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Service Quality Evaluation of Transfer Facilities in High-Speed Railway Stations Based on Interval Valued Linguistic Multi-Criteria Decision-Making

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ABSTRACT
High-speed railway stations are critical in facilitating seamless connections between different transportation modes. However, challenges such as mismatched transfer capacities, inefficient mode connections and excessive passenger transfer distances and times hinder the efficiency of these stations, impeding overall transport system development. This paper addresses the need for effective evaluation of transfer facility service quality within high-speed railway stations, providing a foundation for optimising these facilities. Leveraging interval-valued linguistic term sets (IVLTSs), this study develops interval-valued linguistic multi-criteria decision-making (IVL-MCDM) methods to assess service quality while accounting for uncertainty in evaluation indicators and attribute weights. We introduce new dominance degrees to enhance the reliability of evaluations, ensuring consistency in assessing transfer facility service quality. The proposed methods are demonstrated through a case study, highlighting their effectiveness and superiority over traditional IVL-MCDM approaches, particularly in maintaining consistent evaluation information.

KEYWORDS
high-speed railway station; service quality; transfer facilities; multi-criteria decision making; interval linguistic sets.

1. INTRODUCTION

As passengers' demands for travel and transportation service quality continue to rise, and with the modernisation and integration of transportation modes, the railway passenger transportation system has undergone a leap towards modernisation and integration. This has prompted the transition of railway passenger systems from singular railway transportation to integrated transportation systems, where various modes of transportation complement and connect with each other. In this developmental context, high-speed railway stations have gradually evolved into comprehensive passenger hubs dominated by railway transportation [1].

As pivotal nodes in constructing railway passenger systems, high-speed railway stations serve important functions such as facilitating intercity and intracity transportation, as well as enabling seamless connections and transfers between various transportation modes. In terms of intracity transportation integration, high-speed railway stations have largely adopted a development strategy of prioritising large-scale public transportation while supplementing with other transportation modes. Many cities have integrated urban rail transit and surface public bus systems within their high-speed railway stations. High-speed railway stations, characterised by their large footprint and multifunctionality, are highly integrated facilities that efficiently utilise urban land while offering comprehensive services. However, with the rapid growth in passenger volumes, the pressure on rapid passenger flow distribution and transfer within high-speed railway stations has increased significantly, placing higher demands on the design and optimisation of transfer facilities [2].

Due to the differences in operating companies, operating models and management mechanisms of various transportation modes within high-speed railway stations, as well as inconsistent planning and development goals, it is challenging to achieve unified coordination. Consequently, issues such as mismatched transfer capacities, inefficient connections between different transportation modes, and excessive passenger transfer distances and travel times exist within the stations, hindering the development of railway and urban transportation [9-10]. Therefore, it is essential to study the evaluation of service quality for transfer facilities within high-speed railway stations, aiming to provide a reference basis for the optimisation of transfer facilities. The assessment of service quality in high-speed railway station transfer facilities faces challenges such as the lack of a comprehensive evaluation system and the absence of unified quantitative standards for indicators. This paper leverages the advantages of interval-valued linguistic term sets (IVLTSs) in expressing uncertainty in evaluation indicators and attribute weights. The interval-valued linguistic multi-criteria decision-making (IVL-MCDM) methods are developed for assessing the service quality of high-speed railway station transfer facilities.

The main contributions of this paper are as follows. Firstly, an evaluation system for service quality in high-speed railway stations is established and various indicators are quantified. Secondly, considering that fuzzy preference relations (FPRs) constructed from interval-valued linguistic values (IVLVs) may lead to unreliable service quality assessment results, new dominance degrees for IVLVs are introduced to provide more objective and reliable quantification of evaluation indicators and attribute weights. Thirdly, new IVL-MCDM methods are developed for assessing the service quality of transfer facilities.

The rest of this paper is organised as follows. The existing research on transfer facilities in railway stations and interval-valued linguistic decision-making (IVLDM) methods are analysed in Section 2. Then, Section 3 discusses the possibility degree of IVLVs and their drawbacks, and develops new dominance degrees for IVLVs. The service quality evaluation of transfer facilities in high-speed railway stations based on new IVL-MCDM methods is provided in Section 4. An example is presented to verify the performance of the developed IVL-MCDM methods in Section 5. Finally, conclusions are made in Section 6.

2. LITERATURE REVIEW

2.1 Transfer facilities in railway station

Existing research on railway station transfer facilities primarily focuses on scale calculation, layout form, evaluation methods and optimisation.

In scale calculation and layout form, Kouwenhoven et al. [3] examined the correlation between transfer passenger flow and the size of transfer facilities, outlining the required scale for different transfer facilities. Zhang et al. [4-6] established design parameters and per capita occupancy area of transfer channels based on factors like walking speed, space and conflict probability. Bezerra et al. [7] and Iyer et al. [8] simulated airport passenger walking distances to optimise transfer station layouts for minimising walking distances.

Regarding evaluation methods, Diana [11] proposed nine indicators for transportation service satisfaction through correlation and correspondence analysis, aiming to measure passenger satisfaction across diverse urban environments. Hoogendoorn et al. [12] and de Abreu et al. [13] assessed station transfer connections considering layout and surrounding transportation environments. Durmisevic and Sariyildiz [14] devised a service quality evaluation index system for underground transportation platforms using a neural network comprehensive evaluation. Kim et al. [15] employed Rasch analysis to evaluate passenger satisfaction in transfer facilities across information, mobility, comfort, convenience and safety aspects.

In terms of optimisation, Chen et al. [16] studied transfer relationships between transportation modes, focusing on safety and synchronous transfer intervals. Kaveh et al. [17] analysed comprehensive transportation networks within railway stations and proposed optimisation measures based on mode characteristics. Wang et al. [18] conducted a simulation analysis to identify and improve weak links in station operation, enhancing passenger transfer efficiency. Paulsen et al. [19] investigated passenger path selection at railway stations, establishing an optimisation model based on transfer facility service levels and guidance information.

In summary, the analysis suggests (1) a need for a unified framework and indicator system to evaluate high-speed railway transfer facility service quality; (2) an underappreciation of complex linguistic methodologies, particularly interval linguistic sets, for expressing attribute uncertainty and weights; and (3) acknowledgement of expert evaluation criteria's significance in the evaluation framework for transfer service quality.

2.2 Interval-valued linguistic decision-making

In the process of evaluating service quality in transfer facility settings, linguistic term sets (LTSs) have advantages in expressing the fuzziness and uncertainty of attribute weights and indicator values. Considering the flexibility and complexity of evaluation information, interval-valued LTSs (IVLTSs) are commonly used to represent the fuzzy linguistic assessment information provided by experts [20]. Current research on interval-valued linguistic decision-making (IVLDM) problems revolves around comparison rules, aggregation operators, preference relations, consistency and heterogeneous information. Interval linguistic comparison rules and aggregation operators are applicable to solving decision-making problems [21]. Bai et al. [22] developed a possibility-based comparison rule to compare the sizes of interval-valued linguistic values (IVLVs). Jin et al. [23] designed operational rules and aggregation operators for IVLVs, applying them to group decision-making problems in weather observation systems. Fuzzy preference relations and consistency have also been recent research focuses [24-26] and have been used in IVLTSs. Meng et al. [27-28] measured the consistency of interval linguistic preference relations and applied them in group consensus decision-making to make the decision results more reliable and reasonable. Feng et al. [29] developed an algorithm to correct inconsistent individual preferences to ensure the rationality of personal preferences. Wu et al. [30] dealt with an IVLDM problem containing heterogeneous information.

Possibility degree is a commonly used method for ranking IVLVs. In IVLDM problems involving the evaluation of transfer facility service quality, IVLVs are used to represent attribute weights and indicator values. However, the fuzzy preference relation (FPR) constructed from IVLVs possibility degree is inconsistent in most cases. Inconsistent FPRs may lead to illogical service quality assessment results, rendering the evaluation results unreliable [31-32].

3. NOVEL DOMINANCE DEGREES OF IVLVS

Considering that the construction of FPRs based on possibility degrees may lead to unreliable evaluations of transfer facility service quality, this section proposes new dominance degrees to compare IVLVs. Firstly, we review the concept of possibility degrees for IVLVs and analyse the drawbacks of the constructed FPRs by IVLVs. Then, we introduce the new dominance degrees and discuss their properties.

