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Research on Metro Passenger Satisfaction Evaluation Based on Multi-Objective Optimization Model

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Abstract: In recent years, the metro network has been continuously expanding in scale and coverage. However, at the same time, passengers' demands for service quality, comfort experience and operational efficiency have also been constantly rising. To improve the public transportation service system, enhancing the passenger experience and service quality of the subway system has become an important issue that needs to be urgently addressed at present. Given that the subway system involves multiple stakeholders, how to integrate passengers' opinions has become an important direction for promoting the improvement of subway services. Previous evaluations were mostly based on maximizing self-interest, ignoring passengers' altruistic-fair social preferences. In fact, passengers' decisions are jointly influenced by their own needs, fairness and social well-being. Therefore, this paper proposes an altruistic-fair utility multi-objective optimization model based on the probability distribution function. Incorporating social preferences into the assessment framework to depict passengers' decision-making behaviors that balance personal interests with social equity can more comprehensively reflect their behavioral preferences and provide solid support for the evaluation of metro service quality.

Keywords: Metro network; Passengers' demands; Social preferences; Multi-objective optimization model

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1. Introduction

In urban rail transit service systems, traditional passenger satisfaction assessment methods are usually based on the assumption of "rational economic man", that is, when passengers evaluate service quality, they mainly rely on their own perceptual experience. The core of this method lies in regarding passengers as independent individuals, whose behaviors and judgments are completely oriented towards their own interests [1]. However, in actual situations, as a public resource and a socialized service system, the subway serves not just a single individual but the entire social group. When passengers evaluate the service, they often exhibit more complex psychological characteristics.

Specifically, when passengers evaluate subway services, they do not merely focus on their own usage experience [2]. Usually, they consciously or unconsciously take into account the feelings of others and social norms, demonstrating a subjective preference based on the perception of "altruism-fairness". For instance, during A subway ride, Passenger A observed an elderly person with physical disabilities standing inside the carriage, but no one offered their priority seat voluntarily.

Although Passenger A himself was not directly affected and his seat was not occupied, when evaluating the satisfaction of the "Priority Seat usage Regulations" service item, he might give a lower satisfaction score due to his dissatisfaction with the neglect of social rules and his empathy for the rights of vulnerable groups [3]. This behavior indicates that passengers' evaluations are not merely based on dissatisfaction with their own usage experiences, but rather stem from their concern for the situations of others.

From the perspectives of psychology and sociology, this phenomenon can be further explained as a manifestation of the inherent fairness preference and altruistic behavior of human beings. When people evaluate public services, they often place them in a larger social context for consideration. When passengers find that the use of a certain facility fails to meet the needs of some groups, they may feel dissatisfied, even if this design does not directly affect their own usage experience.

Furthermore, this phenomenon also reveals the possible social preference tendencies that passengers may exhibit during the service evaluation process [4]. Passengers not only care about whether they benefit themselves, but also consider whether others are treated fairly and whether social rules are effectively followed. During peak hours, if the flow control measures in subway stations cause some passengers to wait for a long time while others can enter the station quickly, this unfair phenomenon may trigger widespread dissatisfaction. Even if those passengers who smoothly entered the station were not directly affected, they might still criticize the quality of service due to their concern for overall fairness.

Based on the above analysis, as an important public service, the evaluation of the service quality of the subway should not be limited merely to the personal experience of passengers, but also fully consider the complex social and psychological characteristics behind it. By deeply understanding the behavioral patterns of passengers, we can better design and optimize subway services, thereby enhancing overall passenger satisfaction and social well-being. This not only helps improve the travel experience of individuals, but also promotes the development of social fairness and harmony. Therefore, this paper proposes to incorporate passengers' perception of "altruism-fairness" into the satisfaction assessment and construct a multi-objective optimization model. This model can not only depict individual passenger satisfaction but also introduce the consideration of subjective social preferences, thereby more comprehensively reflecting the actual satisfaction level of service quality.

2. The construction of a multi-objective satisfaction evaluation model

A multi-objective optimized group opinion generation model, which aims to balance group consensus and decision-making confidence while integrating fairness and altruism factors in social preferences, thereby achieving the optimal allocation of passenger weights. This model mainly consists of three parts: the construction of the absolute altruistic-fair utility function, the construction of the relative altruistic-fair utility function, and the altruistic-fair-driven multi-objective optimization model. The absolute altruistic-fair utility function directly quantifies the contribution of altruistic and fair behaviors exhibited by individuals in the decision-making process to the overall group utility. The relative altruistic-fair utility function characterizes the relative differences in altruistic and fair tendencies among passengers by normalizing individual utility. Finally, the above two utility functions are combined with the original dual-objective model of consensus and confidence to form a multi-objective optimization framework.

