Multi-Criteria Analysis of a People-Oriented Urban Pedestrian Road System Using an Integrated Fuzzy AHP and DEA Approach: A Case Study in Harbin, China

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Abstract: Increasingly, cities worldwide are striving for green travel and slow traffic, and vigorously developing people-oriented urban pedestrian traffic with sustainability has become a fixture in recent discourse. This paper comprehensively considers the sidewalk's facilities environment and the status of pedestrian traffic flow; divides the urban pedestrian road system (UPRS) into five subsystems around the underpass, overpass, crosswalk, sidewalk, and road crosswalk; and introduces the basic structure as well as the function of each system. Then, the indicators are classified into two types of crosswalk facilities and sidewalk facilities, and a comprehensive pedestrian road indicator system with the combination of subjective and objective is established. Consequently, the integration of the fuzzy AHP and DEA-based symmetrical technique for the subjective evaluation indicator combined with pedestrian traffic characteristics is developed. A nine-step semantics scale of relative importance was used so that the symmetry of the response of pedestrian satisfaction was maintained. Fuzzy evaluation based on AHP is further modeled, and the DEA is employed to achieve an overall evaluation of the quality of service (QoS) for UPRS. The applicability of the established evaluation system is finally verified through a real case study in Harbin, China. The serviceability assessment method in this paper provides a new idea for planners to conduct sustainability evaluation for UPRS in future urban renewal development.

Keywords: urban pedestrian traffic system; multi-criteria analysis; serviceability assessment; fuzzy AHP; DEA

1. Introduction

Pedestrian traffic is essential for sustainability in urban transportation development. Traditional urban and transport infrastructure planning emphasizing motor-oriented transport has fractured public space systems and worsened environmental quality, decreasing active travel [1,2]. A growing number of cities worldwide are striving for green travel and slow traffic, and vigorously developing pedestrian traffic has become a fixture in recent discourse. These difficulties are particularly acute in developing countries with vast populations, such as China, where the design of adequate crossing facilities that take pedestrian and vehicular traffic into account is critical. It is necessary to properly plan the existing pedestrian system to be people-oriented and establish a proper pedestrian road environment around three dimensions of sustainable development: safe, comfortable, and smooth. Therefore, the quality of service (QoS) of the urban pedestrian road system (UPRS) is closely related to residents, the evaluation performance of which has a greater guiding significance for the organization and improvement of pedestrian traffic [3].
In this respect, many studies have attempted to obtain pedestrian traffic flow parameters through the state of pedestrian traffic flow to obtain the QoS of the pedestrian road system, which refers to the classification method of motor vehicle lanes. Among them, sidewalk capacity, pedestrian pace, pedestrian walking space, pedestrian density, and other parameters that reflect the state of pedestrian traffic flow are employed [4–6]. Multiple studies have considered the status of individual pedestrians and analyzed the status of pedestrians under group conditions and subdivided the QoS of sidewalks into seven levels. A fresh approach offered by Chowdhury et al. is a comprehensive experimental design and holistic performance evaluation perspectives, which benefits the estimation of pedestrians’ impact on the coordination of urban corridors [7]. Kadali and Vedagiri investigated pedestrian-tolerated time intervals at unprotected mid-block crossing sites under mixed traffic conditions using diverse roadway geometries, which might be beneficial for designing pedestrian facilities or creating crosswalk warrants [8]. Yang et al. described a unique multiscale simulation technique for assisting in the design of integrated transportation infrastructure and public space. This technique is the most effective strategy to eliminate system externalities while attaining an ecologically and pedestrian-friendly urban design. Additionally, the combined blue-green strategy represents an exciting opportunity to improve local air quality, microclimatic conditions, and human comfort [9].

On the other hand, to assess the QoS of the pedestrian road system, a plethora of studies have established an evaluation index system from the perspective of the infrastructure and supporting environment of the pedestrian road system. Marisamynathan and Vedagiri correctly estimated the pedestrian level of service under mixed traffic conditions and defined threshold values for classification at signalized intersections. The evaluation results indicated that the developed fuzzy C-means method can produce more accurate results and efficient threshold values for the pedestrian level of service score. Similarly, warrants for pedestrian crossing facilities in midblock segments were recommended through pedestrian-vehicle conflict analysis and videographic surveys, which enhance the design of efficient crossing facilities that address both pedestrian and vehicular traffic flow [10,11]. Ke et al. developed a comprehensive index around environmental, economic, social, and transportation efficiency to deal with traffic-oriented development problems combined with the FAHP. An evaluation of 13 stations in Tokyo was carried out with spatial analysis by a heat map of the indicators’ distribution [12]. Tran et al. investigated the priority and significance of traffic- and transportation planning-related indicators in a sustainable transportation infrastructure rating system, and they pointed out that pedestrian paths and sidewalks, bicycle facilities, and traffic facilities contribute considerably to sustainability [13].

On the other hand, substantial work involves developing an evaluation index system of QoS based on pedestrians’ feelings about the road and its supporting facilities and other related factors [14,15]. Yue et al. used driving reliability and error analysis and association rules to analyze 135 pedestrian crash reports in order to identify the contributing factors of inattention, failure intention prediction, and reduced visibility. They noted the combined effect of contributing factors and roadway facility features on injury/fatal pedestrian crashes [16]. Völz et al. presented an approach for predicting pedestrian motions that combines established motion tracking algorithms with data-driven methods based on a hierarchical structure, which offered a fresh approach for predicting pedestrian crossings at crosswalks to avoid accidents and unnecessary slowing down of traffic [17]. Goldhammer et al. utilized a combination of machine learning-based movement models and artificial neural networks to classify pedestrians’ current motion state and predict the future trajectory. This architecture was employed to evaluate motion-specific physical models for starting and stopping, as well as video-based classification of pedestrian motion, which significantly improved the quality of trajectory prediction [18]. Bornioli et al. first demonstrated that the walking experience’s crucial influence elements were safety, comfort, and moderate sensory stimulation by employing theories of environmental affect. They established a methodology to enhance active mobility in the built environment sur-
Rodriguez-Valencia et al. proposed a conceptual framework that considers the contribution of individual perceptions, operational and geometry variables, to explain the perceived quality of service of pedestrian and bicyclist infrastructure. The superior explanatory power of the validation results justifies the relative importance of these supply-oriented and user-oriented factors [20]. Generally, most of the existing pedestrian road system evaluations are based on traffic flow characteristics, such as capacity, walking speed, and personal space, which is developed regarding the classification method of motorized roads. It cannot effectively and genuinely reflect the psychological feelings of pedestrians and the QoS of sidewalks nor has it established a reasonable QoS evaluation system for UPRS. For this reason, evaluation of QoS in UPRS can be defined as a multi-criteria decision-making (MCDM) problem-based symmetrical technique and qualitative models based upon subjective evaluations have mainly been proposed.

The Analytic Hierarchy Process (AHP), Fuzzy Analytic Hierarchy Process (FAHP), and Data Envelopment Analysis (DEA) are the current comprehensive assessment approaches that are frequently utilized to solve many MCDM challenges. The combination of AHP with DEA has the potential to address some of the disadvantages of traditional DEA. Despite this, experts may be imprecise or confusing in their statements. However, the fuzzy set theory may be used to address this non-deterministic problem by converting qualitative to quantitative assessment using fuzzy mathematics membership theory.