3.1 Interval-valued linguistic possible degrees and their drawbacks

Possible degrees of IVLVs address fuzziness and uncertainty in service quality evaluation. It can also compare the dominance degree of different indicators' weights and values, effectively increasing the flexibility of the evaluation process. Then, possible degrees of IVLVs are defined as:

Definition 1 [22]. Let $\tilde{s}_1=\left[s_{\alpha_1},s_{\beta_1}\right]$ and $\tilde{s}_2=\left[s_{\alpha_2},s_{\beta_2}\right]$ be two IVLVs on LTS $S=\left\{s_0,s_1,\dots,s_g\right\}$, the lengths of $\tilde{s}_1$ and $\tilde{s}_2$ are $l\left(\tilde{s}_1\right)=\beta_1-\alpha_1$ and $l\left(\tilde{s}_2\right)=\beta_2-\alpha_2$, then the possibility degree $p\left(\tilde{s}_1\geq\tilde{s}_2\right)$ of $\tilde{s}_1\geq\tilde{s}_2$ is defined as

$$p\left(\tilde{s}_1\geq\tilde{s}_2\right)=\max\left\{1-\max\left(\frac{\beta_2-\alpha_1}{l\left(\tilde{s}_1\right)+l\left(\tilde{s}_2\right)},0\right),0\right\} \tag{1}$$

Also, the possibility degree of IVLVs satisfies the following properties:

Property 1 [22]. Let $\tilde{s}_1=\left[s_{\alpha_1},s_{\beta_1}\right]$ and $\tilde{s}_2=\left[s_{\alpha_2},s_{\beta_2}\right]$ be two IVLVs, then

(1) $0\leq p\left(\tilde{s}_1\geq\tilde{s}_2\right)\leq 1$, $0\leq p\left(\tilde{s}_2\geq\tilde{s}_1\right)\leq 1$;

(2) $p\left(\tilde{s}_1\geq\tilde{s}_2\right)=1$, if $s_{\beta_2}\leq s_{\alpha_1}$. Similarly, $p\left(\tilde{s}_2\geq\tilde{s}_1\right)=1$, if $s_{\beta_1}\leq s_{\alpha_2}$;

(3) $p\left(\tilde{s}_1\geq\tilde{s}_2\right)=0$, if $s_{\beta_1}\leq s_{\alpha_2}$. Similarly, $p\left(\tilde{s}_2\geq\tilde{s}_1\right)=0$, if $s_{\beta_2}\leq s_{\alpha_1}$;

(4) $p\left(\tilde{s}_1\geq\tilde{s}_1\right)=0.5$;

(5) $p\left(\tilde{s}_1\geq\tilde{s}_2\right)+p\left(\tilde{s}_2\geq\tilde{s}_1\right)=1$.

To demonstrate the performance of sorting using FPRs constructed by possible degrees, two examples are presented as follows.

Example 1. Let $\tilde{s}_1=[s_3,s_4]$, $\tilde{s}_2=[s_{3.3},s_{3.7}]$, $\tilde{s}_3=[s_{0.4},s_{6.3}]$, $\tilde{s}_4=[s_2,s_{7.9}]$ be four IVLVs, then rank the four IVLVs.

The FPR P_1 is constructed by the possible degree of IVLVs as follows:

$$P_1=\left(p_{ij}\right)_{4\times 4}=\begin{bmatrix} 0.5 & 0.5 & 0.5217 & 0.2899 \\ 0.5 & 0.5 & 0.5238 & 0.2698 \\ 0.4783 & 0.4762 & 0.5 & 0.3644 \\ 0.7101 & 0.7302 & 0.6356 & 0.5 \end{bmatrix}$$

Because, $0.5217=p_{13}\neq p_{14}-p_{34}+0.5=0.2899-0.3644+0.5=0.4255$ and

$p_{13}p_{34}p_{41}=0.5217\times 0.3644\times 0.7101=0.1350\neq p_{31}p_{43}p_{14}=0.4783\times 0.6356\times 0.2899=0.0881$.

According to the definitions of additive consistent FPRs (ACFPRs) and multiplicative consistent FPRs (MCFPRs), P_1 is not an ACFPR or MCFPR.

An ACFPR or MCFPR [33-34] is constructed to approximate the inconsistent FPR P_1 for ranking the four IVLVs.

(a) According to approximate ACFPR, then

$$w_1^{'}=\frac{0.4529}{c}-\frac{1}{2c}+\frac{1}{4},\ w_2^{'}=\frac{0.4484}{c}-\frac{1}{2c}+\frac{1}{4},\ w_3^{'}=\frac{0.4547}{c}-\frac{1}{2c}+\frac{1}{4},\ w_4^{'}=\frac{0.6440}{c}-\frac{1}{2c}+\frac{1}{4}$$

Thus, $w_4^{'}>w_3^{'}>w_1^{'}>w_2^{'}$.

Then, $\tilde{s}_4>\tilde{s}_3>\tilde{s}_1>\tilde{s}_2$.

(b) According to approximate MCFPR, then

$v_1^{'}=0.1863$, $v_2^{'}=0.1781$, $v_3^{'}=0.2026$, $v_4^{'}=0.4253$.

Thus, $v_4^{'}>v_3^{'}>v_1^{'}>v_2^{'}$.

Then, $\tilde{s}_4>\tilde{s}_3>\tilde{s}_1>\tilde{s}_2$.

Because $p(\tilde{s}_1\geq\tilde{s}_2)=p(\tilde{s}_2\geq\tilde{s}_1)=0.5$ and $p(\tilde{s}_2\geq\tilde{s}_3)=0.5238$, then $\tilde{s}_1\equiv\tilde{s}_2>\tilde{s}_3$. The ranking result is based on possible degree conflicts with those obtained from approximate ACFPR or MCFPR.

Example 1 indicates that FPRs constructed based on possible degrees may be inconsistent. Using approximate methods to construct ACFPRs or MCFPRs instead of existing inconsistent FPRs for ranking may result in conflicting outcomes and decision failures.

Example 2. The service quality evaluation problem of transfer facilities at a high-speed railway station involves four high-speed railway stations S_1, S_2, S_3, S_4 and four attributes C_1, C_2, C_3, C_4, with weights of $w_1=0.4$, $w_2=0.2$, $w_3=0.2$, and $w_4=0.2$. Experts provide preference values for each attribute of the stations in the form of IVLVs, as shown in *Table 1*.

Table 1 – Service quality evaluation information provided by experts

	S_1	S_2	S_3	S_4
C_1	$[s_0,s_4]$	$[s_2,s_{4.9}]$	$[s_5,s_{7.1}]$	$[s_1,s_{5.9}]$
C_2	$[s_0,s_{5.8}]$	$[s_2,s_{4.1}]$	$[s_1,s_{7.1}]$	$[s_1,s_{5.9}]$
C_3	$[s_0,s_{7.1}]$	$[s_2,s_{4.1}]$	$[s_5,s_{7.1}]$	$[s_1,s_{5.9}]$
C_4	$[s_0,s_{7.1}]$	$[s_2,s_{7.9}]$	$[s_3,s_{7.1}]$	$[s_1,s_{5.9}]$

The FPRs constructed by possible degrees under different criteria are provided as follows.

$$P_{C_1}=\begin{bmatrix}0.5 & 0.2899 & 0 & 0.3371\\ 0.7101 & 0.5 & 0 & 0.5\\ 1 & 1 & 0.5 & 0.8714\\ 0.6629 & 0.5 & 0.1286 & 0.5\end{bmatrix},\ P_{C_2}=\begin{bmatrix}0.5 & 0.4810 & 0.4034 & 0.4486\\ 0.5190 & 0.5 & 0.3780 & 0.4429\\ 0.5966 & 0.6220 & 0.5 & 0.5545\\ 0.5514 & 0.5571 & 0.4455 & 0.5\end{bmatrix},$$

$$P_{C_3}=\begin{bmatrix}0.5 & 0.5543 & 0.2283 & 0.5083\\ 0.4457 & 0.5 & 0 & 0.4429\\ 0.7717 & 1 & 0.5 & 0.8714\\ 0.4917 & 0.5571 & 0.1286 & 0.5\end{bmatrix},\ P_{C_4}=\begin{bmatrix}0.5 & 0.3923 & 0.3661 & 0.5083\\ 0.6077 & 0.5 & 0.4900 & 0.6389\\ 0.6339 & 0.5100 & 0.5 & 0.6778\\ 0.4917 & 0.3611 & 0.3222 & 0.5\end{bmatrix}$$

The four FPRs P_{C_1}, P_{C_2}, P_{C_3} and P_{C_4} are aggregated into an FPR:

$$P=\begin{bmatrix}0.5 & 0.4015 & 0.1995 & 0.4279\\ 0.5985 & 0.5 & 0.1736 & 0.5049\\ 0.8005 & 0.8264 & 0.5 & 0.7693\\ 0.5721 & 0.4951 & 0.2307 & 0.5\end{bmatrix}$$

According to the definition of ACFPR, it is easy to prove that P_{e_1}, P_{e_2}, P_{e_3}, and P_{e_4} are non-ACFPRs. After aggregating several non-ACFPRs, the obtained FPR may be inconsistent.

From the above analysis, Example 1 also implies that inconsistent FPR may lead to decision-making errors and Example 2 shows that the aggregated FPRs are unreliable in the service quality evaluation of transfer facilities. The method of ranking IVLVs based on FPRs constructed by possible degrees is problematic. To address the above drawbacks, we will develop the new dominance degrees of IVLVs.

