

Article

Research on Ecological Design of Intelligent Manhole Covers Based on Fuzzy Analytic Hierarchy Process

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Abstract: In response to the global demand for sustainable development in urban areas, there is an urgent need to enhance the ecological environment of urban areas. Urban renewal through sponge cities has become an effective method for achieving this goal. As one of the most dynamic elements in urban spaces, manhole covers play a crucial role in enhancing the city's image. To facilitate urban redevelopment effectively, improve the functionality of urban manhole covers, and promote sustainable urban development, this study explores ecological design factors for urban manhole covers, providing recommendations for future designs in China. Grounded on existing literature research and the urban redevelopment planning of the central district in Maanshan City, the FAHP method was used to determine the weights of five indicators containing environmental esthetics, ecological sustainability, intelligent detection, intelligent interaction, and safety, and scientifically constructed the ecological design and evaluation index system of intelligent grass pot manhole cover. The weighted average algorithm was used to obtain the index priority ranking, and the most critical elements were selected for design and refinement. The evaluation results indicate that safety, ecological sustainability, and the enhancement of the ecological design of intelligent manhole covers show the most significant improvement. The research outcomes can be used as a reference for enhancing urban ecological environments, promoting urban regeneration, and advancing sponge city construction.

Keywords: intelligent manhole cover; ecological design; FAHP; urban renewal; sponge city



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1. Introduction

Urban flooding and water scarcity issues are becoming more prevalent as climate change accelerates and urbanization progresses, leading to an increased likelihood of overload in existing urban stormwater facilities and a negative impact on natural water resources [1,2]. Water resource management plays a vital role in the sustainable development of smart cities [3]. The rational planning and intelligent upgrading of urban stormwater facilities are critical elements in ensuring the sustainable development of urban rainwater resources and preventing urban waterlogging [4]. In April 2012, China first introduced the concept of “sponge cities” [5], aiming to follow the principles of ecological sustainable development. This involves implementing sponge-like designs in buildings, roads, green spaces, and urban infrastructure to strengthen urban water resource planning and management. These designs aim to absorb, regulate, and release rainwater, achieving natural accumulation, infiltration, and purification [6].

Urban stormwater manhole covers play a vital role in the construction of sponge cities. They are an essential component that helps to manage and absorb excess rainwater, preventing floods and alleviating pressure on urban drainage systems. While reducing urban flooding, the solution also needs to prioritize improving water quality and facilitating rainwater harvesting and reuse [7]. Combining green infrastructure with stormwater management facilities, such as grass basins and intelligent rainwater manhole covers, is a perfect solution to meet the requirements of sponge city facilities. As urban infrastructure

for environmental greening, grass basins require water resources for irrigation. The integration of intelligent rainwater manhole covers can create a more systematic, intelligent, and ecological sponge facility. It not only ensures a stable water supply for plants but also reduces urban flooding and mitigates water scarcity issues [8]. Furthermore, the design of intelligent grass manhole covers with sponge features enhances the esthetic appeal of urban space and seamlessly integrates with other landscape elements.

Following years of urban growth, urban renewal emerges as a crucial approach to enhance urban infrastructure, establish thriving urban brands, and cater to the expanding needs of city residents [9]. Urban public infrastructure must continuously enhance ecological civilization and urban quality to build livable, intelligent, and sustainable city brands amid urban reconstruction [10]. The idea of creating “smart cities” has led to the advancement of stormwater infrastructure in urban areas. The emergence of affordable intelligent sensors and advanced data transmission technologies has enabled seamless communication between devices and people, driving the intelligent growth of urban areas [11]. City manhole covers are upgraded to enhance practicality and add an artistic effect to the city’s ecological corridors [12]. Combining smart technology with ecological culture can improve urban manhole covers, creating an ecological space that emphasizes the fusion of ecology, technology, and nature.

The approach of ecological product design considers environmental impacts to guide sustainable design decisions [13]. Choosing a satisfying design solution is a crucial decision during the early stages of new product development. The objective of this research is to use the F-AHP method to tackle the problem of multi-criteria decision-making in urban manhole cover design. It will simultaneously identify evaluation criteria for ecological design and create an ecological design evaluation system.

When faced with multiple criteria, selecting the best product design is a typical multi-criteria decision-making problem, as noted by Vinodh and Kamala [14]. Ecological design can be considered a crucial design criterion [15]. The Analytic Hierarchy Process (AHP) is a popular method used for multi-criteria decision analysis. This method employs a nine-point scale for pairwise comparisons. However, expressing human judgment and preferences accurately through clear numerical values can be challenging due to the inherent uncertainty in human perception. To address the uncertainty, Ahmed proposed combining fuzzy sets with pairwise comparisons. Fuzzy numbers were used to more realistically express human judgment [16]. Fuzzy AHP is widely used in fields like ecology and hydrology for monitoring ecological risks in river corridors and evaluating water resource management plans [17,18].

Building upon previous research, there exists a considerable scope for expansion within the current domain of intelligent manhole cover design. On one hand, existing studies predominantly focus on the technological and artistic aspects of manhole covers. However, within the context of the evolving trend towards ecological smart city development, characterized by the “dual-carbon” initiative, there is still a notable lack of comprehensive research on the ecological design of intelligent manhole covers. On the other hand, further exploration is warranted in the application of the FAHP in intelligent manhole cover design. Simultaneously, practical implementation of FAHP in the development of intelligent manhole cover products remains relatively scarce. Therefore, by employing FAHP to evaluate and rank the ecological design elements of intelligent manhole cover products, guiding product development practices, and conducting ecological design assessments, it is possible to integrate user requirements with ecological design principles. This integration can provide design decision support for optimizing intelligent manhole covers in terms of technology, artistry, culture, usability, and environmental sustainability. This approach facilitates the expansion of innovative thinking in the design of intelligent manhole cover products and introduces new systematic optimization methods for ecological design and evaluation of products.