In [21,22], the authors investigated the hierarchical structure for classifying evaluation indices and employed the integrated AHP/DEA method in the different evaluation stages, verifying the greater practicality and effectiveness in dealing with complex problems. Celen and Yalcin applied the combined methodology of FAHP/TOPSIS/DEA to assess the Turkish electricity distribution market [23]. Lee et al. developed a performance evaluation model using FAHP/DEA to assess the photovoltaics industry in Taiwan, and similar studies appeared in [24]. Rouyendegh et al. collectively utilized DEA with FAHP to quantify the data and structure the model in decision-making in the health care industry [25]. In [26], two main DEA and FAHP were applied to develop a suitable agricultural machinery distribution pattern in Iran. Yang et al. solved the plant layout design problem with DEA and AHP and illustrated the proposed methodology’s effectiveness. Integration of AHP and DEA was also utilized in supplier selection to evaluate alternatives thanks to its efficacy in determining weights of several comparison criteria [27].

Additionally, Wang et al. presented an integrated AHP–DEA technique for assessing the risk of bridges with hundreds or thousands of spans [28]. Azadeh et al. combined DEA and AHP techniques to identify the optimal options by taking a variety of quantitative and qualitative inputs and outputs into account [29]. Lee et al. measured the relative efficiency of the R&D performance in national hydrogen energy technology development by integrating the FAHP and the DEA [30]. Otay et al. developed a novel multi-expert fuzzy approach integrating intuitionistic fuzzy DEA and AHP to solve healthcare institutions’ performance evaluation problems for healthcare management and the healthcare industry [31]. Ghavami et al. developed a novel risk assessment approach for sewer pipeline prioritization using a mix of GIS and AHP-DEA [32]. KAEWFAK et al. carried out a comprehensive risk analysis using the proposed FAHP-DEA methodology to meet the challenges in developing multimodal transportation associated with inherent risks and numerous uncertainties [33].

Furthermore, in this work, the article data of AHP/FAHP or DEA is recaptured from the Science Citation Index Expanded (SCI-EXPANDED) in the Web of Science Core Collection. The publications are obtained using a retrieval type (“AHP” AND “DEA” or “FAHP” AND “DEA”), and the document types are limited to “article” and “review”. We defined the time period as “1 January 2003 to 30 June 2021” in order to collect all relevant articles. Figure 1 presents a comprehensive review in this field, and although there are several kinds of research to handle the transportation performance with different methods, there are no studies on performance evaluation of QoS for UPRS by fuzzy AHP and DEA. Therefore, this paper first comprehensively considers the sidewalk’s facilities environment rounding these elements by concentrating on the microelements that impede them [19].
and the status of pedestrian traffic flow; divides UPRS into five subsystems around the
underpass, overpass, crosswalk, sidewalk, and road crosswalk; and introduces the basic
structure as well as the function of each system. Then, the indicators are classified into two
types of crosswalk facilities and sidewalk facilities, and a comprehensive pedestrian road
indicator system with the combination of subjective and objective is established.

![Distribution of the AHP-DEA and FAHP-DEA publications (2003–2021).](image)

Consequently, the integration of fuzzy AHP and DEA for the subjective evaluation
indicator combined with pedestrian traffic characteristics is developed. Given the pedes-
trian satisfaction, fuzzy evaluation based on AHP is further modeled, and the DEA is
employed to achieve an overall evaluation of QoS for UPRS. Note the applicability of the
established evaluation system is finally verified through a real case study in Harbin city,
China. The remainder of this paper is organized as follows. Section 2 describes the overall
coupling evaluation methods and correlate modeling process and introduces the modeling
framework of the FAHP and DEA. Section 3 mainly identifies a set of evaluation indicator
systems of QoS for UPRS with the combination of subjective and objective and introduces
details of each indicator, respectively. Section 4 illustrates how the methodology is
applied to a practical case to produce an effective assessment performance for the QoS of
UPRS. Finally, the discussion with a more specific perspective on the results, conclusion,
some limitations, and future work of this research are presented in Section 5.

2. Materials and Methods

2.1. Analytic Hierarchy Process

The AHP is a mathematically based MCDM proposed by Pro. Thoms Saatty [34].
AHP allows the complex problem to be deconstructed into hierarchical structures based
on the overall goal, the sub-goals at each level, the evaluation criteria, and the specific
options. AHP has gained widespread acceptance among academics and practitioners for
data analysis, model verification, commercial decision-making, and other applications due
to its suitability for decision-making problems where the evaluation indicator levels are
interlaced and the target value is difficult to describe quantitatively [35,36]. The application
of the AHP can be divided into four major steps, which are as follows [37,38].

1) Define the hierarchical analysis model. Define the unstructured problem and
decompose the problem into hierarchical structures. In this study, UPRS is divided into
five subsystems of the sidewalk, overpasses, underpasses, road sections, crosswalks, and
intersections of crosswalks. Consequently, the final evaluation indicator system was
established from the two perspectives of crossing and non-crossing roads. Additionally,
the indicator system integrates subjective and objective evaluation indicators, which can
evaluate the QoS of the UPRS thoroughly.

2) Establish a hierarchical judgment matrix. The weight of the indicator layer and
target layer can be determined according to the hierarchical judgment matrix. Experts
are tasked with determining the relevance of inputs and outputs through a pairwise
comparison questionnaire with nine levels ranging from absolutely weak (1) to absolutely
important (9). For each of the \( N \) inputs, the weights assigned to each one are \( w_1, w_2, w_3, \ldots, w_N \). It is possible to describe the expert’s pairwise comparisons \( e \) in the format of a matrix:

\[
A_e = \begin{bmatrix}
w_{11} & w_{12} & \cdots & w_{1N} \\
w_{21} & w_{22} & \cdots & w_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
w_{N1} & w_{N2} & \cdots & w_{NN}
\end{bmatrix}
\]

(1)

(3) **Hierarchical sorting.** The ranking problem of the AHP is equivalent to solving the eigenvector of the judgment matrix. The weights of each input are determined by using the largest eigenvalue and eigenvector, which is derived as follows:

\[
A_e \cdot w_e = \lambda_{\text{max}} \cdot w_e
\]

where \( w_e \) is the eigenvector (weight vector), and \( \lambda_{\text{max}} \) is the maximum eigenvalue of \( A_e \).

(4) **Check consistency property.** The judgment matrix obtained by AHP is not necessarily reasonable, and the consistency needs to be checked. The AHP quality is substantially correlated with the experts’ consistency of assessments during the pairwise comparisons. Preference transitivity states that if \( A \) prefers \( B \) and \( B \) prefers \( C \), then \( A \) prefers \( C \).

For all \( a_{iN/Ne} = 1 \), \( \sum_{i=1}^{N} \lambda_i = N \), if \( \lambda_1, \lambda_2, \ldots, \lambda_n \) satisfy Equation (2), when the judgment matrix is entirely consistent, \( \lambda_1 = \lambda_{\text{max}} = N \), and the other eigenvalue are all zero, when the matrix \( A_e \) is not entirely consistent, then \( \lambda_1 = \lambda_{\text{max}} > N \), and the remaining eigenvalue \( \lambda_1, \lambda_2, \ldots, \lambda_n \) satisfy \( \sum_{i=2}^{N} \lambda_i = N - \lambda_{\text{max}} \). Therefore, the eigenvalue changes accordingly when the judgment matrix does not satisfy consistency entirely, and the consistency index (CI) and consistency ratio (CR) are defined as:

\[
\text{CI} = \frac{\lambda_{\text{max}} - N}{N - 1}
\]

(3)

\[
\text{CR} = \frac{\text{CI}}{\text{RI}}
\]

(4)

where RI is the random index, which can be used to test the consistency effect. In Table 1, we provide the average consistency index of a comparable size pairwise comparison matrix.

**Table 1. Random index.**

|   | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|---|----|----|----|----|----|----|----|----|----|
|   | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

The judgment matrices whose order is below 2 are entirely consistent, so RI is only formal. When the order is greater than 2, the ratio of the consistency indicator CI to the average random consistency indicator RI with the same order as the random consistency ratio CR is taken. If CR less than 0.1, the judgment matrix is considered to have satisfactory consistency.