3.2 Novel dominance degrees for IVLVs

Directly comparing IVLVs results in inconsistent FPR construction. Indirect comparison effectively avoids the above problems by using appropriate reference values. Therefore, the concept of dominance degrees of IVLVs with $[s_0, s_g]$ as the reference value is defined as follows:

Definition 2. Let $a=[s_\alpha, s_\beta]\in I_{[s_0,s_g]}$ be an IVLV, where $I_{[s_0,s_g]}$ is all closed subintervals of $[s_0, s_g]$, then the degrees of $[s_\alpha, s_\beta]\geq[s_0, s_g]$ and $[s_\alpha, s_\beta]\leq[s_0, s_g]$ are represented as:

$$\theta\left([s_\alpha, s_\beta]\geq[s_0, s_g]\right)=\frac{\alpha+\beta}{2g} \tag{2}$$

$$\theta\left([s_\alpha, s_\beta]\leq[s_0, s_g]\right)=1-\frac{\alpha+\beta}{2g} \tag{3}$$

Then, the degrees of IVLVs satisfy the following properties.

Property 2. Let $\tilde{a}_1=[s_{\alpha_1}, s_{\beta_1}]$ and $\tilde{a}_2=[s_{\alpha_2}, s_{\beta_2}]\in I_{[s_0,s_g]}$ be two IVLVs, then

(1) $0\leq\theta\left([s_{\alpha_1}, s_{\beta_1}]\geq[s_0, s_g]\right)\leq 1$;

(2) $\theta\left([s_{\alpha_1}, s_{\beta_1}]\geq[s_0, s_g]\right)+\theta\left([s_{\alpha_1}, s_{\beta_1}]\leq[s_0, s_g]\right)=1$;

(3) $\theta\left([s_{\alpha_1}, s_{\beta_1}]\geq[s_0, s_g]\right)\geq\theta\left([s_{\alpha_2}, s_{\beta_2}]\geq[s_0, s_g]\right)\Leftrightarrow\frac{\alpha_1+\beta_1}{2g}\geq\frac{\alpha_2+\beta_2}{2g}$;

Proof.

(1) Because $\tilde{a}_1=[s_{\alpha_1}, s_{\beta_1}]\in I_{[s_0,s_g]}$, $\theta\left([s_{\alpha_1}, s_{\beta_1}]\geq[s_0, s_g]\right)=\frac{\alpha_1+\beta_1}{2g}$, then $0\leq\theta\left([s_{\alpha_1}, s_{\beta_1}]\geq[s_0, s_g]\right)\leq 1$.

(2) $\theta\left([s_{\alpha_1}, s_{\beta_1}]\geq[s_0, s_g]\right)+\theta\left([s_{\alpha_1}, s_{\beta_1}]\leq[s_0, s_g]\right)=\frac{\alpha_1+\beta_1}{2g}+1-\frac{\alpha_1+\beta_1}{2g}=1$.

(3) Because $\theta\left([s_{\alpha_1}, s_{\beta_1}]\geq[s_0, s_g]\right)=\frac{\alpha_1+\beta_1}{2g}$, $\theta\left([s_{\alpha_2}, s_{\beta_2}]\geq[s_0, s_g]\right)=\frac{\alpha_2+\beta_2}{2g}$,

then, $\theta\left(\left[s_{\alpha_1}, s_{\beta_1}\right] \geq \left[s_0, s_g\right]\right) \geq \theta\left(\left[s_{\alpha_2}, s_{\beta_2}\right] \geq \left[s_0, s_g\right]\right) \Leftrightarrow \frac{\alpha_1+\beta_1}{2g} \geq \frac{\alpha_2+\beta_2}{2g}$.

By comparing $\tilde{a}_1$ and $\tilde{a}_2$ with reference value $\left[s_0, s_g\right]$, the concepts of interval-valued linguistic additive dominance degree (ILVADD) and multiplicative dominance degree (ILVMDD) are developed and their properties are discussed.

(1) ILVADD

Definition 3. Let $\tilde{a}_1 = \left[s_{\alpha_1}, s_{\beta_1}\right]$ and $\tilde{a}_2 = \left[s_{\alpha_2}, s_{\beta_2}\right] \in I_{\left[s_0, s_g\right]}$ be two IVLVs, f is a strictly monotone increasing function (SMIF) on $[0,1]$, and $f(x) \geq 0$, $\forall x \in [0,1]$, then the ILVADD $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right)$ of $\tilde{a}_1 \geq \tilde{a}_2$ is defined as

$$\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) = \frac{f\left(\theta\left(\tilde{a}_1 \geq \left[s_0, s_g\right]\right)\right) - f\left(\theta\left(\tilde{a}_2 \geq \left[s_0, s_g\right]\right)\right)}{2f(1)} + 0.5 \tag{4}$$

Then, the ILVADD also satisfies the following properties.

Property 3. Let $\tilde{a}_1 = \left[s_{\alpha_1}, s_{\beta_1}\right]$, $\tilde{a}_2 = \left[s_{\alpha_2}, s_{\beta_2}\right]$ and $\tilde{a}_3 = \left[s_{\alpha_3}, s_{\beta_3}\right] \in I_{\left[s_0, s_g\right]}$ be three IVLVs, f is a SMIF on $[0,1]$, then

(1) $0 \leq \rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) \leq 1$;

(2) $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) + \rho_f\left(\tilde{a}_2 \geq \tilde{a}_1\right) = 1$;

(3) $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) = \rho_f\left(\tilde{a}_1 \geq \tilde{a}_3\right) + \rho_f\left(\tilde{a}_3 \geq \tilde{a}_2\right) - 0.5$.

Proof.

(1) and (2) are obvious.

(3) $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) = \frac{f\left(\frac{\alpha_1+\beta_1}{2g}\right) - f\left(\frac{\alpha_2+\beta_2}{2g}\right)}{2f(1)} + 0.5$,

$$\rho_f\left(\tilde{a}_1 \geq \tilde{a}_3\right) = \frac{f\left(\frac{\alpha_1+\beta_1}{2g}\right) - f\left(\frac{\alpha_3+\beta_3}{2g}\right)}{2f(1)} + 0.5,$$

$$\rho_f\left(\tilde{a}_3 \geq \tilde{a}_2\right) = \frac{f\left(\frac{\alpha_3+\beta_3}{2g}\right) - f\left(\frac{\alpha_2+\beta_2}{2g}\right)}{2f(1)} + 0.5.$$

Then, $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) = \rho_f\left(\tilde{a}_1 \geq \tilde{a}_3\right) + \rho_f\left(\tilde{a}_3 \geq \tilde{a}_2\right) - 0.5$. All the properties are proven.

Property 4. Let $\tilde{a}_1 = \left[s_{\alpha_1}, s_{\beta_1}\right]$ and $\tilde{a}_2 = \left[s_{\alpha_2}, s_{\beta_2}\right] \in I_{\left[s_0, s_g\right]}$ be two IVLVs, f is an SMIF on $[0,1]$, then

(1) $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) = 0.5 \Leftrightarrow \frac{\alpha_1+\beta_1}{2g} = \frac{\alpha_2+\beta_2}{2g}$;

(2) $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) > 0.5 \Leftrightarrow \frac{\alpha_1+\beta_1}{2g} > \frac{\alpha_2+\beta_2}{2g}$;

(3) $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) < 0.5 \Leftrightarrow \frac{\alpha_1+\beta_1}{2g} < \frac{\alpha_2+\beta_2}{2g}$.

Proof.

(1) Because $\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) = \frac{f\left(\frac{\alpha_1+\beta_1}{2g}\right) - f\left(\frac{\alpha_2+\beta_2}{2g}\right)}{2f(1)} + 0.5$, then

$$\rho_f\left(\tilde{a}_1 \geq \tilde{a}_2\right) = 0.5 \Leftrightarrow f\left(\frac{\alpha_1+\beta_1}{2}\right) = f\left(\frac{\alpha_2+\beta_2}{2}\right) \Leftrightarrow \frac{\alpha_1+\beta_1}{2g} = \frac{\alpha_2+\beta_2}{2g}.$$

The proofs of (2) and (3) are similar to (1).

Theorem 1. Let $\tilde{s}_i = \left[s_{\alpha_i}, s_{\beta_i}\right] \in I_{\left[s_0, s_g\right]} \left(i \in N\right)$ be an IVLV, $P = \left(p_{ij}\right)_{n\times n}$ be an FPR constructed by possible degrees, then there exists an ACFPR $A = \left(a_{ij}\right)_{n\times n}$ satisfying the following properties.

(1) if $p_{ij} > 0.5$, then $a_{ij} > 0.5$;

(2) if $p_{ij} = 0.5$, then $a_{ij} = 0.5$;

(3) if $p_{ij} < 0.5$, then $a_{ij} < 0.5$.

Proof.