The paper was organized as follows: Section 1 describes the research background and methodology of this paper. Section 2 clarifies the study location and methods. Section 3

details the ecological design plan for smart grass basins and outlines the practical implementation process. Section 4 assesses the design implementation through a design evaluation. The final section includes the conclusion and summary.

2. Materials and Methods

2.1. Research Location

Maanshan City, a famous industrial city in Anhui Province, China, was selected to analyze the ecological design and evaluation indexes of intelligent manhole cover. Maanshan City (Figure 1) is located in the eastern part of Anhui Province and built on rich iron ore resources. Based on the new development situation, Maanshan City is paying more and more attention to creating a good urban ecological environment. In order to standardize the construction and management of sponge city, improve the urban ecological environment, and build a sponge city with abundant rainfall in the Yangtze River Delta, in July 2022, Maanshan City launched the urban renewal plan of the central urban area (Figure 2). The regeneration of city units is divided into 5 blocks and 15 groups, among which the reconstruction of old residential areas is the key object of reconstruction. In the process of city regeneration, as the “rivet” and a key part of the city’s rainwater system in Maanshan City [19], which belongs to the north subtropical humid monsoon climate, the climate is warm and humid, and the rainy season coincides with the heat; Maanshan City has an annual average rainfall of 1100 mm, and July is the month with the most rainfall in a year, with an average monthly rainfall of 182.5 mm over many years. Based on the climate background of the city, the drainage work is crucial, and the good or bad function of manhole covers in the city to some extent affects people’s overall satisfaction with the city [20], so its update design is crucial.

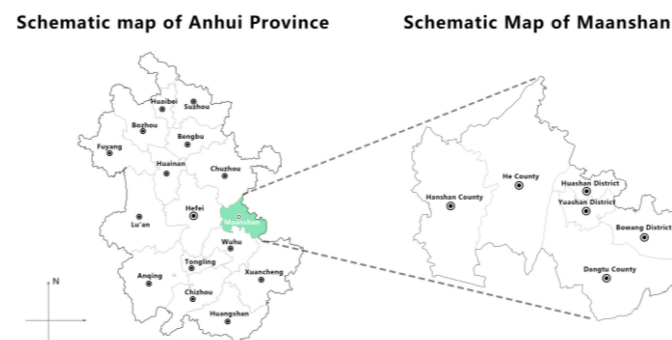


Figure 1. The location of Maanshan City in Anhui Province.

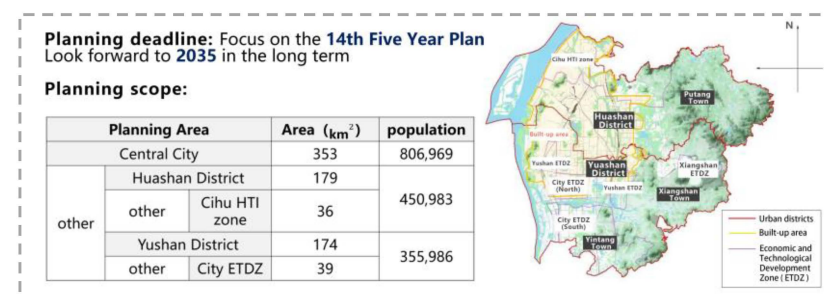


Figure 2. Urban renewal plan for the central urban area of Maanshan.

This study takes the urban manhole cover in the urban renewal planning of Maanshan City as the breakthrough point and combines the design requirements of ecology, intelligence, innovation, and the feedback of public evaluation to complete the ecological design and evaluation of the urban intelligent manhole cover in Maanshan City.

2.2. Ecological Design

Ecological design originates from people's reflections on the deterioration of the earth's environment. Eco-design is also called green design, among which the "3R" principle of green design is widely known, and then the 5R principle [21] and 10R principle [22] have been proposed. The "3R" principle is "Reduce" to reduce pollution, "Recycle" to recycle, and "Reuse" to reuse. In 2002, the Chinese Academy of Engineering and the German chemical company BASF introduced the 3R principle, and in 2005, the 5R principle (Reduce, Reuse, Recycle, Rethink, Repair) was formulated on the basis of the 3R principle at the global Thinkers Forum. In today's world of sustainable development, there is a global call for green economic activities and lifestyles, and thus the 10Rs have been proposed, with additions including recharging (or refilling), remanufacturing, replacing (or re-adding), cleaning (or refining), and removing. In today's sustainable development, the world calls for green economic activities and lifestyles. Scholars have summarized five principles of ecological design, i.e., optimal use of resources, optimal use of energy, minimization of pollution, humanization, and technological advancement [23]. The principle of optimal use of resources and energy requires using environmentally friendly materials and clean energy and improving the utilization rate of various resources. The principle of minimization of pollution requires the reduction or elimination of ecological pollution throughout the life cycle of the product as much as possible. The principle of humanized design requires that product design should not only conform to ergonomics but also meet people's physiological and psychological needs. The principle of technological advancement emphasizes the provision of technologically advanced green products to meet social needs.

In addition, the following ecological design methods can be used in the specific design process: (1) Life cycle design [24]: this method aims to ensure that the product minimizes resource consumption and environmental impact throughout its life cycle [25]. (2) Detachable design: in the product design process, the easy disassembly, maintenance, and recycling of the product are considered to reduce resource waste. (3) Modular design: this refers to the decomposition of the product into independent standardized modules so as to achieve the flexibility and scalability of product parts [26]. (4) Recycling design: emphasizing that after the end of the product life, the waste will be turned into valuable resources, which is in line with the circular economy model [27] and realizes sustainable development. (5) Manufacturing and assembly design (DFMA): help reduce assembly costs by improving the assembly process and minimizing the number of parts [28], thereby reducing the production cost of the product and achieving the maximum economic benefit [29].

2.3. FAHP

Based on the fuzzy comprehensive evaluation method and the analytic hierarchy process, scholars have proposed the fuzzy analytic hierarchy process, namely FAHP [30]. This method can effectively solve the error problem caused by the traditional AHP method, which is easily affected by individual extreme values and subjective judgments of respondents [31].