In the decision-making process, altruism and fairness are two key social psychological and economic factors, which directly affect the outcomes of individual and collective decisions. Altruism refers to the situation where an individual, when making decisions, not only focuses on their own interests but also considers the welfare of others [5]. Fairness, on the other hand, reflects that individuals tend to prioritize those options that can achieve a more balanced distribution of resources or benefits when choosing a solution. These two usually play a complementary role in the decision-making process, jointly promoting the improvement of social welfare and the realization of overall fairness. Based on the altruistic-fair linear utility function model, this paper integrates this model into the dual-objective decision-making framework, with the aim of obtaining more reasonable and diversified collective decision-making opinions.

$$\mathrm{R}_i=\mathrm{A}_i(\omega)+\frac{\gamma_i}{I\text{-}1}\sum_{i+j}\mathrm{A}_j(\omega)-\frac{\mu_i}{P}\sum_{\mathrm{A}_j>\mathrm{A}_i}(\mathrm{A}_j(\omega)-\mathrm{A}_i(\omega))-\frac{v_i}{Q}\sum_{\mathrm{A}_j<\mathrm{A}_i}(\mathrm{A}_i(\omega)-\mathrm{A}_j(\omega)) \tag{1}$$

In the original altruistic-fair utility function model, x_i measures the absolute utility of the independent individual passenger e_i. In this study, we characterize the absolute income x_i in the altruistic fairness preference model through the probability density function of a single passenger and the overlapping area $A_i(\omega)$ between the aggregated probability density functions. The larger the overlapping area $A_i(\omega)$ is, the more consistent the opinions of passengers e_i and the collective will be. The higher the utility that passengers obtain, the higher the social acceptance of the decision tends to be.

Given that the phenomenon that the marginal utility of individual total utility decreases as the level of altruistic-fair utility increases is more in line with the actual situation. To accurately describe this phenomenon, we cannot use a simple linear function to describe the relative utility of individual altruism and fairness. Usually, a nonlinear utility function is needed. The logarithmic function can successfully simulate the characteristics of diminishing marginal utility. Therefore, we define the normalized passenger e_i altruistic-fair relative utility level $\overline{\mathrm{R}}_i(\omega)$ using the logarithmic function as follows:

$$(\omega)=\begin{cases} 0, & 0<\mathrm{A}_i(\omega)\text{，}\ \mathrm{R}_i<0 \\ log_2\left(\frac{\mathrm{R}_i}{\mathrm{A}_i(\omega)}+1\right), & 0<\mathrm{A}_i(\omega)\text{，}\ 0\leqslant\mathrm{R}_i\leqslant\mathrm{A}_i(\omega) \\ 1, & 0<\mathrm{A}_i(\omega)\text{，}\ \mathrm{A}_i(\omega)<\mathrm{R}_i \end{cases} \tag{2}$$

The geometric meaning of $A_i(\omega)$ is the overlapping area between passenger e_i and collective opinion. Therefore, $A_i(\omega)$ must be greater than or equal to 0. Here, $A_i(\omega) = 0$ indicates that there is no overlapping area between the opinion distribution of passenger e_i and the probability density function of collective opinions. This situation reflects that the position of passenger e_i is completely opposed to the collective opinion and the collective consensus is completely contrary. Altruistic-fair utility R_i is based on some kind of relationship between passengers and collective opinions.

When constructing and optimizing a collective satisfaction model, one cannot solely rely on collective opinions to adjust or replace individual judgments. Otherwise, it may weaken passengers' independent judgment rights, leading to the one-sidedness of service quality assessment. Taking consensus alone as the measurement standard obviously cannot fully reflect the true level of service and its impact on different passenger groups. This can be expressed mathematically as follows:

$$\overline{\mathrm{R}}(\omega)=\frac{1}{I}\sum_i\overline{\mathrm{R}}_i(\omega) \tag{3}$$

$$\begin{gathered} max\mathrm{A}(\omega),\ min\mathrm{A}(\omega) \\ s.t.\begin{cases} \mathrm{A}(\omega)=\sum_i\int_X Min\{f_1(x),f_{QA}(x)\}\,dx \\ f_{QA}(x)=\dfrac{d\left(F_{QA}\left(\sum_i\omega_i\left(F_i^{-1}(p)\right)\right)\right)}{dx} \\ \sum_i\omega_i=1,\ \omega_i\in[0,1] \end{cases} \end{gathered} \tag{4}$$

