)	2	3	3	4	2
Urban population density (UPD)	4	2	4	5	4
Environmental contribution index horizontal (ECIH)	18	20	25	20	5
Availability of underground space (AoUS)	4	4	5	3	2
Underground Traffic Complexity (UTC)	4	1	3	3	4
Pipeline type requirements (PTR)	5	2	3	4	2
Pipeline quantity requirements(PQR)	4	4	1	3	2
Road width (RW)	4	4	3	5	2

6. Conclusions

Urban underground space is a non-renewable resource of the city, and the government must consider the sustainability of urban underground space when conducting urban master planning. UUUT are considered to be one of the sustainable urban underground space infrastructure. The sustainability of the UUUT should be considered at an early stage of planning in order to make rational use of the urban underground space. Therefore, an objective and scientific sustainability evaluation model is very important for government departments to make decisions on utility tunnel projects. This study proposes to use MIVES to measure economic, social, environmental and technical indicators in a quantitative and unified way, and to apply the real option theory, which is closer to the actual situation of the project, to calculate the economic benefits of the utility tunnel project. Based on MIVES and real option theory, an investment decision model is developed to analyze the sustainability of a utility tunnel at the early planning stage. The established investment decision impact index system of UUUT project can be adjusted according to the different cities and the preferences of decision makers. We use a case study to validate the investment decision model proposed in this paper.

When planning and constructing UUUTs, governments generally focus on assessing the economic benefits of integrated pipeline corridor construction, while ignoring the social and environmental benefits as well as the technical feasibility of underground urban utility tunnel construction. The main contributions of this paper are: (1) the established investment decision framework can assist the government in the early analysis of the sustainability of underground urban utility tunnel project, and can also be used to select and rank multiple options; (2) from the perspective of sustainable development, an investment index system for UUUT is established, which includes social, environmental, economic and technical aspects. Particular consideration has been given to the technical influences on the construction of UUUT, an aspect that is considered by experts to be of secondary importance (The economic impact has the highest weight, accounting for 40.33%, followed by the technical impact, accounting for 23.87%); (3) the real option theory is combined with the MIVES sustainability assessment model, which takes into account the uncertainty of public infrastructure projects and the value of management flexibility, making the sustainability assessment of underground urban utility tunnel more in line with objective reality.

The index system established in this study may have a certain subjectivity due to the final determination of factors and the determination of weights based on the experience and knowledge of relevant experts. In the future, based on the index system in this research, more historical data from infrastructure projects can be referred to establish another index system for similar types of projects. Additionally, the potential for integrating this investment decision model with GIS technology for underground urban utility tunnel planning can be investigated.

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