Assume that $a_{ij} = \dfrac{f\left(\theta\left(\tilde{s}_i \geq \left[s_0, s_g\right]\right)\right) - f\left(\theta\left(\tilde{s}_j \geq \left[s_0, s_g\right]\right)\right)}{2f(1)} + 0.5$. It is easy to prove that $A = \left(a_{ij}\right)_{n\times n}$ is an ACFPR.

(1) $$\begin{aligned} & p_{ij} > 0.5 \Rightarrow \frac{\beta_i - \alpha_j}{\left(\beta_i - \alpha_i\right) + \left(\beta_j - \alpha_j\right)} > 0.5 \\ & \Rightarrow \frac{\alpha_i + \beta_i}{2g} > \frac{\alpha_j + \beta_j}{2g} \Rightarrow f\left(\frac{\alpha_i + \beta_i}{2g}\right) > f\left(\frac{\alpha_j + \beta_j}{2g}\right) \Rightarrow a_{ij} > 0.5 \end{aligned},$$

(2) $$\begin{aligned} & p_{ij} = 0.5 \Rightarrow \frac{\beta_i - \alpha_j}{\left(\beta_i - \alpha_i\right) + \left(\beta_j - \alpha_j\right)} = 0.5 \\ & \Rightarrow \frac{\alpha_i + \beta_i}{2g} = \frac{\alpha_j + \beta_j}{2g} \Rightarrow f\left(\frac{\alpha_i + \beta_i}{2g}\right) = f\left(\frac{\alpha_j + \beta_j}{2g}\right) \Rightarrow a_{ij} = 0.5 \end{aligned},$$

(3) $$\begin{aligned} & p_{ij} < 0.5 \Rightarrow \frac{\beta_i - \alpha_j}{\left(\beta_i - \alpha_i\right) + \left(\alpha_j - {}_j\right)} < 0.5 \\ & \Rightarrow \frac{\alpha_i + \beta_i}{2g} < \frac{\alpha_j + \beta_j}{2g} \Rightarrow f\left(\frac{\alpha_i + \beta_i}{2g}\right) < f\left(\frac{\alpha_j + \beta_j}{2g}\right) \Rightarrow a_{ij} < 0.5 \end{aligned}.$$

Theorem 1 suggests that when FPRs, constructed based on possibility degrees, are inconsistent, an ACFPR can be derived to resolve this inconsistency. Given the inherent uncertainty and vagueness in the evaluation of service quality indicators, FPRs may not always align due to various subjective judgements involved in the decision-making process.

In this case, the ACFPR ensures that rankings derived from inconsistent fuzzy preference relations are reconciled into a consistent order, offering a more reliable approach for assessing the service quality of the stations. For example, when comparing different transfer facilities at high-speed railway stations, if certain criteria like transfer distance or wait time yield conflicting rankings, the ACFPR resolves these conflicts. This means that the decision-makers can confidently rely on the ACFPR instead of inconsistent FPRs, improving the reliability and accuracy of the service quality evaluation.

Thus, in practical decision-making for evaluating the transfer facilities in high-speed railway stations, the ACFPR serves as a better alternative to replace unreliable or inconsistent evaluations. It allows for a more consistent and objective assessment process, which is crucial in addressing issues such as mismatched transfer capacities or inefficient connections, ultimately leading to better planning and enhanced passenger experience at the stations.

(2) ILVMDD

Definition 3. Let $\tilde{s}_1 = \left[s_{\alpha_1}, s_{\beta_1}\right]$ and $\tilde{s}_2 = \left[s_{\alpha_2}, s_{\beta_2}\right] \in I_{\left[s_0, s_g\right]}$ be two IVLVs, h is an SMIF on $[0,1]$, and $h(x) \geq 0$, $\forall x \in [0,1]$, then the ILVMDD $\varphi_h\left(\tilde{s}_1 \geq \tilde{s}_2\right)$ of $\tilde{s}_1 \geq \tilde{s}_2$ is defined as

$$\varphi_g\left(\tilde{s}_1 \geq \tilde{s}_2\right) = \frac{h\left(\tilde{s}_1 \geq \left[s_0, s_g\right]\right)}{h\left(\tilde{s}_1 \geq \left[s_0, s_g\right]\right) + h\left(\tilde{s}_2 \geq \left[s_0, s_g\right]\right)} \tag{5}$$

Property 5. Let $\tilde{s}_1=\left[s_{\alpha_1},s_{\beta_1}\right]$, $\tilde{s}_2=\left[s_{\alpha_2},s_{\beta_2}\right]$ and $\tilde{s}_3=\left[s_{\alpha_3},s_{\beta_3}\right]\in I_{\left[s_0,s_g\right]}$ be three IVLVs, h is an SMIF on $[0,1]$, then

(1) $0\le\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)\le 1$;

(2) $\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)+\varphi_h\left(\tilde{s}_2\ge\tilde{s}_1\right)=1$;

(3) $\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)\varphi_h\left(\tilde{s}_2\ge\tilde{s}_3\right)\varphi_h\left(\tilde{s}_3\ge\tilde{s}_1\right)=\varphi_h\left(\tilde{s}_2\ge\tilde{s}_1\right)\varphi_h\left(\tilde{s}_3\ge\tilde{s}_2\right)\varphi_h\left(\tilde{s}_1\ge\tilde{s}_3\right)$.

Proof.

(1) and (2) are obvious.

(3)

$$\begin{aligned}
&\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)\varphi_h\left(\tilde{s}_2\ge\tilde{s}_3\right)\varphi_h\left(\tilde{s}_3\ge\tilde{s}_1\right)\\
&=\frac{h\left(\frac{\beta_1+\alpha_1}{2g}\right)}{h\left(\frac{\beta_1+\alpha_1}{2g}\right)+h\left(\frac{\beta_2+\alpha_2}{2g}\right)}\times\frac{h\left(\frac{\beta_2+\alpha_2}{2g}\right)}{h\left(\frac{\beta_2+\alpha_2}{2g}\right)+h\left(\frac{\beta_3+\alpha_3}{2g}\right)}\times\frac{h\left(\frac{\beta_3+\alpha_3}{2g}\right)}{h\left(\frac{\beta_1+\alpha_1}{2g}\right)+h\left(\frac{\beta_3+\alpha_3}{2g}\right)}\\
&=\frac{h\left(\frac{\beta_2+\alpha_2}{2g}\right)}{h\left(\frac{\beta_1+\alpha_1}{2g}\right)+h\left(\frac{\beta_2+\alpha_2}{2g}\right)}\times\frac{h\left(\frac{\beta_3+\alpha_3}{2g}\right)}{h\left(\frac{\beta_2+\alpha_2}{2g}\right)+h\left(\frac{\beta_3+\alpha_3}{2g}\right)}\times\frac{h\left(\frac{\beta_1+\alpha_1}{2g}\right)}{h\left(\frac{\beta_1+\alpha_1}{2g}\right)+h\left(\frac{\beta_3+\alpha_3}{2g}\right)}\\
&=\varphi_h\left(\tilde{s}_2\ge\tilde{s}_1\right)\varphi_h\left(\tilde{s}_3\ge\tilde{s}_2\right)\varphi_h\left(\tilde{s}_1\ge\tilde{s}_3\right)
\end{aligned}$$

Property 6. Let $\tilde{s}_1=\left[s_{\alpha_1},s_{\beta_1}\right]$, $\tilde{s}_2=\left[s_{\alpha_2},s_{\beta_2}\right]\in I_{\left[s_0,s_g\right]}$ be two IVLVs, h is an SMIF on $[0,1]$, then

(1) $\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)=0.5\Leftrightarrow\frac{\beta_1+\alpha_1}{2g}=\frac{\beta_2+\alpha_2}{2g}$;

(2) $\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)>0.5\Leftrightarrow\frac{\beta_1+\alpha_1}{2g}>\frac{\beta_2+\alpha_2}{2g}$;

(3) $\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)<0.5\Leftrightarrow\frac{\beta_1+\alpha_1}{2g}<\frac{\beta_2+\alpha_2}{2g}$.

Proof.

(1) Because $\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)=\frac{h\left(\frac{\beta_1+\alpha_1}{2g}\right)}{h\left(\frac{\beta_1+\alpha_1}{2g}\right)+h\left(\frac{\beta_2+\alpha_2}{2g}\right)}$,

then, $\varphi_h\left(\tilde{s}_1\ge\tilde{s}_2\right)=0.5\Leftrightarrow h\left(\frac{\beta_1+\alpha_1}{2g}\right)=h\left(\frac{\beta_2+\alpha_2}{2g}\right)\Leftrightarrow\frac{\beta_1+\alpha_1}{2g}=\frac{\beta_2+\alpha_2}{2g}$.

The proofs of (2) and (3) are similar to (1).

Theorem 2. Let $\tilde{s}_i=\left[s_{\alpha_i},s_{\beta_i}\right]\in I_{\left[s_0,s_g\right]}(i\in N)$ be an IVLV, $P=\left(p_{ij}\right)_{n\times n}$ be an FPR constructed by possible degrees, then there exists an MCFPR $B=\left(b_{ij}\right)_{n\times n}$ satisfying the following properties.