2.3.1. Implementation Steps of FAHP Weight Calculation

1. Construct the hierarchical structure model: This model includes three levels, i.e., the target level, guideline level, and indicator level. The guideline level is subordinate to the target level, and the indicator level is subordinate to the guideline level. Users' needs obtained through methods such as questionnaire surveys and on-site interviews will be filtered and summarized for constructing this model, as shown in Figure 3.
2. Constructing the fuzzy judgment matrix: A key step in the FAHP method, the purpose is to compare the relative importance between indicators at the same level and the relative importance of each indicator to the indicators of the higher level. Subsequently, the obtained important comparisons are quantified. The fuzzy judgment reference is shown in Table 1, where experts score the indicators based on this table, construct the judgment matrix, and calculate the indicator weights.

Assuming the upper-level parent indicator T includes the lower-level sub-indicators $r_1, r_2, r_3, \dots, r_n$, where n is the number of indicators or the matrix order, referring to the above table, pairwise comparisons of the indicators result in the fuzzy judgment matrix Q :

$$T = (r_{ij})_{n \times n} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \quad (1)$$

In the formula, r_{ij} represents the comparison between factors r_i and r_j , $i, j = 1, 2, \dots, n$.

3. Calculation of indicator weights: After obtaining the fuzzy judgment matrix, calculations need to be performed on the matrix. In this paper, the summation method formula is used to calculate the weights [32]. The summation method is simple to calculate, can reach conclusion quickly, and at the same time, the calculation process of the summation method is less affected by external factors and has high stability and consistency. The summation method is suitable for most analytical scenarios, and the formula is as follows:

$$W_i = \frac{\sum_{j=1}^n r_{ij} + \frac{n}{2} - 1}{n(n-1)} \quad (2)$$

In this formula, W_i represents the weight of the indicator r_i , and n is the order of the matrix.

4. Consistency check: To ensure the correctness of the fuzzy judgment matrix, it is necessary to perform a consistency check on the obtained results. The calculation formula is as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

The consistency ratio (CR) is calculated as follows:

$$CR = CI/RI \quad (4)$$

In the formula, λ_{max} is the maximum eigenvalue of the judgment matrix. n is the order of the matrix. CI is the consistency index of the fuzzy judgment matrix. CR is the consistency ratio threshold. RI is the average consistency index of a large number of randomly generated pairwise comparison matrices of the same order, which serves as a benchmark to determine the extent to which the CI deviates from randomness, and the values of RI corresponding to different matrix orders (n) are shown in Table 2. Upon obtaining the result, if $CR \leq 0.1$, the fuzzy judgment matrix is considered to pass the consistency check. Otherwise, the judgment matrix needs to be readjusted until it passes the check.

5. Weight ranking of need indicators: The weight ranking is determined by comparing the values of the lowest-level factors relative to the higher-level factors. The comprehensive weight is obtained by multiplying the weight values of the two levels. Finally, the weight ranking of each lowest-level indicator relative to the target layer is obtained, and a consistency check is performed again.

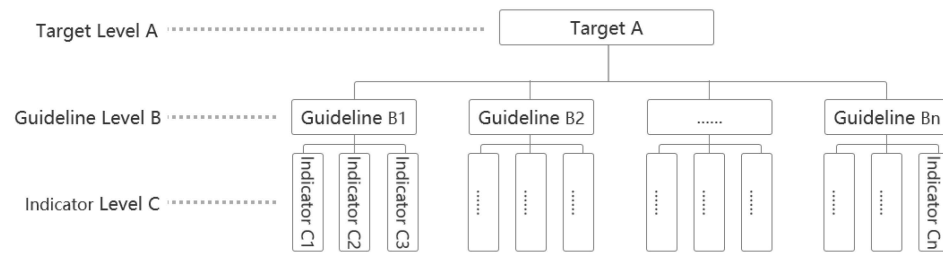


Figure 3. Indicator hierarchy model.

Table 1. Quantization of the FAHP 9-point scale.

Scale q_{ij}	Definition	Explanation
1	Equally important	In comparison between factor i and factor j
3	Slightly important	In comparison between factor i and factor j
5	Clearly important	In comparison between factor i and factor j
7	Strongly important	In comparison between factor i and factor j
9	Absolutely important	In comparison between factor i and factor j
2, 4, 6, 8	The median value of the above two adjacent judgments	The relative importance level between the above two adjacent levels.
Reciprocal correspondence	Contrastive comparison	If the relative importance of factor i to factor j is r_{ij} , the relative importance of factor j to factor i is $1/r_{ij}$

Table 2. RI values of order 1–9 of the judgment matrix.

Matrix Order (n)	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

2.3.2. Implementation Steps of FAHP Evaluation

After completing the design, evaluate each indicator based on the indicator hierarchy model using the fuzzy comprehensive evaluation method. The evaluators are users interviewed during the construction of the indicator hierarchy. The implementation steps are as follows:

1. Determine the set of evaluation indicators $U = \{u_1, u_2, \dots, u_n\}$, where n is the number of evaluation indicators.
2. Establish the set of evaluation comments $V = \{v_1, v_2, \dots, v_m\}$.
3. Construct a single fuzzy evaluation matrix, that is, the fuzzy matrix $R = (r_{ij})_{n \times m}$ from U to V as follows:

$$R = (r_{ij})_{n \times m} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \quad (5)$$

where $i = 1, 2, \dots, n$; $j = 1, 2, \dots, m$; and r_{ij} represents the membership degree of the indicator u_i to the evaluation comment v_j .

