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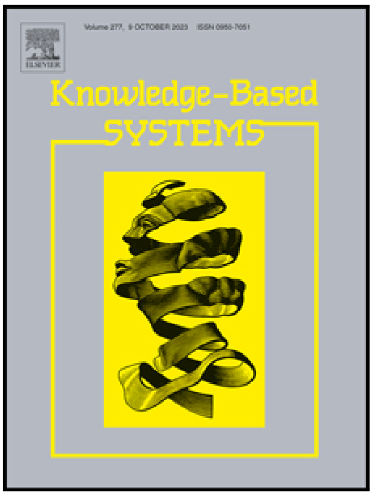

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Towards a Collective Opinion Generation Approach with Multiple Objectives for Evaluating Rail Transit Station Accessibility in Urban Areas

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Abstract: Urban rail transit can alleviate traffic congestion if sufficient ridership is achieved. The accessibility to rail transit stations largely determines public willingness to utilize urban rail transit. The current studies on the accessibility to rail transit stations tend to concentrate solely on individual rail transit lines or stations, neglecting the impact of the external macro-environment. Consequently, the outcomes of these measurements cannot accurately reflect the overall accessibility level of the region, nor do they furnish decision-makers with references for devising plans for rail transit development. This study introduces a novel approach for evaluating the accessibility to urban rail transit stations from a macro-level standpoint, utilizing expert knowledge. The study conducts an analysis of the impact of political, economic, social, and technological factors on the accessibility to rail transit stations in urban areas. Subsequently, a comprehensive evaluation indicator system is developed based on the aforementioned analysis. Then, experts are summoned to provide their subjective evaluations for every indicator, which are depicted as probability distribution functions. The collective evaluation is derived through the aggregation of individual evaluations utilizing a bi-objective optimization approach that factors in both the collective fairness utility and the confidence level. Finally, the Quantile Average method is employed to consolidate the collective assessment outcomes of individual indicators, thereby deriving the level of accessibility to rail transit stations in urban areas. We design a small-scale application experiment and attempt to evaluate the accessibility to rail transit stations in *Wuchang District, Wuhan* with the proposed approach in order to demonstrate the feasibility of the approach.

***Keywords*:** Accessibility to rail transit stations; Expert opinion aggregation; Fairness utility; Bi-objective optimization model.

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1. Introduction

In recent decades, China's major cities have rapidly expanded in size and population due to the acceleration of urbanization, which has resulted in significant strain on the urban transportation system, leading to intensified environmental pollution, serious traffic congestion and frequent traffic accidents. The urban rail transit system (including trams, subway systems, etc.) is a form of urban public transportation that is typically electrically powered. This mode of transportation boasts several benefits, including but not limited to its ability to accommodate a large number of passengers, its high speed, and its safety. Meanwhile, the urban rail transit system is commonly acknowledged as an environmentally friendly mode of transportation that can effectively alleviate traffic congestion and mitigate environmental pollution [1]. Hence, the Chinese government regards the urban rail transit system as a viable solution to address urban transportation issues and allocates substantial financial resources towards its development. By the end of 2022, 290 urban rail transit lines are operational in 53 cities throughout China, encompassing a total operational mileage of 9,584 km[1]. In several cities, the rail transit network has also gradually developed from a single subway system to a combination of light rail, subway, tram and other systems operating together. However, compared to cities that have effectively constructed and managed urban rail transit systems, such as Tokyo, the urban rail transit systems in Chinese cities exhibit lower efficacy in terms of ridership attraction. In 2019, the urban rail transit system in Tokyo transported 10.7 million passengers daily, utilizing a network of 304 kilometers of rail lines. In comparison, the urban rail system in Shanghai transported 10.63 million passengers daily, utilizing a distance of 705 kilometers of lines. Similarly, Beijing's urban rail system transported 10.35 million passengers daily, utilizing a distance of 698.6 kilometers of lines [2].

The efficacy of the urban rail transit system in addressing urban transportation issues is dependent on the ability to attract a substantial number of commuters to utilize the rail transit system. It has been demonstrated that urban rail system exhibits superiority over other modes of transportation concerning its speed, safety and comfort, thereby rendering it the optimal option for commuters [3-5]. Regrettably, commuters can only access and depart from the rail transit system via designated stations, but the government is incapable of ensuring that the rail transit stations are ubiquitously situated throughout the city. Therefore, before utilizing the rail transit system, commuters must consider the ease of reaching rail transit stations, which is also known as accessibility in the transportation field.