If this is the case, the expert will be required to make changes to the pairwise comparison matrix’s initial values in order to achieve a level of consistency that is considered acceptable. Nevertheless, decision-makers may not have all the details or a comprehensive understanding of the situation, and the experiences and judgments are not well defined, making it difficult to make decisions. Many recent studies have advocated the use of fuzzy set theory in combination with AHP.
2.2. Data Envelopment Analysis

The evaluation method based on satisfaction from the perspective of pedestrians fully reflects the overall subjective attitude on the existing UPRS. Nevertheless, the personal performance of sidewalk service quality at the general level appears to be fail regarding being viewed objectively. For this reason, technical indicators integrated with satisfaction were given to conduct a comprehensive evaluation method in this research. DEA is a technique that focuses on the efficacy of an assessment unit with many indicator inputs and outputs and is based on the idea of effectiveness, which is also a great approach for solving issues involving multiple objectives, and the relative effectiveness of decision-making units (DMUs) is referred to as DEA effectiveness [39]. For a given group of DMUs, the quality of a specific DMU is pointed out by the effective coefficient acquired from the input and output evaluation indicators. In a word, DEA can obtain a quantitative indicator of the comprehensive efficiency of each DMU through a comprehensive analysis of input-output data. Therefore, DEA can evaluate and rank the relative effectiveness of similar DMU, further indicate the reasons and improvement direction of DEA invalidity for each DMU, and finally provide decision-making information for managers [40].

For a certain DMU, given an input vector of \( x = (x_1, x_2, ..., x_m)^T \), and an output vector of \( y = (y_1, y_2, ..., y_s)^T \), we can utilize \((x, y)\) to represent the production activities. For any DMU \( j \in [1, n] \), the corresponding input and output vectors are \( x = (x_{1j}, x_{2j}, ..., x_m)^T \), \( y = (y_{1j}, y_{2j}, ..., y_{sj})^T \), respectively, and \( x_{ij} > 0, y_{ij} > 0, i = 1, 2, ... , m; r = 1, 2, ... , s. x_{ij} \) is the input of the \( j \)-th DMU to the \( i \)-th type input and \( y_{ij} \) is the output of the \( j \)-th DMU to the \( r \)-th type input. Furthermore, \( x_{ij} \) and \( y_{ij} \) are known data, which can be derived from historical data. Due to the different functions of various inputs and outputs, it is indispensable to comprehensively evaluate DMU and regard them as a production process with only one overall input and output.

When there is less information between the input and output or complicated mutual substitution between them, the influence of subjective consciousness should be avoided as much as possible. We do not give the input weight \( v = (v_1, v_2, ..., v_m)^T \) and output weight \( u = (u_1, u_2, ..., u_m)^T \) in advance, but first, regard them as variables, and then determine them according to a specific principle in the analysis process. Here, \( v_i \) is the weight of the \( i \)-th type input, and \( u_r \) is the weight of the \( r \)-th type output. Each DMU has a corresponding efficiency evaluation indicator:

\[
h_j = \frac{u^T y_j}{v^T x_j} = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}}, j = 1, 2, ..., n
\]  

There are always appropriate weight coefficients \( v \) and \( u \), such as \( h_j \leq 1 \). Generally, the larger \( h_{j0} \) indicates that DMU\( j0 \) can obtain more output through minor input. Therefore, it is essential to determine whether the DMU\( j0 \) is optimal according to the maximum value of \( h_{j0} \) under different weights. Taking the efficiency indicator of the \( j0 \)-th DMU as the goal and the efficiency indicators of all DMU as constraints, the following \( C^2R \) model can be constructed by:

\[
\max \ h_{j0} = \frac{\sum_{r=1}^{s} u_r y_{rj0}}{\sum_{i=1}^{m} v_i x_{ij0}}, \quad \text{s.t.} \quad \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1, j = 1, 2, ..., n, \quad v = (v_1, v_2, ..., v_m)^T \geq 0, \quad u = (u_1, u_2, ..., u_m)^T \geq 0,
\]  

where \( v \geq 0 \) means that for \( i = 1, 2, ..., m, v_i \geq 0 \), there is at least \( i_0 \) \((1 \leq i_0 \leq m)\) satisfying \( v_{i0} > 0 \). The above formula is a fractional planning problem, which Charnes-Cooper can
transfer. Let \( t = (v^T x_0)^{-1} \), \( \omega = tv, \mu = tu \). It can be turned into the following linear programming models:

\[
(P) \begin{cases}
    \max h_j = \mu^T y_0 \\
    s.t. \omega^T x_j - \mu^T y_0 \geq 0, j = 1, 2, \ldots, n \\
    \omega^T x_0 = 1 \\
    \omega \geq 0, \mu \geq 0
\end{cases}
\]  \tag{7}

Hence, the \( C^2R \) model can be expressed by \( P \), the dual programming \( D' \) of which is:

\[
(D') \begin{cases}
    \min \theta^* \\
    s.t. \sum_{j=1}^{n} \lambda_j x_j \leq \theta x_0 \\
    \sum_{j=1}^{n} \lambda_j y_j \geq y_0 \\
    \lambda_j \geq 0, j = 1, 2, \ldots, n
\end{cases}
\]  \tag{8}

For this reason, the effectiveness of DMU\(_{ij0}\) can be confirmed by \( D' \). At the same time, we further introduce the slack variable \( s^+ \) and the residual variable \( s^- \) to turn the above constraints from inequality to equality, which can be expressed as:

\[
(D) \begin{cases}
    \min \theta^* \\
    s.t. \sum_{j=1}^{n} \lambda_j x_j + s^+ \leq \theta x_0 \\
    \sum_{j=1}^{n} \lambda_j y_j - s^- \leq y_0 \\
    \lambda_j \geq 0, j = 1, 2, \ldots, n \\
    s^+ \geq 0, s^- \geq 0
\end{cases}
\]  \tag{9}

Finally, \( D \) can be processed as the dual programming of \( P \) directly.

The DEA evaluation method includes two processes of comprehensive evaluation indicator and validity verification. Since there are too many indicators in this research, it is gratuitous to integrate them to obtain two inputs and two outputs. The total value is determined based on the indicator weight according to the formula \( z_{kj} = \sum_{i} w_{ij} y_{ki} \), where \( z_{ki} \) is the \( i \)-th total indicator value of the \( k \)-th DMU, \( w_{ij} \) is the weight of the \( j \)-th sub-indicator of the \( i \)-th comprehensive indicator, and \( y_{ki} \) is the normalized value of the \( j \)-th sub-indicator under the \( i \)-th comprehensive indicator of the \( k \)-th DMU. In this research, the weight was determined by combining the G1 method and the AHP method. The G1 method is divided into three processes of importance ordering, pairwise comparison, and determining weight.

**Step1: Importance ordering.** Assuming \( x_i \) is more salient than \( x_j \), i.e., \( x_i > x_j \), the importance of each indicator can further be presented as \( x_1 > x_2 > \ldots > x_m \).