3. Results and discussion

The urban rail transit department plans to optimize and upgrade the metro service system in the near future, with the aim of further enhancing passengers' travel experience on the basis of the current operation. With the continuous expansion of urban rail transit networks and the rising expectations of citizens for service quality, service quality has become an important factor influencing passenger satisfaction and the operational performance of metro systems. Take Chengdu Metro as an example. As the core rail transit system in the urban area of Chengdu, Chengdu Metro undertakes a huge passenger flow, connects major functional areas and major transportation hubs throughout the city, and provides efficient and convenient services for citizens' daily travel. Therefore, it was selected as the research object. Through the analysis of market information, six key demand indicators were identified, including: transfer convenience, network connection quality, ticket price rationality, handrail humanization, availability of charging facilities and temperature comfort. Based on these indicators, this study deeply explores the service elements that passengers are most concerned about and need to be prioritized for optimization through satisfaction assessment. It should be particularly noted that this research is currently in the trial operation stage of the method.

To more accurately quantify passengers' satisfaction with various service indicators, the questionnaire divides the satisfaction of each service indicator into 10 levels (extremely dissatisfied, very dissatisfied, dissatisfied, relatively dissatisfied, average, relatively satisfied, satisfied, very satisfied, close to perfect, extremely satisfied). At the same time, to reduce the arbitrariness and extreme tendencies of the scoring, each respondent is required to select at least three different satisfaction levels for scoring, and ensure that the total probability of each level assigned is equal to 1. A total of 18 questionnaires were collected this time. After strict data review and screening, 3 incomplete or non-compliant questionnaires were eliminated, and finally 15 valid questionnaires were obtained, with an effective rate of 83.3%. Although the sample size of this study is relatively small, given that the main objective of this research is to conduct academic exploration and verify the feasibility of the model in practical application scenarios, the collected data can initially reflect passengers' true views on the quality of subway services. Future research can further expand the sample size on this basis to enhance the representativeness of the results.

During the process of data analysis and visualization, we visually present the distribution of opinions by drawing PDF curves, which can clearly show the concentration trend and dispersion degree of passengers' evaluation results for various indicators. Specifically, we collected 15 passengers in the questionnaire survey ($e_1, e_2, e_3, \ldots, e_{15}$). Fitting processing was carried out for the evaluation data made for each index. To transform these discrete evaluation results into continuous probability density distributions, choosing an appropriate probability distribution model is a crucial step (**Figure 1**).