(1) if $p_{ij}>0.5$, then $b_{ij}>0.5$;

(2) if $p_{ij}=0.5$, then $b_{ij}=0.5$;

(3) if $p_{ij}<0.5$, then $b_{ij}<0.5$.

Proof.

Assume that $b_{ij}=\frac{h\left(\theta\left(\tilde{s}_i\ge\left[s_0,s_g\right]\right)\right)}{h\left(\theta\left(\tilde{s}_i\ge\left[s_0,s_g\right]\right)\right)+h\left(\theta\left(\tilde{s}_j\ge\left[s_0,s_g\right]\right)\right)}$. It is easy to prove $B=\left(b_{ij}\right)_{n\times n}$ is an MCFPR.

(1) $$\begin{aligned} & p_{ij} > 0.5 \Rightarrow \frac{\beta_i - \alpha_j}{(\beta_i - \alpha_i) + (\beta_j - \alpha_j)} > 0.5 \Rightarrow \frac{\alpha_i + \beta_i}{2g} > \frac{\alpha_j + \beta_j}{2g} \\ & \Rightarrow h\left(\frac{\alpha_i + \beta_i}{2g}\right) > h\left(\frac{\alpha_j + \beta_j}{2g}\right) \Rightarrow b_{ij} > 0.5 \end{aligned}.$$

(2) $$\begin{aligned} & p_{ij} = 0.5 \Rightarrow \frac{\beta_i - \alpha_j}{(\beta_i - \alpha_i) + (\beta_j - \alpha_j)} = 0.5 \Rightarrow \frac{\alpha_i + \beta_i}{2g} = \frac{\alpha_j + \beta_j}{2g} \\ & \Rightarrow h\left(\frac{\alpha_i + \beta_i}{2g}\right) = h\left(\frac{\alpha_j + \beta_j}{2g}\right) \Rightarrow b_{ij} = 0.5 \end{aligned}.$$

(3) $$\begin{aligned} & p_{ij} < 0.5 \Rightarrow \frac{\beta_i - \alpha_j}{(\beta_i - \alpha_i) + (\beta_j - \alpha_j)} < 0.5 \Rightarrow \frac{\alpha_i + \beta_i}{2g} < \frac{\alpha_j + \beta_j}{2g} \\ & \Rightarrow h\left(\frac{\alpha_i + \beta_i}{2g}\right) < h\left(\frac{\alpha_j + \beta_j}{2g}\right) \Rightarrow b_{ij} < 0.5 \end{aligned}.$$

The above theorem indicates that when the FPRs constructed by possible degrees are inconsistent, there exists an MCFPR. This MCFPR ensures that the ranking results obtained from the inconsistent FPRs are consistent with those determined by the MCFPRs. It also implies that in the decision-making process, the MCFPR *B* can be used to replace the inconsistent FPR *P*.

Theorem 2 indicates that when FPRs based on possibility degrees are inconsistent, an MCFPR can be used to resolve this inconsistency. In the context of assessing the service quality of transfer facilities in high-speed railway stations, this concept can be applied to handle the uncertainties and subjectivity that arise when evaluating service criteria. By applying an MCFPR, the evaluation process ensures that the rankings of the facilities remain consistent despite the inconsistency in the initial FPRs. This consistency is crucial for making well-informed decisions in assessing the transfer facilities. The MCFPR helps ensure that the decision-makers can reliably use the results of the service quality evaluation, even when individual criteria might conflict.

In practical applications, the MCFPR acts as a tool for resolving inconsistencies in the evaluation of service quality, making the decision-making process more robust and actionable for station optimisation.

Next, the relationship among possible degrees, IVLADD and IVLMDD will be explored.

Lemma 1. Let $\tilde{s}_1 = [s_{\alpha_1}, s_{\beta_1}]$ and $\tilde{s}_2 = [s_{\alpha_2}, s_{\beta_2}] \in I_{[s_0, s_g]}$ be two IVLVs, then

(1) $p(\tilde{s}_1 \geq \tilde{s}_2) > 0.5 \Leftrightarrow \rho_f(\tilde{s}_1 \geq \tilde{s}_2) > 0.5 \Leftrightarrow \varphi_h(\tilde{s}_1 \geq \tilde{s}_2) > 0.5$;

(2) $p(\tilde{s}_1 \geq \tilde{s}_2) = 0.5 \Leftrightarrow \rho_f(\tilde{s}_1 \geq \tilde{s}_2) = 0.5 \Leftrightarrow \varphi_h(\tilde{s}_1 \geq \tilde{s}_2) = 0.5$;

(3) $p(\tilde{s}_1 \geq \tilde{s}_2) < 0.5 \Leftrightarrow \rho_f(\tilde{s}_1 \geq \tilde{s}_2) < 0.5 \Leftrightarrow \varphi_h(\tilde{s}_1 \geq \tilde{s}_2) < 0.5$.

f and h are the SMIFs on $[0,1]$, and $f(x) \geq 0$, $h(x) \geq 0$, $\forall x \in [0,1]$,

$$p(\tilde{s}_1 \geq \tilde{s}_2) = \min\left\{\max\left(\frac{\beta_1 - \alpha_2}{l(\tilde{s}_1) + l(\tilde{s}_2)}, 0\right), 1\right\},\ \rho_f(\tilde{s}_1 \geq \tilde{s}_2) = \frac{f\left(\frac{\beta_1 + \alpha_1}{2g}\right) - f\left(\frac{\beta_2 + \alpha_2}{2g}\right)}{2f(1)} + 0.5,$$

$$\varphi_h(\tilde{s}_1 \geq \tilde{s}_2) = \frac{h\left(\frac{\beta_1 + \alpha_1}{2g}\right)}{h\left(\frac{\beta_1 + \alpha_1}{2g}\right) + h\left(\frac{\beta_2 + \alpha_2}{2g}\right)}.$$

Proof.

$$p\left(\tilde{s}_1 \geq \tilde{s}_2\right) > 0.5 \Leftrightarrow \frac{\alpha_1+\beta_1}{2g} > \frac{\alpha_2+\beta_2}{2g}$$

(1) $\Leftrightarrow f\left(\frac{\alpha_1+\beta_1}{2g}\right) > f\left(\frac{\alpha_2+\beta_2}{2g}\right) \Leftrightarrow p_f\left(\tilde{s}_1 \geq \tilde{s}_2\right) > 0.5$.

$$\Leftrightarrow h\left(\frac{\alpha_1+\beta_1}{2g}\right) > h\left(\frac{\alpha_2+\beta_2}{2g}\right) \Leftrightarrow \varphi_h\left(\tilde{s}_1 \geq \tilde{s}_2\right) > 0.5$$

Similarly, (2) and (3) can be proven.

Example 3 (continued with Example 1). Rank the four IVLVs by ILVADD and ILVMDD.

Assume that $f(x)=\sqrt{x}+1, x\in[0,1]$, then

$\rho_f\left(\tilde{s}_1 \geq \tilde{s}_2\right)=0.5$, $\rho_f\left(\tilde{s}_3 \geq \tilde{s}_4\right)=0.3605$, $\rho_f\left(\tilde{s}_1 \geq \tilde{s}_3\right)=\rho_f\left(\tilde{s}_2 \geq \tilde{s}_3\right)=0.5143$, and $\rho_f\left(\tilde{s}_1 \geq \tilde{s}_4\right)=\rho_f\left(\tilde{s}_2 \geq \tilde{s}_4\right)=0.3748$.

Then, an ACFPR is constructed as:

$$A^{'}=\left[a_{ij}^{'}\right]_{4\times 4}=\begin{bmatrix} 0.5 & 0.5 & 0.5143 & 0.3748 \\ 0.5 & 0.5 & 0.5143 & 0.3748 \\ 0.4857 & 0.4857 & 0.5 & 0.3605 \\ 0.6252 & 0.6252 & 0.6395 & 0.5 \end{bmatrix}$$

The weights are calculated as $w_1=\frac{0.4723}{c}-\frac{1}{2c}+\frac{1}{4}$, $w_2=\frac{0.4723}{c}-\frac{1}{2c}+\frac{1}{4}$, $w_3=\frac{0.4580}{c}-\frac{1}{2c}+\frac{1}{4}$, and $w_4=\frac{0.5975}{c}-\frac{1}{2c}+\frac{1}{4}$.

Assume that $c=2$, then

$w_1=0.2361$, $w_2=0.2361$, $w_3=0.2290$, $w_4=0.2987$,

Thus, $w_4 > w_1 = w_2 > w_3$.

Then, $\tilde{s}_4 > \tilde{s}_1 = \tilde{s}_2 > \tilde{s}_3$.

The ranking result of ACFPR $A^{'}$ by ILVADD is consistent with that of inconsistent FPR P_1.