**Step2: Pairwise comparison.** Let the relative importance of the indicator \( x_{k-1} \) to \( x_k \) be \( r_k, k = m, m - 1, m - 2, \ldots, 3, 2 \), define \( r_k = w_{k-1}/w_k \), and the importance assignment is described in Table 2.

| \( r_k \) | Linguistic Terms of Indicator \( x_{k-1} \) and \( x_k \) Comparative Judgments |
|----------|-----------------------------------------------|
| 1.8      | Absolutely importance                        |
| 1.6      | Very strong importance                      |
| 1.4      | Fairly importance                           |
| 1.2      | Slightly importance                         |
| 1.0      | Equal importance                            |
Step 3: Determining weight. Under the condition of \( r_{k-1} > 1/r_k \), the weight can be calculated by

\[
\omega_m = \left( 1 + \sum_{k=2}^{m} \prod_{i=k}^{r} r_i \right)^{-1}.
\]

Let \( a_j \) and \( b_j \) be the weights of the indicator \( x_j \) determined by G1 and AHP, respectively, then the total weight is \( w_m = k_1 a_j + k_2 b_j \), \( j = 1, 2, \ldots, m \), where the \( k_1 \) and \( k_2 \) are the weight assignment coefficient; \( k_1 = k_2 = 0.5 \). Furthermore, the judgment of DEA validity can be conducted as follows: If \( \theta^* = 1 \), and \( s^* = s^* = 0 \), we think the DMU_{jo} is DEA validity; if \( \theta^* = 1 \), but at least one input or output slack variable is more significant than zero, we regard DMU_{jo} as weak DEA validity; and if \( \theta^* < 1 \), we think DMU_{jo} is DEA invalidity.

2.3. Integration of the Fuzzy AHP and DEA

Fuzzy evaluation is a comprehensive assessment approach that uses the membership degree theory of fuzzy mathematics to translate qualitative evaluation into quantitative evaluation. It is suitable for solving various fuzzy and difficult uncertainty issues with precise results and a robust system. The evaluation method based on the fact that satisfaction starts from the perspective of pedestrians fully reflects the overall subjective attitude on the existing UPRS. Nevertheless, the personal performance of sidewalk service quality at the general level appears to fail regarding being viewed objectively. For this reason, technical indicators with integrated satisfaction were given to conduct a comprehensive evaluation method in this study, and a performance assessment model that incorporates fuzzy AHP and DEA to evaluate the QoS of UPRS was developed, and the model is as follows.

Step 1: Construct fuzzy pairwise comparison matrices from each expert.

In this study, the service quality satisfaction of pedestrian roads is divided into five levels: satisfied, fairly satisfied, neutral, fairly dissatisfied, and very dissatisfied. As shown in Table 3, each expert’s pairwise comparison matrix is converted into a fuzzy pairwise comparison matrix. A nine-step semantics scale of relative importance is used to maintain the symmetry of the response. Additionally, the judgment matrix needs to be quantified appropriately. We can, for example, obtain a matrix \( \tilde{A}_{le} \) for expert \( e \) by comparing the inputs in pairs:

\[
\tilde{A}_{le} = \begin{bmatrix}
\tilde{a}_{11e} & \tilde{a}_{12e} & \cdots & \tilde{a}_{1Ne} \\
\tilde{a}_{21e} & \tilde{a}_{22e} & \cdots & \tilde{a}_{2Ne} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{a}_{Ne} & \tilde{a}_{1Ne} & \cdots & \tilde{a}_{NNe}
\end{bmatrix}
\]

Table 3. Semantics scale of relative importance.

| Linguistic Terms of Element Comparative Judgments | Scale |
|-----------------------------------------------|-------|
| Absolutely important (AI)                    | 9     |
| Very strong importance (VI)                  | 7     |
| Fairly importance (FI)                       | 5     |
| Slightly importance (SI)                     | 3     |
| Equal importance (E)                         | 1     |
| Slightly weak (SW)                           | 1/3   |
| Fairly weak (FW)                             | 1/5   |
| Very strong-weak (VW)                        | 1/7   |
| Absolutely weak (AW)                         | 1/9   |

Step 2: Construct fuzzy aggregated pairwise comparison matrices.

The synthetic operation of the fuzzy matrix is applied to obtain the comprehensive evaluation model. Finally, the final evaluation grade can be obtained according to the
maximum membership. There are four familiar operators in fuzzy mathematics as follows:

\[
M(\lor, \land), b_j = \sum_{i=1}^{n} (a_{ij} r_{ij}) ; \quad M(\land, \lor), b_j = \sum_{i=1}^{n} \left( a_{ij} \land r_{ij} \right) ; \\
M(\land, \boxdot), b_j = \sum_{i=1}^{n} \left( a_{ij} \cdot r_{ij} \right) ; \quad M(\lor, \boxdot), b_j = \sum_{i=1}^{n} \left( a_{ij} \lor r_{ij} \right) ;
\]

This study was selected as the fuzzy evaluation model operator, the AHP was employed to determine the weights, and the final results were obtained. All experts’ fuzzy pairwise comparison matrices are synthesized using the average geometric approach. There are \( e \) sets of fuzzy pairwise comparison matrices for inputs (outputs) when there are \( e \) experts’ inputs (outputs). When comparing two inputs (outputs) side by side, \( e \) triangular fuzzy numbers can be found. The fuzzy number for the relative importance of inputs \( n_i \) and \( n_j \) can be obtained from:

\[
\tilde{a}_{In_i'N} = (\tilde{a}_{In_i'N}1 \otimes \tilde{a}_{In_i'N}2 \otimes \cdots \otimes \tilde{a}_{In_i'N}e)^{1/e}
\]  

where \( \tilde{a}_{In_i'N} = (h_{In_i'N}, f_{In_i'N}, k_{In_i'N}) \).

The inputs are represented by a fuzzy aggregated pairwise comparison matrix as:

\[
\tilde{A}_1 = \begin{bmatrix}
\tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1N} \\
\tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2N} \\
\vdots & \vdots & & \vdots \\
\tilde{a}_{IN1} & \tilde{a}_{IN2} & \cdots & \tilde{a}_{INN}
\end{bmatrix}
\]  

where \( \tilde{a}_{In_i'N} = (h_{In_i'N}, f_{In_i'N}, k_{In_i'N}) \).

Using the same method, the fuzzy aggregated pairwise comparison matrix is calculated for the outputs as well.

**Step 3: Calculate the triangular fuzzy weights.**

When calculating the lower value of the triangle fuzzy weight of each input, the geometric average of the lower values of fuzzy triangular numbers in each row \( \tilde{A}_1 \) is used as the input. The same technique is used for the intermediate and higher values, respectively, and the fuzzy weights for the relative importance of the inputs are represented by the following Equation (13):

\[
\tilde{w}_1 = \begin{bmatrix}
\tilde{w}_{11} \\
\tilde{w}_{12} \\
\vdots \\
\tilde{w}_{1M'} \\
\vdots \\
\tilde{w}_{1N}
\end{bmatrix}
\]

where:

\[
\tilde{w}_{1M'} = (h_{1M'}, f_{1M'}, k_{1M'}) \\
h_{1M'} = \left( h_{1M'1} \times h_{1M'2} \times \cdots \times h_{1M'N} \right)^{1/N} \\
f_{1M'} = \left( f_{1M'1} \times f_{1M'2} \times \cdots \times f_{1M'N} \right)^{1/N} \\
k_{1M'} = \left( k_{1M'1} \times k_{1M'2} \times \cdots \times k_{1M'N} \right)^{1/N}
\]

The same approach is employed to produce the triangular fuzzy weights indicating the outputs’ relative importance.
Step 4: Calculate the triangular fuzzy weights with α-cut.
If the interval of confidence is defined at level, the fuzzy weights of the inputs are:

\[
\tilde{w}_{\text{in}} = \begin{bmatrix}
[w_{\alpha}^{1H}, w_{\alpha}^{1K} \\
w_{\alpha}^{2H}, w_{\alpha}^{2K} \\
\vdots \\
w_{\alpha}^{nH}, w_{\alpha}^{nK}
\end{bmatrix}
\]  

(14)

The same approach is employed to produce the triangular fuzzy weights indicating the outputs’ relative importance.