4. Determine the weights of the evaluation indicators $A = (a_1, a_2, \dots, a_n)$, which is the indicator weight vector W calculated from Equation (2).
5. Calculate the evaluation comment vector by multiplying the fuzzy judgment matrix R with the weight vector A . This results in the final comment vector C for each individual indicator, as follows:

$$C = A \times R = (a_1, a_2, \dots, a_n) \times \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} = (c_1, c_2, \dots, c_m) \quad (6)$$

6. Analysis of the evaluation results involves applying a percentage scoring system principle. The final comment vector C is multiplied by the assigned scores of the evaluation comment set V , and the results s are added to obtain the final score S , as follows:

$$s = (s_1, s_2, \dots, s_m) = C \times V = (c_1, c_2, \dots, c_m) \times (v_1, v_2, \dots, v_m) \quad (7)$$

2.4. Construction of the Evaluation Indicator System

When developing the indicator hierarchy for the ecological design of the intelligent manhole cover, it is imperative to ground the framework on the aforementioned five principles of ecological design and corresponding methodologies. This process must be complemented by a thorough literature review and on-site investigations to establish a scientifically robust and practical indicator system for evaluating and guiding the ecological design of the intelligent manhole cover. By targeting the ecological design of the intelligent manhole cover as the focal point, the following specific guidelines and subsidiary indicators have been identified:

1. Environmental esthetics (B1): This dimension encompasses the seamless integration of the manhole cover into its surrounding urban landscape, fostering a visually appealing and harmonious esthetic. This objective aims to enhance the urban esthetic value contributed by the green spaces within the city [33]. In the design to reflect the specific factors are as follows: environmental greening (C1) in the manhole cover to reserve space to place the appropriate amount of green plants, to cover a large number of urban manhole covers with plants, to improve the urban green environment, to enhance the visual esthetics, and to protect the residents of the physical and mental health development [34]. Urban culture (C2) in the urban renewal design should consider the renewal of urban culture [35], design urban manhole covers with urban characteristics, history, and culture, such as extracting urban cultural symbols and patterns placed on the manhole covers, stimulating the public's sense of cultural identity, and promoting the development of urban culture. Environmental lighting (C3), i.e., LED light strips or spotlights, can be laid on the manhole covers located on the green space, which can illuminate the manhole cover design features, beautify the green space, and improve safety and visibility at night when the light is dim.
2. Ecological sustainability (B2): This dimension focuses on the design of manhole covers that align with the principles of green environmental protection and sustainable development. The ecological design of urban public facilities is essential for enhancing environmental performance, improving energy efficiency, and optimizing resource utilization [36]. Specific considerations in the design are as follows: environmentally friendly materials (C4), the materials of urban manhole cover design are prioritized to choose environmentally friendly materials that can be recycled so that they can be reused as other product materials after the end of the function of the manhole cover [37]. Environmentally friendly energy (C5), solar panels can be added to the manhole cover layout to utilize solar energy to power the cover and solve the battery pollution problem. New materials (C6): the main body of the manhole cover is designed to use new materials, such as carbon fiber, graphene sheet, ultra-molecular weight polyethylene, etc., so that the urban manhole cover has the characteristics of lightweight, high strength, and so on.
3. Intelligent detection (B3): This dimension encompasses the integration of sensors into manhole covers for comprehensive urban information monitoring. The following considerations can be made for the intelligent design of manhole covers: water detection (C7), with sensors set on the surface of the cover to monitor the overall precipitation of the city and detect water quality during rainfall, providing a data basis for the improvement of urban drainage [38]. Air detection (C8): well covers located in residential areas can be equipped with additional air detection equipment as appropriate to achieve multi-area interconnected detection, providing residents

with a reference for travel but also for sudden air pollution to indicate the direction. Equipment detection (C9) can be equipped with a well cover self-test system and real-time self-test component health status for maintenance personnel to replace parts to provide assistance [39].

4. Smart interaction (B4): This focuses on enhancing the user experience for both residents and maintenance personnel, serving as a crucial component in the implementation and management of urban renewal [40]. Embodied in the specific factors are as follows: emergency response (C10), well cover self-test system real-time monitoring of equipment integrity, in the event that the equipment suffers from abnormal disassembly, emergency alert management personnel. Easy assembly design (C11), to simplify the set of foundation materials and manhole cover body assembly mode, improves the traditional manhole cover assembly of non-replaceable. Modularized design (C12): modularize the internal parts of the cover to provide convenience for maintenance personnel to replace parts. Equipment interconnection (C13), network intelligent interconnection, can share information with other intelligent facilities in the city, such as the manhole cover from the intelligent street light to obtain energy, the street light from the manhole cover to obtain nighttime traffic information, and adjusting the lighting needs.
5. Security (B5): This aspect emphasizes the safety design of the manhole cover and its components to ensure their normal operation. Key considerations include the following: Anti-theft design (C14), such as special anti-theft structure, intelligent positioning system, combined with emergency response function. Waterproof design (C15), waterproof design for the external parts of the manhole cover from the aspects of material, structure, and sealing to ensure the normal operation of the electronic components. Structural design (C16), rationalization design of the position, and linking method of the internal parts structure of the manhole cover to ensure the stable operation of the overall function of the manhole cover.

Summarizing the guidelines and indicators mentioned above, the ecological design and evaluation indicator system for intelligent manhole covers is presented in Table 3.

Table 3. Ecological design and evaluation indicator system of intelligent manhole cover.

Target Level	Guideline Level	Indicator Level
Ecological Design and Evaluation of Intelligent Manhole Covers	B1: Environmental esthetics	C1: Environmental greening C2: Urban culture C3: Environmental lighting
	B2: Ecological sustainability	C4: Eco-friendly materials C5: Eco-friendly energy C6: New materials
	B3: Intelligent detection	C7: Water testing C8: Air detection C9: Device detection
	B4: Smart interaction	C10: Emergency response C11: Easy assembly design C12: Modular design C13: Device interconnection
	B5: Security	C14: Anti-theft design C15: Waterproof design C16: Structural design

2.5. The Design and Evaluation Process

The design and evaluation process of the intelligent manhole covers can be seen in Figure 4.