Assume that $h(x)=2^x, x\in[0,1]$, then

$\varphi_h\left(\tilde{s}_1 \geq \tilde{s}_2\right)=0.5$, $\varphi_h\left(\tilde{s}_3 \geq \tilde{s}_4\right)=0.4654$, $\varphi_h\left(\tilde{s}_1 \geq \tilde{s}_3\right)=\varphi_h\left(\tilde{s}_2 \geq \tilde{s}_3\right)=0.5032$, and $\varphi_h\left(\tilde{s}_1 \geq \tilde{s}_4\right)=\varphi_h\left(\tilde{s}_2 \geq \tilde{s}_4\right)=0.4686$.

Then, an MCFPR is constructed as:

$$B^{'}=\left[b_{ij}^{'}\right]_{4\times 4}=\begin{bmatrix} 0.5 & 0.5 & 0.5032 & 0.4686 \\ 0.5 & 0.5 & 0.5032 & 0.4686 \\ 0.4968 & 0.4968 & 0.5 & 0.4654 \\ 0.5314 & 0.5314 & 0.5346 & 0.5 \end{bmatrix}$$

The weights are calculated as $v_1=v_2=0.2427$, $v_3=0.2395$, and $v_4=0.2751$.

Thus, $v_4 > v_1 = v_2 > v_3$.

Then, $\tilde{s}_4 > \tilde{s}_1 \equiv \tilde{s}_2 > \tilde{s}_3$.

The ranking result of MCFPR $B^{'}$ by ILVMDD is consistent with that of inconsistent FPR P_1.

The FPRs constructed by possible degrees are inconsistent, and the ranking results obtained by approximate ACFPRs or MCFPRs conflict with those obtained by FPR P_1 in Example 1. In Example 3, the ranking results obtained by ILVADD or ILVMDD are the same as those obtained by FPR P_1. Thus, the definitions of ILVADD or ILVMDD are more reasonable than the possibility degree when they are used in decision-making problems.

Example 4 (continued with Example 2). Construct and aggregate the four FPRs by IVLADD and IVLMDD.

Firstly, the FPRs under different criteria by IVLADD are constructed. Assume that $f(x)=x+1$, $x\in[0,1]$, then

$$A'_{C_1}=\begin{bmatrix}0.5&0.4547&0.3734&0.4547\\0.5453&0.5&0.4188&0.5\\0.6266&0.5813&0.5&0.5813\\0.5453&0.5&0.4188&0.5\end{bmatrix},\ A'_{C_2}=\begin{bmatrix}0.5&0.4953&0.4641&0.4828\\0.5047&0.5&0.4688&0.4875\\0.5359&0.5313&0.5&0.5188\\0.5172&0.5125&0.4813&0.5\end{bmatrix},$$

$$A'_{e_3}=\begin{bmatrix}0.5&0.5156&0.4219&0.5031\\0.4844&0.5&0.4063&0.4875\\0.5781&0.5938&0.5&0.5813\\0.4969&0.5125&0.4188&0.5\end{bmatrix},\ A'_{e_4}=\begin{bmatrix}0.5&0.4563&0.4531&0.5031\\0.5438&0.5&0.4969&0.5469\\0.5469&0.5031&0.5&0.5500\\0.4969&0.4531&0.4500&0.5\end{bmatrix}.$$

It is easy to prove that A'_{C_1}, A'_{C_2}, A'_{C_3} and A'_{C_4} are ACFPRs. Then, the four FPRs aggregated into an ACFPR as:

$$A'=\begin{bmatrix}0.5&0.4753&0.4172&0.4797\\0.5247&0.5&0.4419&0.5044\\0.5828&0.5581&0.5&0.5625\\0.5203&0.4956&0.4375&0.5\end{bmatrix}.$$

The four FPRs under different criteria should be calculated by IVLMDD. Assume that $h(x)=\sqrt{x}, x\in[0,1]$, then

$$B'_{C_1}=\begin{bmatrix}0.5&0.4323&0.3651&0.4323\\0.5677&0.5&0.4302&0.5\\0.6349&0.5698&0.5&0.5698\\0.5677&0.5&0.4302&0.5\end{bmatrix},\ B'_{C_2}=\begin{bmatrix}0.5&0.4937&0.4583&0.4783\\0.5063&0.5&0.4646&0.4846\\0.5417&0.5354&0.5&0.5200\\0.5217&0.5154&0.4800&0.5\end{bmatrix},$$

$$B'_{C_3}=\begin{bmatrix}0.5&0.5190&0.4338&0.5036\\0.4810&0.5&0.4152&0.4846\\0.5662&0.5848&0.5&0.5698\\0.4964&0.5154&0.4302&0.5\end{bmatrix},\ B'_{C_4}=\begin{bmatrix}0.5&0.4585&0.4561&0.5036\\0.5415&0.5&0.4975&0.5450\\0.5439&0.5025&0.5&0.5475\\0.4964&0.4550&0.4525&0.5\end{bmatrix}$$

It is easy to prove that B'_{C_1}, B'_{C_2}, B'_{C_3} and B'_{C_4} are MCFPRs. Then, the four FPRs are aggregated into an FPR as:

$$B'=\begin{bmatrix}0.5&0.4659&0.4135&0.4689\\0.5317&0.5&0.4466&0.5024\\0.5828&0.5516&0.5&0.5550\\0.5290&0.4966&0.4442&0.5\end{bmatrix}$$

FPRs constructed by IVLADD or IVLMDD exhibit consistency. Consistent FPRs help maintain the consistency of the ranking process for alternative stations during service quality evaluation and yield reliable evaluation results. In Example 2, the FPRs constructed by possibility degree are inconsistent, and the aggregated FPRs are almost not consistent. The ranking results produced by the aggregated FPRs are unreliable. Therefore, in the multi-criteria service quality evaluation process, the role played by consistent FPRs constructed by IVLADD or IVLMDD is superior to that of inconsistent FPRs constructed by possibility degree.

4. SERVICE QUALITY EVALUATION OF TRANSFER FACILITIES

Here, new IVL-MCDM methods based on IVLADD and IVLMDD are developed to ensure the consistency of evaluation information for service quality evaluation of transfer facilities. The problem descriptions are provided as follows.

Assume that $S=\{s_1,s_2,\ldots,s_n\}$ is a set of high-speed railway stations, and $C=\{c_1,c_2,\ldots,c_m\}$ is a set of criteria. For each station $s_i \in S$, experts provide preference values c_{ij} for criteria $c_i \in C$. Let $w=(w_1,w_2,\ldots,w_m)^T$ be the criteria weight vector, where $w_j \in [0,1]$, $j=1,2,\ldots,m$ and $\sum_{j=1}^{m} w_j = 1$. c_{ij} represents the assessment information provided by experts for the j-th criterion of station s_i, $c_{ij}=\left[s_{\alpha_{ij}},s_{\beta_{ij}}\right] \in I_{\left[s_0,s_g\right]}$, and all preference values constitute the evaluation matrix $C=\left(c_{ij}\right)_{n\times m}$.

4.1 IVL-MCDM method based on IVLADD

Step 1: Given the SMIF $f(x)\geq 0$, $\forall x \in [0,1]$, calculate $d_{il}^{j}=\dfrac{f\left(\dfrac{\alpha_{ij}+\beta_{ij}}{2g}\right)-f\left(\dfrac{\alpha_{lj}+\beta_{lj}}{2g}\right)}{2f(1)}+0.5$, $i,l \in N$, $j=1,2,\ldots,m$, and construct the evaluation matrix $D_j=\left(d_{il}^{j}\right)_{n\times n}$.

The SMIF serves as the foundation for evaluating the service quality of transfer facilities. This step involves identifying and quantifying the key indicators that define service quality. By calculating and organising these values into an evaluation matrix, we can systematically compare different transfer facilities based on multiple criteria. This matrix serves as a tool for aggregating the data and preparing for the subsequent steps of the evaluation.

Step 2: Given the criteria weight w_j, then calculate the comprehensive matrix $D=\sum_{j=1}^{m} w_j D_j=\left(d_{il}\right)_{n\times n}$.

Not all evaluation criteria are equally important when assessing the overall service quality. Therefore, each criterion is assigned a weight based on its significance. The weights are applied to the respective evaluation indicators in the matrix. The result is a comprehensive evaluation matrix where each criterion is not only measured but also weighted according to its importance. This enables a more nuanced and prioritised assessment of the transfer facilities' service quality.

Step 3: assume that $c \geq \dfrac{n-1}{2}$, and calculate the transfer facility service quality $\varpi_i=\dfrac{1}{nc}\sum_{l=1}^{n} d_{il}-\dfrac{1}{2c}+\dfrac{1}{n}$ of each station.

These assumptions guide the calculation of service quality for each station. The calculated service quality reflects the real-world conditions that impact the transfer facilities, allowing for a practical comparison of stations in terms of their ability to provide seamless transfer services.

Step 4: Rank the stations by ϖ_i.