3. Results

3.1. Identification of Indicators

The key to constructing the urban pedestrian traffic indicator system is to select reasonable evaluation indicators and analyze their relationship. In this work, the UPRS was divided into five subsystems of sidewalks, overpass, underpass, intersection, and road section to complete the preliminary selection. Then, a set of subjective and objective comprehensive evaluation systems was established from the two aspects of the quantitative and qualitative analysis. Furthermore, the primary data of pedestrian satisfaction was obtained through questionnaire surveys, and the appropriate methods integrated with subjective and objective was selected to evaluate the UPRS comprehensively. The evaluation indicators selected should be preliminarily streamlined using reasonable screening methods during the optimizing process. One-sided inspection and overall inspection were carried out after the indicators with inclusive relationships were eliminated. Combined with the urban pedestrian traffic in China, the indicators were refined concerning the relevant regulations. Considering the characteristics of UPRS, the indicators were divided into two types of crosswalk facilities and sidewalk facilities. Overpasses, underpasses, road crosswalks, and intersections of crosswalks belong to crossing roads, and sidewalks are non-crossing roads. Finally, the evaluation indicator system was established from two aspects of sidewalk and crosswalk facilities, as shown in Figure 2.

3.2. Quantification of Evaluation Indicators

3.2.1. Sidewalk System

(1) Density \(A_1\). Sidewalk network density refers to the ratio of the length to the area of the selected sidewalk, which can be obtained from \(A_1 = \frac{L_B}{M}\), where \(L_B\) is the length and \(M\) is the area. According to the guidelines for planning and designing urban walking and bicycle traffic systems, different classes have specific reference values for sidewalk density. For the first class, the reference value in the guidelines is 14–20 km/km²; for the second class and the third class, the reference value is 10–14 and 6–10 km/km², respectively.

(2) Connectivity \(A_2\). Connectivity is the strength of the interconnection of the nodes in the area relying on the sidewalk. The higher the connectivity, the better the service quality of the sidewalk. \(A_2\) can be obtained from:

\[
A_2 = \frac{L}{e n H} = \frac{L}{e \sqrt{n M}}
\]  

(15)

where \(L\) is the total mileage, \(e\) is the non-linear coefficient, \(n\) is the several nodes connected, and \(H\) is the average space linear distance between two adjacent nodes.
Optimization

(3) **Effective width** $A_3$. The effective width refers to the modified value of the design width by the correction isolation coefficient, which depends on the isolation form between pedestrian and non-motorized vehicles. The coefficient is set to 1.0 when there is no isolation belt, and the rest is set to 0.9. $A_3$ can be obtained from $A_3 = D \cdot \alpha$, where $D$ is the design width and $\alpha$ is the isolation coefficient. Moreover, the sidewalk width and the isolation form shall be determined comprehensively according to the pedestrian zone, pedestrian flow, road function, and other factors. The *Code for Design of Urban Road Engineering* divides the service quality of pedestrian roads into four levels, as shown in Table 4 [41].

**Table 4. Service quality standard of pedestrian road.**

|                           | Level I | Level II | Level III | Level IV |
|---------------------------|---------|----------|-----------|----------|
| Road area per capita (m²) | >2.0    | 1.2–2.0  | 0.5–1.2   | <0.5     |
| Longitudinal space per capita (m) | >2.5    | 1.8–2.5  | 1.4–1.8   | <1.4     |
| Lateral space per capita (m) | >1.0    | 0.8–1.0  | 0.7–0.8   | <0.7     |
| Walking Speed (m/s)       | >1.1    | 1.0–1.1  | 0.8–1.0   | <0.8     |
| Maximum service traffic [people/(h·m)] | 1580    | 2500     | 2940      | 3600     |
The reference values of the sidewalk width in *Guidelines for Planning and Design of Urban Walking and Bicycle Traffic Systems* are shown in Table 5 [42].

Table 5. Width requirement of pedestrian road.

| Level | Width (m) |
|-------|-----------|
| Level I | 4.5–8.0 |
| Level II | 3.0–6.0 |
| Level III | 2.5–4.0 |

4) **Occupancy factor** $A_4$. The sidewalk is mainly occupied by unreasonable obstacles and constructions, the occupancy factor of which is between $[0, 1]$, and the smaller the value, the more perfect the sidewalk is. $A_4$ can be obtained from $A_4 = Z_L / C_L$, where $Z_L$ is the occupied length and $C_L$ is the full sidewalk length.

5) **Recreational facilities proportion** $A_5$. The recreational facilities mainly include shelters and public seats on the pedestrian road, which can be installed on the walking road and the extensions of buildings. The most used shelter facilities are sidewalk trees, which can improve the travel quality of pedestrians. There are two types of green belts, and one is a single street tree with a tree pool. Another form is that there are plants and shrubs under the trees. The public seats are usually combined with bus stops. Additionally, the places and sections with significant traffic, such as the entrance and exit of public buildings and the green road in scenic spots, also provide seats. It can be reflected by the proportion of seats set at the bus stop as follows:

$$A_5 = K_1 \beta_1 + K_2 \beta_2$$  \hspace{1cm} (16)

where $\beta_1$ is the green rate of a street tree, $\beta_2$ is the scale of bus stations with seats, $K_1$ and $K_2$ are weights, and $K_1$ is 0.6 and $K_2$ is 0.4. $\beta_1$ and $\beta_2$ can be derived from:

$$\beta_1 = \frac{R_B}{M_R}, \quad \beta_2 = \frac{N_Z}{N_S},$$  \hspace{1cm} (17)

where $R_B$ is the green belt rate of a street tree, $M_R$ is the total road area, $N_Z$ is the number of bus stops with seats, and $N_S$ is the number of bus stops. Thus, the indicator of recreational facilities is between $[0, 1]$, and the greater the value, the higher the service quality.

6) **Pedestrian space area** $A_6$. Pedestrian space area refers to the average occupied area of pedestrians on the road. The pedestrians are usually affected by pedestrian space and psychological space when walking on the road. Therefore, pedestrian space shall be considered significantly during the development of the pedestrian traffic environment. $A_6$ can be obtained from:

$$A_6 = \frac{A_7 \times A_3}{P_Y}$$  \hspace{1cm} (18)

where $P_Y$ is the pedestrian flow rate. The *Road Capacity Manual* promulgated in America takes pedestrian space as a service evaluation benchmark for sidewalks and divides the service into six levels, as shown in Table 6 [43].

Table 6. The service level of pedestrian space.

| Level | Pedestrian Space (m$^2$/p) | Description |
|-------|-------------------------|-------------|
| A     | >3.5                    | Enough space for free movement |
| B     | 2.5–3.5                 | Specific space for free movement |
| C     | 1.5–2.5                 | Enough physiological space, insufficient mental space |
| D     | 1.0–1.5                 | Enough physiological space, seriously insufficient mental space |
| E     | 0.5–1.5                 | Specific physiological space, no mental space |
| F     | <0.5                    | Seriously insufficient physiological space, hardly walk |
(7) Pedestrian walking speed \( A_7 \). According to the *Road Capacity Manual*, the pedestrian walking speed is mainly affected by the crowd’s proportion of older people (\( \geq 65 \) years old). The average walking speed is 1.2 m/s when the proportion is less than 20%, while the average walking rate decreases to 1.0 m/s if the proportion exceeds 20%. Table 7 lists the sidewalk service grading standards in China [44]. Table 8 lists the sidewalk service grading standards in America [43].