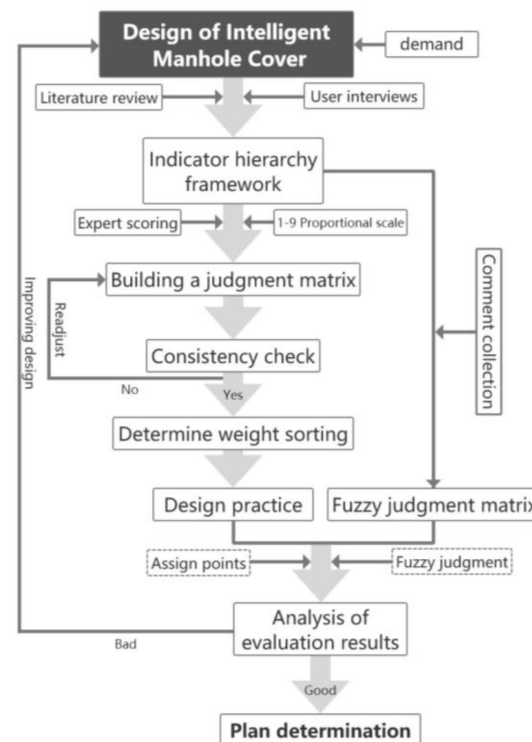


Figure 4. Design and evaluation process of intelligent manhole cover.

2.6. Calculation of Weight for Evaluation Indicator System

The smart manhole cover is a basic facility design that integrates city managers, maintenance personnel, and city residents. A fuzzy comprehensive evaluation was conducted for 9 design experts, 3 engineering experts, and 2 social management experts, and the indicators were evaluated and scored by 14 experts based on a quantitative FAHP 9-point scale. Following the outlined steps, based on the judgment matrix of the guideline level and the indicator level for each design element, we calculated the weight of the requirements and performed a consistency check.

The calculation process is shown in the attached table (Tables A1–A6), and the calculated weights and importance rankings for each criterion and indicator are shown in Table 4.

Table 4. Comprehensive weight and ranking of each evaluation indicator.

Guideline Level	W	Rank	Indicator Level	Weight of the Whole	Rank
B1	0.1408	3	C1	0.0646	5
			C2	0.0592	6
			C3	0.0170	13
B2	0.3404	2	C4	0.0466	8
			C5	0.1679	2
			C6	0.1259	4
B3	0.0639	5	C7	0.0090	16
			C8	0.0159	14
			C9	0.0391	10
B4	0.1017	4	C10	0.0340	11
			C11	0.0095	15
			C12	0.0408	9
			C13	0.0174	12
B5	0.3531	1	C14	0.1306	3
			C15	0.0484	7
			C16	0.1741	1

2.7. Analysis of Indicator Weight Results

Multiplying the weights of guidelines and indicators in the guideline level with those in the indicator level, we obtain the weights of all indicators relative to the target level. The visual representation of the data is presented in the following bar chart (Figure 5).

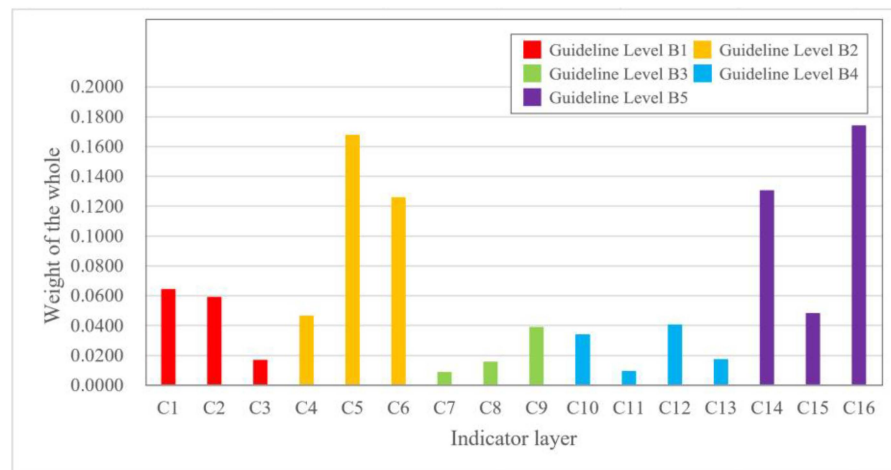


Figure 5. Bar chart of indicator weights.

From the bar chart, it is evident that in the ecological design of intelligent basin covers, the most important indicators are C5 “Eco-friendly Energy” and C6 “New Materials” under the B2 “Ecological Sustainability” guideline, and C14 “Anti-theft Design” and C16 “Structural Design” under the B5 “Security” guideline. This prioritization is determined by the paramount importance of safety and the overarching principles of ecological design. These factors should be given priority consideration during the actual design process as they represent essential attributes of the product.

The second most important indicators include C1 “Urban Greening,” C2 “Urban Culture,” C4 “Eco-friendly Materials,” C9 “Device Detection,” C12 “Modular Design,” and C15 “Waterproof Design.” In practical design, it is advisable to satisfy these indicators as much as possible, provided they do not conflict with the top-priority indicators, to ensure a positive user experience.

The last group of indicators, including C3, C7, C8, C11, and C13, are considered less crucial based on their lower position in the analysis results. Users may find these features less essential, and designers can consider them optionally or choose to omit them. Considering the importance analysis of these indicators, all indicators are categorized into three levels of importance (Table 5).

Table 5. The importance level of each indicator.

Importance Level	Indicator Layer
1	C5, C6, C14, C16
2	C1, C2, C4, C9, C12, C15
3	C3, C7, C8, C11, C13

3. Case Study

Utilizing the theoretical insights gained from the fuzzy analytic hierarchy process (FAHP) analysis of ecological design and evaluation for intelligent manhole covers, innovative practices are implemented in their ecological design. These covers, primarily installed in urban green spaces, are an integral part of the cityscape and foundational infrastructure.