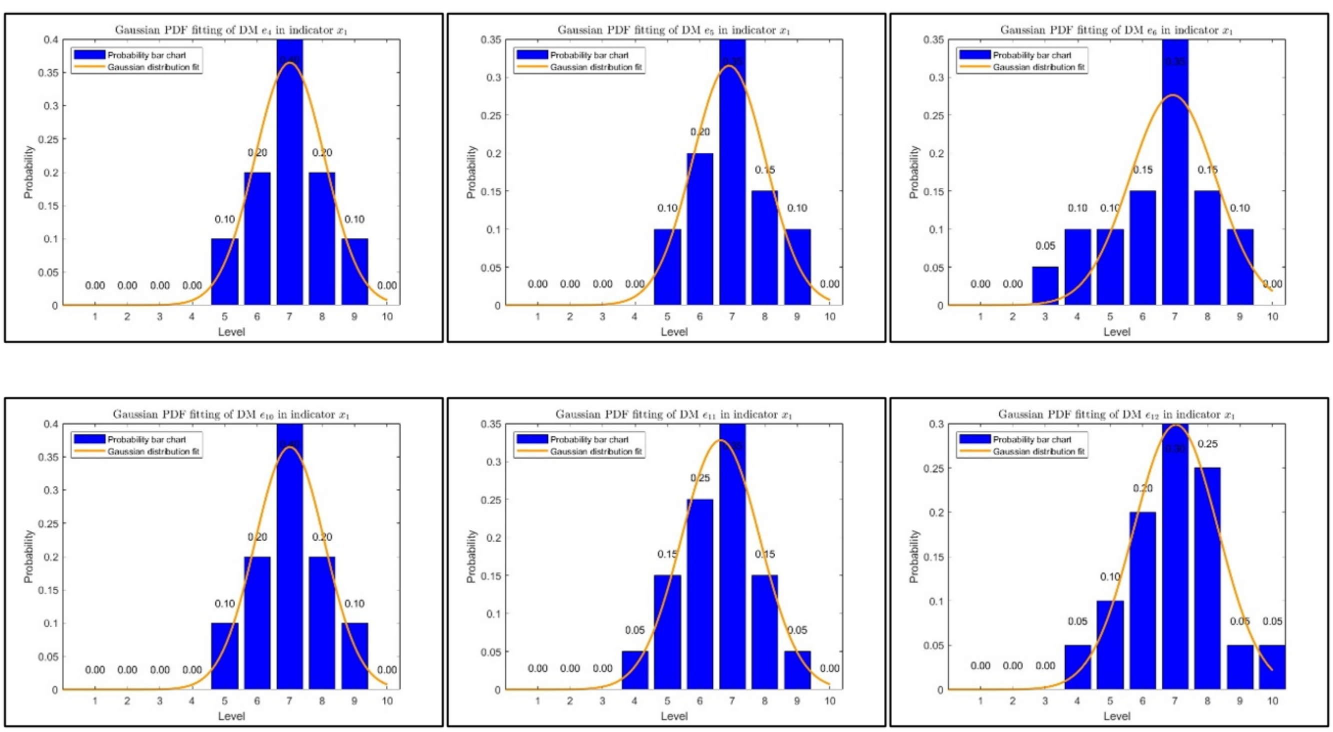

Figure 1. The probability density function fitting results of each indicator.

Using the multi-objective optimization function constructed in this study, the evaluation data of 15 passengers in index x_1 were aggregated and processed, and the optimal solution was solved again with the help of the GA algorithm of MATLAB R2023a software. The generated results are presented in the form of a probability density function (PDF) in **Figure 2**.

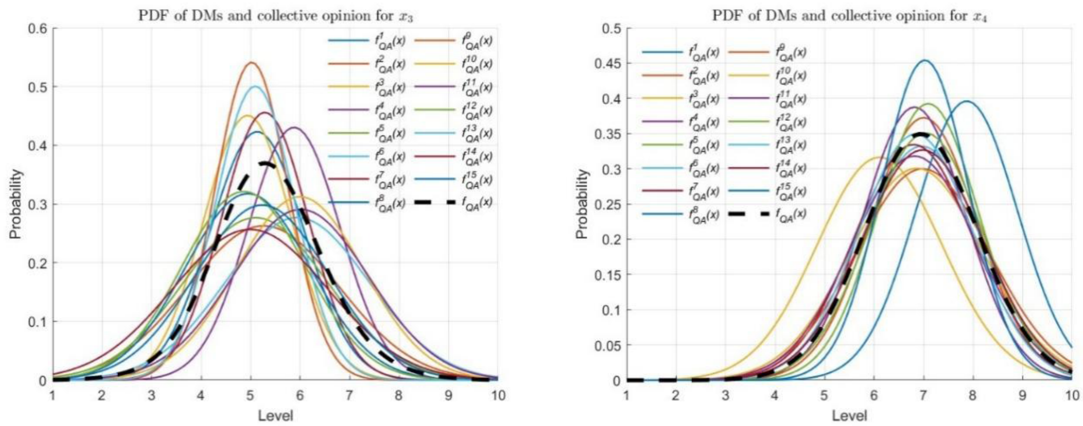

Figure 2. Collective opinion generation of indicators.

The results show that the median values of the aggregation probability density functions of various service demand indicators of Chengdu Metro are respectively: 6.91 > 6.73 > 6.55 > 6.18 > 5.27 > 4.73. It can be seen that different demand areas show different degrees of attention. Based on the multi-objective optimization model, this paper further clarifies the priority ranking of passengers' different service demands. "Fare rationality" was rated as the most satisfactory demand indicator, reflecting passengers' high sensitivity to economic burden. Reasonable fares can effectively enhance the overall travel appeal, especially in the frequent commuting subway travel scenario

4. Conclusion

This study proposes a group decision-making model based on multi-objective optimization to evaluate the priority of the demand for improving subway passenger satisfaction. This model constructs a multi-objective function integrating group consensus degree, satisfaction confidence degree and passengers' fair perception, and solves it through genetic algorithm. The experimental results show that, on the premise of fully considering the differences in evaluations among different passengers, this model can significantly improve the stability and reliability of group opinion aggregation. Meanwhile, compared with the traditional dual-objective method, this multi-objective model can better reflect the process of weighing opinions among passengers, achieving a better balance between "consensus" and "fairness" in the optimization plan of metro services. These findings provide new quantitative analysis tools for metro service management.

Disclosure statement

The author declares no conflict of interest.

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