| Level | Space Area (m\(^2\)) | Longitudinal, Lateral Space (m) | Walking Speed (m/s) | Traffic Capacity (p/h · m) |
|-------|------------------------|-------------------------------|---------------------|--------------------------|
| A     | >3                     | 3, 1                          | 1.2                 | 1440                     |
| B     | 2–3                    | 2.4, 0.9                      | 1.1                 | 1830                     |
| C     | 1.2–2                  | 1.8, 0.8                      | 1.0                 | 5200                     |
| D     | 0.5–1.2                | 1.4, 0.7                      | 0.8                 | 2940                     |
| E     | <0.5                   | 1.0, 0.6                      | 0.6                 | 3600                     |

Table 7. Pedestrian service level standards established in China.

| Level | Space Area (m\(^2\)) | Average Walking Speed (m/s) | Flow Rate (p/min · m) | V/C |
|-------|------------------------|----------------------------|----------------------|-----|
| A     | \( \geq 5.6 \)         | \( \geq 1.30 \)            | \( \leq 16 \)        | \( \leq 0.21 \) |
| B     | >3.7–5.6               | >1.27–1.30                 | >16–23               | >0.21–0.31 |
| C     | >2.2–3.7               | >1.22–1.27                 | >23–33               | >0.31–0.44 |
| D     | >1.4–2.2               | >1.14–1.22                 | >33–49               | >0.44–0.65 |
| E     | >0.75–1.4              | >0.75–1.44                 | >49–75               | >0.65–1.0  |
| F     | \( \leq 0.75 \)        | \( \leq 0.75 \)            | Unsure               | Unsure      |

Table 8. Pedestrian service level standards established in America.

(8) Pedestrian flow \( A_8 \). Pedestrian flow refers to the number of pedestrians passing through a certain point in a unit of time, usually expressed by the number of pedestrians in 1 or 15 min. \( A_8 \) can be obtained from:

\[
A_8 = 60 \times \frac{V_{15}}{15 \times A_3}
\]

where \( V_{15} \) is pedestrian traffic in 15 min.

(9) Pedestrian satisfaction \( A_9 \). Pedestrian satisfaction is the intuitive reflection on the UPRS, which reflects the pedestrian’s subjective evaluation and the degree of satisfaction with the comfort of the pedestrian road. The pedestrian satisfaction is between [0, 1]. The satisfaction level is shown in Table 9.

| Evaluation level | I     | II    | III   | IV    | V     |
|------------------|-------|-------|-------|-------|-------|
| Satisfaction degree | [0.9, 1] | [0.8, 0.9] | [0.7, 0.8] | [0.6, 0.7] | [0, 0.6] |

3.2.2. Crosswalk System

(1) Pedestrian flow of crosswalk facilities \( B_1 \). In this paper, crosswalk facilities refer to intersection crosswalks, overpasses, and underground passages. The pedestrian flow of crosswalk facilities is the traffic flow through the above three facilities, similar to \( A_8 \).

(2) Adjacent facilities distance \( B_2 \). The distance between adjoining crosswalk facilities can reflect the rationality of the layout. The *Guidelines for Planning and Design of Urban Pedestrian and Bicycle Traffic System* indicate that crosswalk facilities’ reference value in residential and commercial pedestrian areas should not be more than 250 m, and the recommended indicators are shown in Table 10 [42].
Table 10. Recommended indicators (in m).

| Level     | I    | II   | III  |
|-----------|------|------|------|
| Pedestrian precincts classification Class I | 130–200 | 150–200 | 200–250 |
| Class II  | 200–250 | 200–300 | 250–400 |
| Class III | 250–300 | 300–400 | 400–600 |

(3) Pedestrians walking speed $B_3$. The pedestrian speed is the distance traveled by the pedestrian per unit time, which reflects pedestrian traffic flow objectively as an essential indicator.

(4) Distance to the nearest bus stop $B_4$. The distance between crosswalk facilities and adjoining bus stops reflects the connectivity between crossing facilities and bus stops. A reasonable distance is beneficial to improve the convenience of the pedestrian system.

(5) Effective width $B_5$. The effective width of crosswalk facilities refers to the practical part that pedestrians can use, which can cause pedestrians to bypass it if unreasonable facilities exist. The calculation for $B_5$ is similar to the practical width $A_3$ of the sidewalk. $B_5$ can be obtained from $B_5 = W_T - W_O$, where $W_T$ is the total width of crosswalk facilities and $W_O$ is the pedestrian detour distance.

4. Case Study

4.1. Identification of Survey Region

The evaluation indicators system of the service quality of UPRS constructed in this paper employs the fuzzy AHP to evaluate the subjective indicator and DEA to make a comprehensive evaluation. Four urban regions of Harbin city in China are used as the object to verify the effectiveness of the proposed method, namely Lesong Plaza commercial area, Qingbin Rd residential area, provincial government administrative area, and Xuefu Rd educational area. The features of each survey region are shown in Table 11, and the schematic diagram is shown in Figure 3. This paper also takes aerial photographs of typical intersections in the four survey regions to observe the pedestrian road infrastructure intuitively, as shown in Figure 4.

Table 11. Survey region feature.

| Code      | Property         | Arterial                | Sub-Arterial Road   | Area/m² |
|-----------|------------------|-------------------------|---------------------|---------|
| Qingbin Rd. area | Z-1 Residential | Hexing Rd., Xi Dazhi St. | Qingbin Rd., Zhenxing St. | 184,800 |
| Xuefu Rd. area | Z-2 Educational  | Xuefu Rd.               | Xuefu Si St., Xuefu San St. | 1,283,000 |
| Provincial government area | Z-3 Administrative | Zhongshan Rd., Heping Rd., Wenchang St., Wenfu St. | Wenzhong St. | 243,000 |
| Lesong Plaza area | Z-4 Commercial  | San Da Dongji Rd., Haping Rd. | Xingfu Rd., Leyuan St. | 358,400 |

4.2. Satisfaction Result

Pedestrian satisfaction indicators were picked from the evaluation system to characterize the service quality of UPRS from an emotional level. Nine indicators were consequently chosen for questionnaire surveys from the three perspectives of safety, patency, and comfort to acquire pedestrian satisfaction, as shown in Table 12.

Five satisfaction levels are set for each indicator of strongly satisfied, fairly satisfied, neutral, fairly dissatisfied, and strongly dissatisfied, represented by A, B, C, D, and E, respectively. Each survey region was assigned 100 questionnaires in this research, and 89, 90, 87, and 83 valid questionnaires were received from Z-1, Z-2, Z-3, and Z-4. To facilitate statistical analysis, we further added questionnaires, and the final beneficial questionnaires in each area reached 100. After sorting out, the frequency distribution of satisfaction selection in the four survey areas was captured, as shown in Figure 5.
Table 11. Survey region feature.

| Code | Property    | Arterial Road | Sub-Arterial Road | Area/m² |
|------|-------------|---------------|-------------------|---------|
| Z-1  | Residential | Hexing Rd., Xi Dazhi St. Qingbin Rd., Zhenxing St. | Qingbin Rd. area | 184,800 |
| Z-2  | Educational | Xuefu Rd. Xuefu Si St., Xuefu San St. | Xuefu Rd. area | 1,283,000 |
| Z-3  | Administrative | Zhongshan Rd., Heping Rd., Wenchang St., Wenfu St. Wenzhong St. | Provincial government area | 243,000 |
| Z-4  | Commercial | San Da Dongli Rd., Haping Rd. Xingfu Rd., Leyuan St. | Lesong Plaza area | 358,400 |

Figure 3. Survey area distribution.