Based on the results of weight calculation, in the environmental esthetic B1 level, according to the environmental greening index with the highest weight value, it is chosen to integrate the ecological grass pots with the manhole cover to give the manhole cover

the function of environmental greening. In the ecologically sustainable B2 level, the environmental energy has the highest weight value, and at the same time, because the electric energy required for the well cover product is not high, it is chosen to add solar panels as the source of energy supply for the well cover. In the intelligent detection B3 level, the air detection function has a higher weight, and combined with the high weight of safety in the guideline level, the gas detection function in the manhole cover should be added in the manhole cover design to detect the concentration of different gases. In the smart interaction B4 level, the emergency response and modular design requirements have high weights, so in the manhole cover design, the manhole cover information reporting function needs to be added and modular components should be used for easy installation and later maintenance. According to the calculation results of security B5 level, functional innovation should be carried out on the basis of ensuring the security and anti-theft of the well cover.

Under the ecological design philosophy, the manufacturing materials for manhole covers are carefully selected to be recyclable metals and composite materials. This choice aims to minimize production losses, enhance corrosion resistance, and extend the lifespan of the covers. The use of these materials aligns with the principles of green environmental protection and sustainable development. The intelligent manhole cover serves as a carrier for various sensors, such as angular velocity sensors, laser rangefinders, and gas sensors [41]. This integration enables the collection of crucial data on the inclination, movement, underground gas, liquid levels, and other relevant parameters. By utilizing communication technologies, these data are seamlessly interconnected with a digitized monitoring platform. Maintenance personnel can access real-time safety information about the manhole covers through terminals [42] (Figure 6).

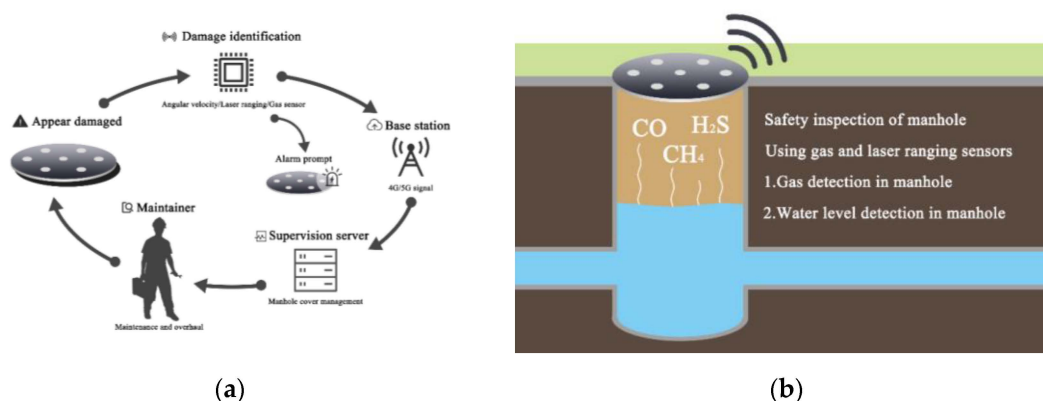


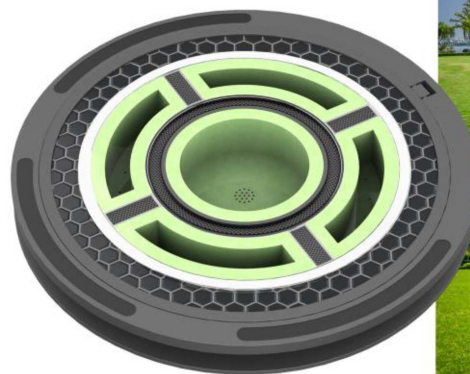
Figure 6. (a) Intelligent manhole cover principle. (b) Inspection of the manhole.

The intelligent manhole cover design solution, obtained through systematic planning and integrated design, is a remarkable innovation (Figure 7). This design incorporates various components, each serving a specific purpose while contributing to the overall ecological sustainability and functionality of the manhole cover. The grass basin, a key component, not only blends the manhole cover with its surrounding environment but also efficiently utilizes rainwater resources. It can be planted with grass and flowers, allowing some rainwater to be absorbed by the vegetation, thus contributing to water conservation and environmental sustainability. The lamp tube, another significant feature, serves as nighttime illumination, enhancing the urban night scene. Its innovative use of infrared sensors ensures that the lamp tube flashes when pedestrians pass by at night, effectively alerting them to the presence of the manhole cover and promoting safety. Moreover, the manhole cover is equipped with integrated sensors that monitor the condition inside the well. These sensors, including those for underwater level, underground gas concentration, and leakage and combustion detection, provide real-time data on the well's status. In case of malfunctions or damage, the manhole cover quickly responds by popping up the safety

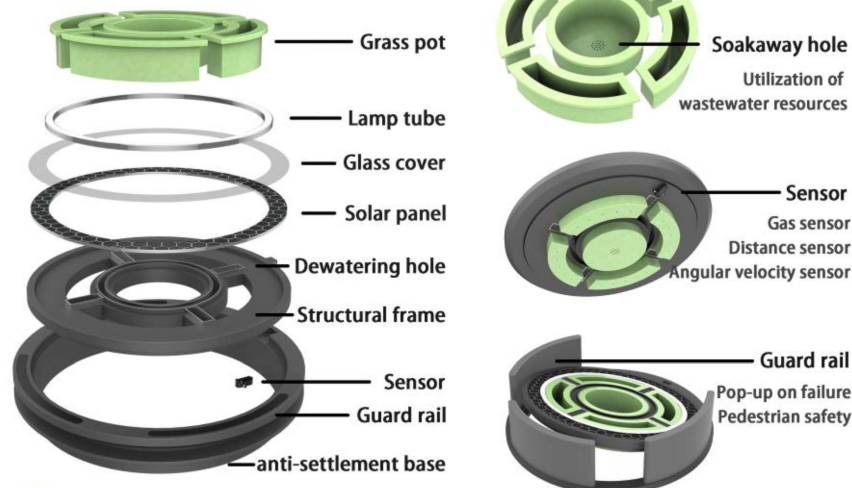
guardrail, flashing lights, and activating a speaker to alert pedestrians. Simultaneously, it transmits well status information to the manhole data management center, notifying maintenance personnel for prompt handling. The design also incorporates solar panels, allowing the manhole cover to collect power for nighttime illumination and efficient information transmission. This feature not only enhances the functionality of the manhole cover but also reduces its dependence on non-renewable energy sources, further promoting ecological sustainability.