After calculating the service quality for each station, the stations are ranked based on their performance. This ranking provides a clear, ordered list of stations from the best to the worst in terms of their transfer facility service quality. The ranking helps decision-makers prioritise which stations require improvements or optimisations, enabling them to focus resources on enhancing the stations that are lagging behind in service quality.

4.2 IVL-MCDM method based on IVLMDD

Step 1: Given the SMIF $h(x) \geq 0$, $\forall x \in [0,1]$, calculate $e_{il}^{j} = \frac{h\left(\frac{\alpha_{ij}+\beta_{ij}}{2g}\right)}{h\left(\frac{\alpha_{ij}+\beta_{ij}}{2g}\right)+h\left(\frac{\alpha_{lj}+\beta_{lj}}{2g}\right)}$, $i,l \in N$, $j=1,2,\ldots,m$, and construct the evaluation matrix $E_j = \left(e_{il}^{j}\right)_{n\times n}$.

Step 2: Given criteria weight w_j, and calculate the comprehensive matrix $E = \prod_{j=1}^{m} E_j^{w_j} = \left(e_{il}\right)_{n\times n}$.

Step 3: Calculate the transfer facility service quality $v_i = \frac{1}{\sum_{l=1}^{n}\frac{e_{il}+e_{li}}{e_{il}} - n}$ of each station.

Step 4: Rank the stations by v_i.

The explanations are similar to Section 4.1.

5. RESULTS

5.1 Service quality evaluation influence analysis of transfer facilities

Factors affecting the transfer service quality of high-speed railway stations include hub location, compatibility between railways and other transportation modes, transfer facility service capacity and information systems. The location selection of high-speed railway stations affects transfers. Railway stations located in city centres can fully utilise underground spaces, optimise transfer facility layouts and form good connections with surrounding hubs. Meanwhile, railway stations located on the outskirts of cities can reduce their impact on urban traffic, increase investment in urban rail transit construction, optimise internal transfer systems, and facilitate passengers' convenient access to and from urban areas. Reasonable planning of transfer facility scale and layout, along with well-organised coordination of internal and external transportation operations, are essential to ensure smooth transfer environments within hubs. Railway hubs need corresponding transportation networks to be fully functional. If the hub's functions do not match its transportation network capacity, the overall transportation function will not be fully utilised, leading to resource waste. Transfer facilities serve as the physical basis for realising various functions and roles of transfer systems within railway hubs [35]. Their service capacity mainly depends on factors such as facility scale, layout, distribution capacity and the degree of connection between different facilities. Railway hubs, with their large-scale infrastructure and complex internal layouts, require complementary passenger guidance systems when constructing transfer systems. These systems provide information services to passengers, facilitating their timely access to transfer information and improving transfer efficiency.

Based on the above analysis of the main influencing factors of transfer in railway hubs, this paper considers the rationality of railway hub location (C_1), coordination (C_2), service level (C_3) and efficiency (C_4) as evaluation criteria.

5.2 Evaluation process

Then, there are six high-speed railway stations (S_1-S_6) to be evaluated. The weight vector is $w=(0.27,0.24,0.13,0.36)^T$ .The service quality evaluation information is provided by experts in forms of IVLVs, and is shown in *Table 2*.

Table 2 – Service quality evaluation information of different stations

	C_1	C_2	C_3	C_4
S_1	$[s_{4.2}, s_{5.4}]$	$[s_{3.2}, s_{6.6}]$	$[s_{3.2}, s_{6.5}]$	$[s_{4.2}, s_{6.3}]$
S_2	$[s_{2.5}, s_{4.3}]$	$[s_{2.2}, s_{4.5}]$	$[s_{2.2}, s_{3.3}]$	$[s_{6}, s_{6.5}]$
S_3	$[s_{2.2}, s_{6.3}]$	$[s_{4.2}, s_{5.3}]$	$[s_{3.4}, s_{3.9}]$	$[s_{3.6}, s_{6.3}]$
S_4	$[s_{6}, s_{6.4}]$	$[s_{5.3}, s_{5.5}]$	$[s_{6}, s_{7.1}]$	$[s_{2.5}, s_{4.5}]$
S_5	$[s_{5.2}, s_{6.3}]$	$[s_{2.4}, s_{3.5}]$	$[s_{3.4}, s_{5.4}]$	$[s_{3.3}, s_{5.2}]$
S_6	$[s_{6}, s_{6.4}]$	$[s_{5.3}, s_{6.5}]$	$[s_{2.2}, s_{4.5}]$	$[s_{5.4}, s_{6.3}]$

The new IVL-MCDM methods based on IVLADD and IVLMDD are used to evaluate the transfer facility service quality, respectively.

(1) IVL-MCDM based on IVLADD

Step 1: Assume $f(x) = x+1, x \in [0,1]$, then construct the ACPFRs by IVLADD under different criteria as *Table 3*.

Table 3 – ACFPRs under different criteria

	C_1						C_2					
	S_1	S_2	S_3	S_4	S_5	S_6	S_1	S_2	S_3	S_4	S_5	S_6
S_1	0.5000	0.5438	0.5172	0.4563	0.4703	0.4563	0.5000	0.5484	0.5047	0.4844	0.5609	0.4688
S_2	0.4563	0.5000	0.4734	0.4125	0.4266	0.4125	0.4516	0.5000	0.4563	0.4359	0.5125	0.4203
S_3	0.4828	0.5266	0.5000	0.4391	0.4531	0.4391	0.4953	0.5438	0.5000	0.4797	0.5563	0.4641
S_4	0.5438	0.5875	0.5609	0.5000	0.5141	0.5000	0.5156	0.5641	0.5203	0.5000	0.5766	0.4844
S_5	0.5297	0.5734	0.5469	0.4859	0.5000	0.4859	0.4391	0.4875	0.4438	0.4234	0.5000	0.4078
S_6	0.5438	0.5875	0.5609	0.5000	0.5141	0.5000	0.5313	0.5797	0.5359	0.5156	0.5922	0.5000
	C_3						C_4					
	S_1	S_2	S_3	S_4	S_5	S_6	S_1	S_2	S_3	S_4	S_5	S_6
S_1	0.5000	0.5656	0.5375	0.4469	0.5141	0.5469	0.5000	0.4688	0.5094	0.5547	0.5313	0.4813
S_2	0.4344	0.5000	0.4719	0.3813	0.4484	0.4813	0.5313	0.5000	0.5406	0.5859	0.5625	0.5125
S_3	0.4625	0.5281	0.5000	0.4094	0.4766	0.5094	0.4906	0.4594	0.5000	0.5453	0.5219	0.4719
S_4	0.5531	0.6188	0.5906	0.5000	0.5672	0.6000	0.4453	0.4141	0.4547	0.5000	0.4766	0.4266
S_5	0.4859	0.5516	0.5234	0.4328	0.5000	0.5328	0.4688	0.4375	0.4781	0.5234	0.5000	0.4500
S_6	0.4531	0.5188	0.4906	0.4000	0.4672	0.5000	0.5188	0.4875	0.5281	0.5734	0.5500	0.5000

Step 2: Aggregate the ACFPRs under different criteria into an ACFPR, $C = 0.27C_1 + 0.24C_2 + 0.13C_3 + 0.36C_4$, then the aggregated ACFPR is shown in *Table 4*.

Table 4 – The aggregated ACFPR based on IVLADD

	S_1	S_2	S_3	S_4	S_5	S_6
S_1	0.5000	0.5207	0.5140	0.4972	0.5197	0.4800
S_2	0.4793	0.5000	0.4933	0.4765	0.4990	0.4593
S_3	0.4860	0.5067	0.5000	0.4832	0.5057	0.4660
S_4	0.5028	0.5235	0.5168	0.5000	0.5225	0.4828
S_5	0.4803	0.5010	0.4943	0.4775	0.5000	0.4603
S_6	0.5200	0.5407	0.5340	0.5172	0.5397	0.5000

Step 3: Assume that c=3, then the service quality values of six high-speed stations are calculated as $\varpi_1 = 0.1684, \varpi_2 = 0.1615, \varpi_3 = 0.1638, \varpi_4 = 0.1694, \varpi_5 = 0.1619, \varpi_6 = 0.1751$.

Step 4: The service quality results are ranked by $S_6 \geq S_4 \geq S_1 \geq S_3 \geq S_5 \geq S_2$.

(2) IVL-MCDM based on IVLMDD

Step 1: Assume $h(x) = x^2, x \in [0,1]$, then construct the MCPFRs by IVLMDD under different criteria as *Table 5*.