Figure 4. Actual road intersection of survey regions.
Table 12. Evaluation indicators of satisfaction.

| Indicators               | Description                                                                 |
|--------------------------|----------------------------------------------------------------------------|
| Safety                   |                                                                            |
| $a_1$: Road smoothness   | Are you satisfied with the smoothness of the sidewalks?                     |
| $a_2$: Crossing facilities | Are you satisfied with the crossing facilities on the sidewalks?            |
| $a_3$: Isolation between pedestrians and motors | Are you satisfied with the isolation between pedestrians and motors on sidewalks? |
| Patency                  |                                                                            |
| $a_4$: Road width        | Are you satisfied with the width of the sidewalk?                          |
| $a_5$: Location of crossing facilities | Are you satisfied with the location of the crossing facilities?            |
| $a_6$: Occupation status | Are you satisfied with the occupation status of the sidewalks?             |
| Comfort                  |                                                                            |
| $a_7$: Greening facilities | Are you satisfied with the greening facilities of the sidewalks?         |
| $a_8$: Recreational facilities | Are you satisfied with the recreational facilities of the sidewalks?    |
| $a_9$: Design of crossing facilities | Are you satisfied with the design of the crossing facilities? |

Figure 5. Satisfaction rank frequency of each indicator from Z-1 to Z-4.

This paper treats the four selected survey regions as different DMUs and transportation professionals conducted a data survey on the technical indicators of each region. Consequently, the primary pedestrian traffic data were acquired. At the same time, the data were standardized before the comprehensive evaluation, as shown in Table 13.

The counted survey questionnaires were employed to obtain the evaluation matrix after determining the indicator weight through AHP, and the satisfaction results were acquired by performing the fuzzy evaluation.
Table 13. Original and normalized data of technical indicators.

|                 | Z-1   | Z-2   | Z-3   | Z-4   | Z-1   | Z-2   | Z-3   | Z-4   |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|
| *Sidewalk*     |       |       |       |       |       |       |       |       |
| Density (km/km²) | 8.87  | 5.67  | 1.414 | 9.722 | 23    | 15    | 37    | 25    |
| Connectivity   | 1.42  | 0.701 | 1.63  | 1.13  | 10    | 5     | 78    | 7     |
| Effective width (m) | 6     | 5.5   | 5     | 4.5   | 28    | 26    | 24    | 21    |
| Occupancy factor (%) | 10    | 38    | 12.4  | 25    | 12    | 44    | 15    | 29    |
| Recreation facilities ratio (%) | 8    | 32    | 14    | 11    | 12    | 49    | 22    | 17    |
| Pedestrian space area (m²/p) | 2.1   | 1.8   | 3     | 1.2   | 26    | 22    | 37    | 15    |
| Walking speed (m/s) | 1.2   | 0.92  | 1.19  | 1.12  | 27    | 20    | 27    | 25    |
| Pedestrian flow (p/min/m) | 21    | 23    | 8     | 15    | 31    | 34    | 12    | 22    |
| Pedestrian satisfaction | 0.85  | 0.75  | 0.85  | 0.75  | 27    | 23    | 27    | 23    |
| *Crosswalk*    |       |       |       |       |       |       |       |       |
| Pedestrian flow (p/min/m) | 7     | 25    | 5     | 12    | 69    | 19    | 4     | 9     |
| Facilities distance (m) | 156   | 320   | 108   | 250   | 19    | 38    | 13    | 30    |
| Distance to the nearest bus stop (m) | 46    | 110   | 73    | 105   | 20    | 33    | 22    | 31    |
| Pedestrian walking speed (m/s) | 0.9   | 0.94  | 1.23  | 1.13  | 21    | 22    | 29    | 27    |
| Effective width (m) | 4     | 4     | 5     | 6     | 21    | 21    | 26    | 32    |

(1) Determine the indicator weight.

The AHP was applied to establish a judgment matrix for the indicator layer and the target layer, the weights of each evaluation indicator of different levels were further calculated, and the total weight was finally obtained after the consistency checking. Table 14 shows the judgment matrices and the weights of indicators under the various goal layers of safety, patency, and comfort, while Table 15 shows the consistency checking data.

Table 14. The pairwise comparison matrix of a single indicator of AHP.

| Criteria | Safety | Patency | Comfort | Weight |
|----------|--------|---------|---------|--------|
| a₁       | 1      | 3       | 5       | 0.637  |
| a₂       | 1/3    | 1       | 3       | 0.258  |
| a₃       | 1/5    | 1/3     | 1       | 0.105  |

Table 15. Consistency check.

| Criteria | Safety | Patency | Comfort | λₘₐₓ | CI | RI | CR |
|----------|--------|---------|---------|------|----|----|----|
| Safety   | 3.039  | 0.019   | 0.580   | 0.033 qualification |
| Patency  | 3.039  | 0.019   | 0.580   | 0.033 qualification |
| Comfort  | 3.064  | 0.032   | 0.580   | 0.057 qualification |

The judgment matrices and weights under layers of safety, patency, and comfort can be further obtained after completing the indicators’ calculation, as shown in Table 16.

Table 16. The pairwise comparison matrix of criteria of AHP.

| Criteria | Safety | Patency | Comfort | Weight |
|----------|--------|---------|---------|--------|
| Safety   | 1      | 5       | 5       | 0.714  |
| Patency  | 1/5    | 1       | 1       | 0.143  |
| Comfort  | 1/5    | 1       | 1       | 0.143  |

The final weight of the indicators can be obtained by combining the weights of a single indicator and the three target layers, as shown in Table 17.
Table 17. The final weight of indicators.

| Indicator            | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ | $a_7$ | $a_8$ | $a_9$ |
|----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| First-level weight   | 0.637 | 0.258 | 0.105 | 0.637 | 0.105 | 0.258 | 0.649 | 0.072 | 0.279 |
| Second-level weight  | 0.714 | 0.714 | 0.714 | 0.143 | 0.143 | 0.143 | 0.143 | 0.143 | 0.143 |
| Final weight         | 0.454 | 0.184 | 0.075 | 0.091 | 0.015 | 0.035 | 0.093 | 0.010 | 0.040 |

4.3. Fuzzy Evaluation

Table 18 epitomizes that the final weight of the indicator is $W = [0.454, 0.184, 0.075, 0.090, 0.015, 0.035, 0.093, 0.010, 0.040]$. According to the fuzzy comprehensive evaluation model, the evaluation grade vector $L$ for each region may be calculated as $L = W \times R$. The pedestrian service satisfaction grade of the UPRS in each survey area was eventually achieved based on the principle of maximum membership, as shown in Table 18.

Table 18. Satisfaction evaluation results.

| Z-1 | Z-2 | Z-3 | Z-4 |
|-----|-----|-----|-----|
| 11  | 61  | 19  | 9   |
| 7   | 23  | 61  | 4   |
| 8   | 45  | 34  | 12  |
| 13  | 43  | 28  | 14  |
| 5   | 27  | 45  | 38  |
| 4   | 6   | 45  | 15  |
| 3   | 11  | 59  | 33  |
| 7   | 43  | 20  | 22  |
| 5   | 12  | 32  | 9   |
| 5   | 7   | 45  | 26  |
| 7   | 45  | 24  | 6   |
| 10  | 38  | 33  | 7   |
| 6   | 12  | 32  | 9   |
| 9   | 37  | 31  | 7   |
| 14  | 32  | 9   | 8   |
| 2   | 16  | 32  | 12  |
| 7   | 45  | 26  | 6   |
| 11  | 38  | 28  | 6   |
| 8.93 | 44.32 | 32.05 | 11.39 | 3.06 |
| 11.39 | 3.06 |
| 8.53  | 29.72 | 39.25 | 11.75 | 3.97 |
| 6.60  | 32.90 | 26.67 | 7.87  | 48.56 |
| 21.35 | 8.28 |
| 10.47 | 3.74 |

4.4. DEA Evaluation

In this paper, the evaluation indicators were classified into two types of sidewalk and crosswalk, the infrastructure indicators were inputs, and the operating indicators were outputs. Table 19 illustrates the total indicator weights. The final result was further calculated, as shown in Table 20.