Ecological design of intelligent manhole cover

Product design



Product module



Instruction diagram

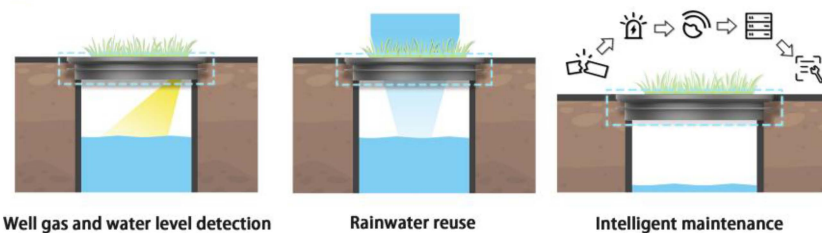


Figure 7. Ecological design of smart manhole cover.

Overall, the intelligent manhole cover design solution is a comprehensive and innovative approach that addresses various challenges related to urban infrastructure and

environmental sustainability. Its intelligent features, ecological design, and focus on safety make it a standout solution for modern urban environments.

4. Discussion

To validate the effectiveness of the proposed solution, the fuzzy analytic hierarchy process (FAHP) is employed for design evaluation. The study aims to assess the approval of various user groups for the intelligent manhole cover design. After providing detailed explanations to the participants, a quantitative questionnaire is administered, comparing the design proposal with the ecological design indicators of a regular manhole cover. Participants are then asked to rate the effectiveness of the intelligent manhole cover design, and their satisfaction with the ecological design is calculated and evaluated. In order to verify the difference in effectiveness between the smart grass pot manhole cover and the traditional manhole cover, the same design was evaluated for the traditional manhole cover product. Select the traditional manhole cover style, as shown in Figure 8.



Figure 8. Conventional manhole cover.

The design evaluation utilizes a five-level scoring system with a defined set of evaluation comments, denoted as $V = \{V_1 \text{ Highly Effective (100 points), } V_2 \text{ Effective (75 points), } V_3 \text{ Neutral (50 points), } V_4 \text{ Ineffective (25 points), and } V_5 \text{ Highly Ineffective (0 points)}\}$. Through this approach, a total of 201 valid questionnaires are collected. Following independent sample testing, 100 questionnaires are selected as valid data (Tables 6 and 7).

Table 6. Voting statistics for assessment metrics for smart grass pot well covers.

Scoring Item	V ₁	V ₂	V ₃	V ₄	V ₅
C1	51	35	12	2	0
C2	54	32	10	4	0
C3	17	58	19	2	4
C4	40	41	12	7	0
C5	50	28	15	6	1
C6	33	46	14	7	0
C7	14	54	23	0	9
C8	32	50	15	3	0
C9	27	52	18	3	0
C10	28	43	22	7	0
C11	39	45	6	6	4
C12	35	42	16	7	0
C13	52	23	14	11	0
C14	21	48	21	9	1
C15	40	43	15	2	0
C16	48	30	15	7	0

Table 7. Voting statistics on assessment indicators for conventional manhole covers.

Scoring Item	V ₁	V ₂	V ₃	V ₄	V ₅
C1	V1	V2	V3	V4	V5
C2	6	6	23	43	22
C3	3	4	27	46	20
C4	4	3	6	32	55
C5	13	5	16	21	45
C6	13	13	12	34	28
C7	17	21	21	31	10
C8	4	7	24	27	38
C9	2	5	20	20	53
C10	3	6	10	26	55
C11	8	4	8	24	56
C12	2	5	9	35	49
C13	4	8	12	29	47
C14	2	10	14	39	35
C15	17	4	2	49	28
C16	6	23	7	34	30

The fuzzy evaluation matrix for the intelligent manhole cover is obtained through the normalization of questionnaire data. The results are as follows:

$$R_1 = (r_{ij})_{n \times m} = \begin{bmatrix} 0.51 & 0.35 & 0.12 & 0.02 & 0 \\ 0.54 & 0.32 & 0.1 & 0.04 & 0 \\ 0.17 & 0.58 & 0.19 & 0.02 & 0.04 \\ 0.4 & 0.41 & 0.12 & 0.07 & 0 \\ 0.5 & 0.28 & 0.15 & 0.06 & 0.01 \\ 0.33 & 0.46 & 0.14 & 0.07 & 0 \\ 0.14 & 0.54 & 0.23 & 0 & 0.09 \\ 0.32 & 0.5 & 0.15 & 0.03 & 0 \\ 0.27 & 0.52 & 0.18 & 0.03 & 0 \\ 0.28 & 0.43 & 0.22 & 0.07 & 0 \\ 0.39 & 0.45 & 0.06 & 0.06 & 0.04 \\ 0.35 & 0.42 & 0.16 & 0.07 & 0 \\ 0.52 & 0.23 & 0.14 & 0.11 & 0 \\ 0.21 & 0.48 & 0.21 & 0.09 & 0.01 \\ 0.4 & 0.43 & 0.15 & 0.02 & 0 \\ 0.48 & 0.3 & 0.15 & 0.07 & 0 \end{bmatrix} \quad R_2 = (r_{ij})_{n \times m} = \begin{bmatrix} 0.06 & 0.06 & 0.23 & 0.43 & 0.22 \\ 0.03 & 0.04 & 0.27 & 0.46 & 0.2 \\ 0.04 & 0.03 & 0.06 & 0.32 & 0.55 \\ 0.13 & 0.05 & 0.16 & 0.21 & 0.45 \\ 0.13 & 0.13 & 0.12 & 0.34 & 0.28 \\ 0.17 & 0.21 & 0.21 & 0.31 & 0.1 \\ 0.04 & 0.07 & 0.24 & 0.27 & 0.38 \\ 0.02 & 0.05 & 0.2 & 0.2 & 0.53 \\ 0.03 & 0.06 & 0.1 & 0.26 & 0.55 \\ 0.08 & 0.04 & 0.08 & 0.24 & 0.56 \\ 0.02 & 0.05 & 0.09 & 0.35 & 0.49 \\ 0.04 & 0.08 & 0.12 & 0.29 & 0.47 \\ 0.02 & 0.1 & 0.14 & 0.39 & 0.35 \\ 0.17 & 0.04 & 0.02 & 0.49 & 0.28 \\ 0.06 & 0.23 & 0.07 & 0.34 & 0.3 \\ 0.1 & 0.14 & 0.22 & 0.23 & 0.31 \end{bmatrix}$$