Table 5 – MCFPRs under different criteria

	C_1						C_2					
	S_1	S_2	S_3	S_4	S_5	S_6	S_1	S_2	S_3	S_4	S_5	S_6
S_1	0.5000	0.6659	0.5605	0.3748	0.4107	0.3748	0.5000	0.6815	0.5155	0.4516	0.7340	0.4082
S_2	0.3341	0.5000	0.3902	0.2312	0.2591	0.2312	0.3185	0.5000	0.3322	0.2779	0.5632	0.2438
S_3	0.4395	0.6098	0.5000	0.3197	0.3533	0.3197	0.4845	0.6678	0.5000	0.4362	0.7217	0.3933
S_4	0.6252	0.7688	0.6803	0.5000	0.5376	0.5000	0.5484	0.7221	0.5638	0.5000	0.7702	0.4558
S_5	0.5893	0.7409	0.6467	0.4624	0.5000	0.4624	0.2660	0.4368	0.2783	0.2298	0.5000	0.2000
S_6	0.6252	0.7688	0.6803	0.5000	0.5376	0.5000	0.5918	0.7562	0.6067	0.5442	0.8000	0.5000
	C_3						C_4					
	S_1	S_2	S_3	S_4	S_5	S_6	S_1	S_2	S_3	S_4	S_5	S_6
S_1	0.5000	0.7567	0.6384	0.3541	0.5485	0.6770	0.5000	0.4137	0.5294	0.6923	0.6041	0.4461
S_2	0.2433	0.5000	0.3621	0.1499	0.2809	0.4026	0.5863	0.5000	0.6145	0.7613	0.6838	0.5330
S_3	0.3616	0.6379	0.5000	0.2369	0.4076	0.5428	0.4706	0.3855	0.5000	0.6667	0.5756	0.4172
S_4	0.6459	0.8501	0.7631	0.5000	0.6891	0.7927	0.3077	0.2387	0.3333	0.5000	0.4041	0.2636
S_5	0.4515	0.7191	0.5924	0.3109	0.5000	0.6330	0.3959	0.3162	0.4244	0.5959	0.5000	0.3455
S_6	0.3230	0.5974	0.4572	0.2073	0.3670	0.5000	0.5539	0.4670	0.5828	0.7364	0.6545	0.5000

Step 2: Aggregate the MCFPRs under different criteria into an MCFPR, $C = C_1^{0.27} \times C_2^{0.24} \times C_3^{0.13} \times C_4^{0.36}$, then the aggregated ACFPR is shown in *Table 6*.

Table 6 – The aggregated MCFPR based on IVLMDD

	S_1	S_2	S_3	S_4	S_5	S_6
S_1	0.5000	0.5736	0.5474	0.4852	0.5633	0.4398
S_2	0.4264	0.5000	0.4378	0.3508	0.4474	0.3400
S_3	0.4526	0.5622	0.5000	0.4316	0.5093	0.3961
S_4	0.5148	0.6492	0.5684	0.5000	0.5462	0.4123
S_5	0.4367	0.5526	0.4907	0.4538	0.5000	0.3547
S_6	0.5602	0.6600	0.6039	0.5877	0.6453	0.5000

Step 3: The service quality values of six high-speed stations are calculated as
$v_1 = 0.1761, v_2 = 0.1155, v_3 = 0.1472, v_4 = 0.1819, v_5 = 0.1397, v_6 = 0.2377$.

Step 4: The service quality results are ranked by
$S_6 \geq S_4 \geq S_1 \geq S_3 \geq S_5 \geq S_2$.

5.3 Comparative analysis

The two developed IVL-MCDM methods based on IVLADD and IVLMDD are compared with IVL-TOPSIS [36], IVL-VIKOR [37], IVL-TODIM [38] and IVL-PROMETHEE [39] for verifying the effectiveness in service quality evaluation of transfer facilities. The ranking results of the six high-speed stations are presented in *Figure 1*. The developed IVL-MADM method yields the same results in assessing the service quality of transfer facilities as the IVL-TOPSIS method but differs from the IVL-VIKOR, IVL-TODIM and IVL-PROMETHEE methods. The main reasons for this differential outcome are as follows. Firstly, IVL-TOPSIS is based on the assumption of the complete rationality of experts in evaluating service quality, resulting in more objective assessment outcomes. Secondly, the IVL-VIKOR method introduces compromise coefficients in the process of service quality evaluation, which may lead to subjective assessment results. Thirdly, the IVL-TODIM and IVL-PROMETHEE methods are based on the construction of FPR matrices using possibility degrees. Inconsistent FPRs may fail to fully retain the original service quality evaluation information, further illustrating the drawbacks of using possibility degrees to construct FPRs in decision-making evaluations. Therefore, in the assessment of transfer facility service quality, the two developed IVL-MADM methods are more reasonable compared to the IVL-VIKOR, IVL-TODIM and IVL-PROMETHEE methods.

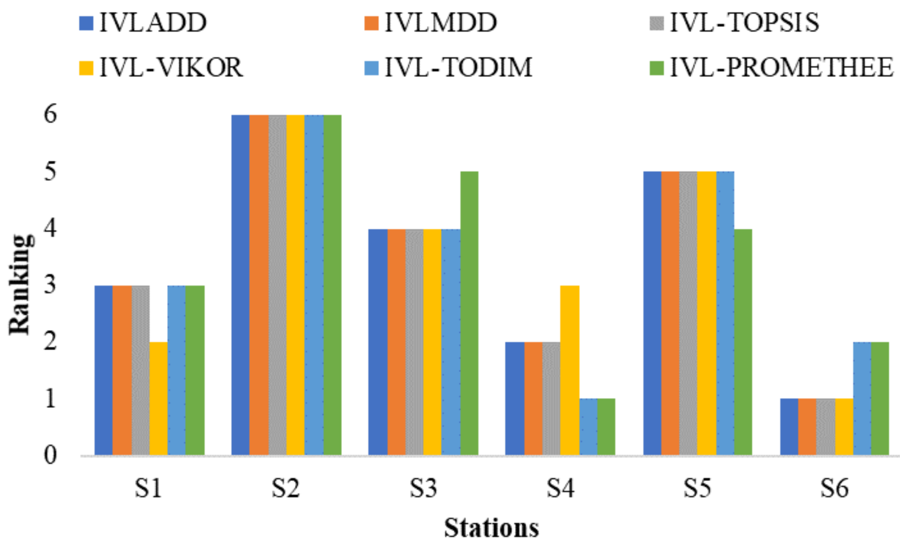

Figure 1 – Ranking results by different IVL-MCDM methods

6. CONCLUSIONS

The methods for evaluating the quality of transfer facilities at high-speed railway stations are proposed. The IVL-MCDM models are developed based on leveraging the advantages of IVLVs in expressing attribute uncertainty and weight uncertainty. Firstly, the drawbacks of inconsistent FPRs constructed based on possibility degrees are revealed. To overcome this issue, the concepts of IVLVADD and IVLVMDD are proposed, and their properties are discussed to ensure the consistency of evaluation information in multi-attribute service quality assessment problems. Then, two IVL-MADM methods based on IVLVADD and IVLVMDD are proposed for evaluating the service quality of transfer facilities at high-speed railway stations. Finally, the rationality and reliability of the developed IVL-MADM methods are demonstrated through numerical examples.

The summarised advantages of the developed decision-making methods are as follows. Firstly, the developed evaluation method provides a useful decision-making framework for assessing the service quality of high-speed railway stations. Secondly, two new dominance degrees, IVLADD and IVLMDD are developed, and their properties are proven to ensure the consistency of constructed FPRs, overcoming the drawbacks of inconsistent FPRs resulting from possibility degree-based constructions and erroneous service quality assessments. Thirdly, the IVL-MADM models based on IVLADD and IVLMDD ensure the consistency of evaluation information throughout the service quality process.

However, the developed framework may be highly theoretical and not eligible for real life. To address the above issues, we will first employ IVLVs to quantify indicators and provide a nuanced approach to capturing uncertainty and subjectivity in real-world conditions. This method allows for a more realistic representation of the variability and ambiguity often encountered in the assessment of high-speed rail transfer facilities. Then, we will apply the developed method to a wide array of large-scale, diverse case studies that can demonstrate its robustness and adaptability. Testing across different high-speed railway station scenarios, such as varied traffic volumes, urban density and regional requirements, allows for refinement of the model and proves its scalability and reliability.

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基于区间值语言多准则决策方法的高铁车站换乘设施服务质量评估

摘要
高铁车站在实现不同交通方式的无缝衔接中具有关键作用。然而，换乘能力不匹配、方式连接效率低下以及乘客换乘距离和时间过长等问题制约了高铁站的效率，阻碍了整体交通系统的发展。本文针对高铁站换乘设施服务质量评估的需求，提出了优化换乘设施的理论基础。研究利用区间值语言术语集（Interval-Valued Linguistic Term Sets, IVLTSs），开发了区间值语言多准则决策（Interval-Valued Linguistic Multi-Criteria Decision-Making, IVL-MCDM）方法，在评估指标和属性权重存在不确定性的情况下评估服务质量。本文引入了新的支配度（Dominance Degrees），以增强评估的可靠性，并确保换乘设施服务质量评估的一致性。通过案例研究验证了所提出方法的有效性，相较于传统的 IVL-MCDM 方法，展现了其在评估信息一致性方面的优越性。

关键词
高铁车站；服务质量；换乘设施；多准则决策；区间语言集