Table 19. Total indicator weights.

| Target Layer | Indicator Layer | Weights |
|--------------|----------------|---------|
|              | G1             | AHP     | Total   |
| Input (X)    | Density $X_{11}$ | 0.1351  | 0.0441  | 0.0896  |
|               | Connectivity $X_{12}$ | 0.3630  | 0.1009  | 0.232   |
|               | Effective width $X_{13}$ | 0.1621  | 0.0944  | 0.1283  |
|               | Occupancy factor $X_{14}$ | 0.1126  | 0.2394  | 0.176   |
|               | Recreation facilities ratio $X_{15}$ | 0.2270  | 0.5213  | 0.3742  |
| Crosswalks $X_2$ | Adjacent distance $X_{21}$ | 0.2940  | 0.637   | 0.4655  |
|               | Distance to nearest bus stop $X_{22}$ | 0.4110  | 0.2583  | 0.3347  |
|               | Effective width $X_{23}$ | 0.2450  | 0.1047  | 0.1749  |
| Output (Y)   | Pedestrian space area $Y_{11}$ | 0.2580  | 0.1348  | 0.1964  |
|               | Walking speed $Y_{12}$ | 0.1700  | 0.1467  | 0.1584  |
|               | Pedestrian flow $Y_{13}$ | 0.2040  | 0.0592  | 0.1316  |
|               | Pedestrian satisfaction $Y_{14}$ | 0.3420  | 0.6593  | 0.5007  |
| Crosswalks $Y_2$ | Pedestrian flow $Y_{21}$ | 0.5450  | 0.2500  | 0.3975  |
|               | Pedestrian crossing speed $Y_{22}$ | 0.4540  | 0.7500  | 0.6020  |
Table 20. Total indicator value.

|      | DMU₁ | DMU₂ | DMU₃ | DMU₄ |
|------|------|------|------|------|
| Z-1  | X₁   | 15   | 32   | 35   | 18   |
| Z-2  | X₂   | 30   | 45   | 30   | 47   |
| Z-3  | Y₁   | 32   | 28   | 34   | 24   |
| Z-4  | Y₂   | 13   | 6    | 5    | 5    |

The model in this paper was solved to obtain the value of the efficiency indicator $\theta$, slack variable $s^+$, residual variable $s^-$, and the judgment indicator $\lambda$, which are shown in Table 21.

Table 21. Numerical calculation results.

|      | $\theta$ | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ | $S_1^-$ | $S_2^-$ | $S_1^+$ | $S_2^+$ | $\sum \lambda$ |
|------|----------|--------------|--------------|--------------|--------------|--------|--------|--------|--------|----------------|
| DMU₁ | Z-1      | 1.000        | 0.000        | 1.000        | 0.000        | 0.000  | 0.000  | 0.000  | 0.000  | 1.000          |
| DMU₂ | Z-2      | 0.572        | 0.000        | 0.586        | 0.272        | 0.000  | 0.000  | 0.000  | 0.000  | 2.981 0.858   |
| DMU₃ | Z-3      | 1.000        | 0.000        | 0.000        | 1.000        | 0.000  | 0.000  | 0.000  | 0.000  | 0.000 1.000   |
| DMU₄ | Z-4      | 0.625        | 0.000        | 0.750        | 0.000        | 0.000  | 0.000  | 6.875  | 0.000  | 4.750 0.750   |

From Table 21, it can be seen from the DEA validity judgment method that the DMU₂ and DMU₃ are DEA valid, the DMU₂ and DMU₄ are DEA invalid. For the invalid DMUs, we can acquire a new DMU with DEA validity adequate decision corresponding to them through the projection approach.

As a case in point, the efficiency indicator of DMU₂ is 0.572, which is less than 1. However, when compared to other systems, this indicates that DMU₂ is relatively inefficient. It can be regarded as achieving the current travel demand by improving facilities as long as 0.572 of the original facilities are invested. Despite this, a gap still exists. From another perspective, this action demonstrates that there is much scope for the future development of pedestrian roads. Among the four survey areas, the pedestrian road systems of Z-1 and Z-3 performed relatively well, being efficient, and the remaining regions have some imbalance problems. In a word, there is a redundancy in the investment of crossing facilities in the Z-4. At the same time, Z-2 has a low output, so decision-makers should focus on these two areas regarding further action.

5. Discussion and Conclusions

As the terminate connectivity of various travel modes in the urban road network, pedestrian traffic undertakes the essential walking functions and provides activities for leisure and exercise in daily life. QoS evaluation in UPRS should consider the influence of basic facilities, such as the pedestrian crossing and the surrounding environment and the traffic flow in the pedestrian road. Nevertheless, most of the existing pedestrian road system evaluations are based on traffic flow characteristics, such as capacity, walking speed, and personal space, which is developed regarding the classification method of motorized roads. It cannot effectively and genuinely reflect the psychological feelings of pedestrians and the QoS of sidewalks nor can it establish a reasonable QoS evaluation system for UPRS.

Under the context of sustainable transportation, this paper aimed to resolve the problem of insufficient planning construction and absent criteria of the QoS evaluation system in UPRS to consider the facilities environment of the sidewalk and the status of pedestrian traffic flow, and select representative indicators to establish a comprehensive pedestrian road indicator system with the combination of subjective and objective. Combining fuzzy evaluation theory with AHP, the subjective indicators were quantified, and comprehensive evaluation was carried out through DEA. Considering the characteristics of UPRS, the evaluation indicators were divided into two types of crosswalk facilities and sidewalk facilities. Among five subsystems, overpasses, underpasses, road crosswalks, and intersections,
crosswalks belong to crossing roads, and sidewalks are non-crossing roads. Consequently, 14 evaluation indicators were identified from the two levels, whose specific explanations and calculation methods were presented. The AHP acquired the weight of the subjective indicators of pedestrian satisfaction, and the evaluation level of satisfaction was obtained through the fuzzy matrix and the indicator weight. Furthermore, a comprehensive evaluation of the entire evaluation indicator system was carried out with the DEA method. Despite this, the urban area of Harbin city in China was taken as the object to verify the effectiveness, and four distinct regions were selected as the survey sites, namely Lesong Plaza commercial area, Qingbin Rd residential area, provincial government administrative area, and Xuefu Rd educational area. The assessment results indicated that the pedestrian road systems of Qingbin Rd residential area and provincial government administrative area are in the best condition, and the remaining regions have some imbalance problems. In a word, there is a redundancy in the investment of crossing facilities in the Lesong Plaza commercial area. Meanwhile, the Xuefu Rd educational area has a low output, so decision-makers should focus on these two areas regarding further action.

Although the evaluation results demonstrated the effectiveness of the proposed methodology, several limitations exist, mainly related to raw data collection. Interestingly, the study was performed throughout the summer. We eliminated certain significant factors of comfort for objective reasons and owing to the inaccessibility of data sources, such as weather conditions, noise pollution, air pollution, and ecological buildings. This results in a modest deficiency in our work, but the ease with which all data in our investigation can be accessed demonstrates that a wide range of replication is possible in other countries or regions of the world, which is also the value of this work. Overall, it is hoped that the findings of this study would assist traffic planners and engineers in better understanding the current conditions affecting pedestrian facilities in terms of safety, patency, and comfort, as this is an issue that must be considered in most urban development today. As a result, the issue of urban pedestrian system sustainability deserves further investigation. According to the authors, future research should compare the results with data from various countries with diverse infrastructure conditions to see if the evaluation system for QoS can be transferred. Moreover, weights under layers of safety, patency, and comfort should be identified under different weather conditions, which is also a significant research scope in the future.

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