The comprehensive evaluation vector is obtained by synthesizing the fuzzy evaluation matrix of the scheme with the weight vector W of each evaluation indicator in the indicator level. Afterward, the total score of the scheme is calculated by weighting the evaluation scores (Table 8).

Table 8. The fuzzy evaluation results of the design scheme.

Scheme	Evaluation Vectors	Score
Ecological design of intelligent manhole cover	$C = (0.3958, 0.3843, 0.1546, 0.0604, 0.0049)$	$S = 77.6425$
Conventional manhole cover	$C = (0.1087, 0.1087, 0.1504, 0.3327, 0.3033)$	$S = 34.8568$

The comprehensive matrix is established by merging the weight vector indices W of the indicator layer. After comprehensive calculation of the fuzzy comprehensive evaluation matrix, the overall evaluation weight vector $C = (0.3958, 0.3843, 0.1546, 0.0604, 0.0049)$. Finally, the total score S of the design is calculated by weighting the overall evaluation weight vector and evaluation scores, resulting in 77.6425. The design score falls within

the “effective” and “very effective” ranges of the evaluation set. By observing the weight vector C and considering that the proportion of “very effective” or “effective” in the design evaluation is 68.4025%, and also scoring 42.7857 points higher compared to conventional manhole cover designs, it can be concluded that the design evaluation has reached a good level according to the fuzzy evaluation level and criteria. This validates that the design scheme meets the needs of maintenance personnel and aligns with the preferences of urban residents.

5. Conclusions

In the context of research promoting the positive transformation of urban manhole covers in sponge city construction and ecological design, this study applies the FAHP method to the design of sponge city manhole covers. It effectively addresses the subjectivity and fuzziness issues in the traditional user research methods during the extraction of user needs. An intelligent manhole cover design scheme is developed and compared with traditional manhole covers through a fuzzy comprehensive evaluation. To some extent, it mitigates the shortcomings of existing manhole covers, improves the deficiencies in traditional manhole cover ecological design, and assists sponge cities in achieving better transformation. Simultaneously, it further confirms the effectiveness of the research method. The product development process constructed in this paper partly compensates for the limitations of traditional design methods. It helps designers accurately identify user group needs in ambiguous scenarios and make design decisions, ensuring the scientific and rational nature of product development. Additionally, this process provides new research ideas for other user-oriented product development and ensures the scientific and rational nature of the product development process.

However, the research still needs further refinement given the limitations of data collection, sample selection, and the proportion of surveyed populations in the complex urban research environment. Therefore, further improvements are warranted in this study.

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Appendix A

The following are the supplementary data for this article:

Table A1. Judgment matrix and weight of each indicator demand (B1–B5) at target layer A.

A	B1	B2	B3	B4	B5	W
B1	1	1/4	2	2	1/3	0.140815
B2	4	1	3	5	1/2	0.340479
B3	1/2	1/3	1	1/2	1/5	0.063892
B4	1/2	1/5	2	1	1/3	0.101723
B5	3	2	5	3	1	0.35309

By matrix calculation, $CI = 0.062275$ and $CR = 0.055603 < 0.1$, satisfying the consistency test.

Table A2. Judgment matrix and weight of each indicator demand (C1–C3) at target layer B1.

B1	C1	C2	C3	W
C1	1	2	3	0.458599
C2	1/2	1	4	0.420382
C3	1/3	1/4	1	0.121019

By matrix calculation, $CI = 0.0539$ and $CR = 0.092931 < 0.1$, satisfying the consistency test.

Table A3. Judgment matrix and weight of each indicator demand (C4–C6) at target layer B2.

B2	C4	C5	C6	W
C4	1	1/3	1/3	0.136986
C5	3	1	2	0.493151
C6	3	1/2	1	0.369863

By matrix calculation, $CI = 0.0268$ and $CR = 0.0462069 < 0.1$, satisfying the consistency test.

Table A4. Judgment matrix and weight of each indicator demand (C7–C9) at target layer B3.

B3	C7	C8	C9	W
C7	1	1/2	1/3	0.140127
C8	2	1	1/4	0.248408
C9	3	4	1	0.611465

By matrix calculation, $CI = 0.0539$ and $CR = 0.092931 < 0.1$, satisfying the consistency test.

Table A5. Judgment matrix and weight of each indicator demand (C10–C13) at target layer B4.

B4	C10	C11	C12	C13	W
C10	1	4	1/2	2	0.334572
C11	1/4	1	1/3	1/2	0.092937
C12	2	3	1	3	0.401487
C13	1/2	2	1/3	1	0.171004

By matrix calculation, $CI = 0.0322667$ and $CR = 0.0358519 < 0.1$, satisfying the consistency test.

Table A6. Judgment matrix and weight of each indicator demand (C14–C16) at target layer B5.

B5	C14	C15	C16	W
C14	1	3	1/2	0.369863
C15	1/3	1	1/3	0.136986
C16	2	3	1	0.493151

By matrix calculation, $CI = 0.0268$ and $CR = 0.0462069 < 0.1$, satisfying the consistency test.

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