The notion of accessibility holds significant importance in the realm of transportation; however, a universally

[1] *Ministry of Transport of the People's Republic of China*

recognized and unambiguous definition of accessibility has yet emerged so far. Ali & Edward [6] conducted a critical analysis of the existing model for measuring public transportation accessibility and introduced the notion of "*system accessibility*", which referred to the level of convenience with which an individual can access a public transportation station through various modes of transportation. The present study proposes the notion of "accessibility to rail transit stations in urban areas", which is based on the definition of "s*ystem accessibility*". Specifically, the concept refers to the ease with which the residents reach the rail transit stations via different modes of transportation within a given urban area. High accessibility to rail transit stations means that residents can quickly reach the stations and thus will prefer to ride rail transit system

In recent times, the accessibility to rail transit stations has attracted widespread attention and scholars have implemented diverse techniques to ascertain the factors that influence the accessibility to rail transit stations and to evaluate the accessibility to rail transit stations across distinct spatial levels. Giannopoulos [7] presented a gravity-based model to assess the accessibility to rail transit stations, considering the impacts of all feasible transportation modes. Schlossberg and Brown[8] measured the walking accessibility within 0.25-0.5 miles of a given subway station. Yang et al. [9] restricted the transportation mode to walking and measured the accessibility using *Kishi's Logit Price Sensitivity Meter* (KLP) model. Li et al.[10] conducted an assessment of accessibility to 17 subway stations located on Xi'an Line 2 by measuring the cost of time, fare, and fatigue. Alfonzo et al. [11] investigated the impact of environmental factors on the selection of walking routes and the maximum walking range of pedestrians within five station areas.

Although researchers have attempted to measure the accessibility to rail transit stations using several methods, existing studies still have some shortcomings as follows:

(1) Previous studies primarily focused on investigating the impact of micro-level factors, such as transportation infrastructure, modes of travel, and individual characteristics, on the accessibility to rail transit stations [7-11]. However, in actuality, the accessibility to rail transit stations is influenced by external factors at a larger scale, including policy, economy, population, and other related factors, and previous studies neglected to explore these macro-external factors.

(2) Previous studies frequently selected some specific factors to measure the accessibility to rail transit stations in order to avoid the challenges of data acquisition and computation [7-11]. Nevertheless, the accessibility to rail transit stations is influenced by numerous factors that may not be directly related. Consequently, the accuracy of measurement outcomes can be compromised when only a limited number of factors are chosen without scientific analysis.

(3) Previous research solely focuses on evaluating the accessibility to particular rail transit stations or specific rail

transit lines [7-11], and the measurements may serve as reference material for optimizing the layout of these stations or lines, but fail to comprehensively represent the overall accessibility to rail stations within the area. Nevertheless, city managers' vision extends beyond individual rail transit stations or lines. They must devise a comprehensive plan for the overall development of the urban rail transit system within the region. Consequently, the measurements from existing studies have limited applicability due to their restricted study scope.

The primary objective of this study is to propose a novel methodology for assessing the accessibility to rail transit stations in urban areas from a macro perspective, including constructing an evaluation index system and introducing the collective opinion generation paradigm for assessing the accessibility to rail transit stations. **Figure 1** provides the procedural framework of our proposed method, and the specific work is as follows:

(1) Comprehensively analyzing the political, economic, social, and technological (PEST) factors affecting the accessibility to rail transit stations in urban areas from a macro perspective, and constructing a comprehensive evaluation index system for the accessibility to rail transit stations in urban areas , including accessibility evaluation indexes and accessibility levels.

(2) Introducing a collective opinion generation paradigm driven by a bi-objective optimization model for evaluating the accessibility to rail stations, which encompasses three processes of work:

(a) Acquiring the outcomes of experts' evaluations for each indicator and representing them through probability distribution functions (PDFs).

(b) Constructing a bi-objective optimization model considering experts' fairness concerns for aggregating individual expert opinions to generate collective opinions, and obtaining the collective evaluation results under each indicator, i.e., the aggregated PDFs.

(c) Assigning the same weights to all indicators and employing the quantile average (QA) aggregation method to derive the comprehensive evaluation result of the accessibility to rail transit stations in urban areas.

(3) Applying the proposed method to evaluate the comprehensive accessibility to rail transit stations in Wuhan to verify its practicality, and providing reference suggestions for city managers to formulate the development strategy of rail transit system based on the evaluation results.

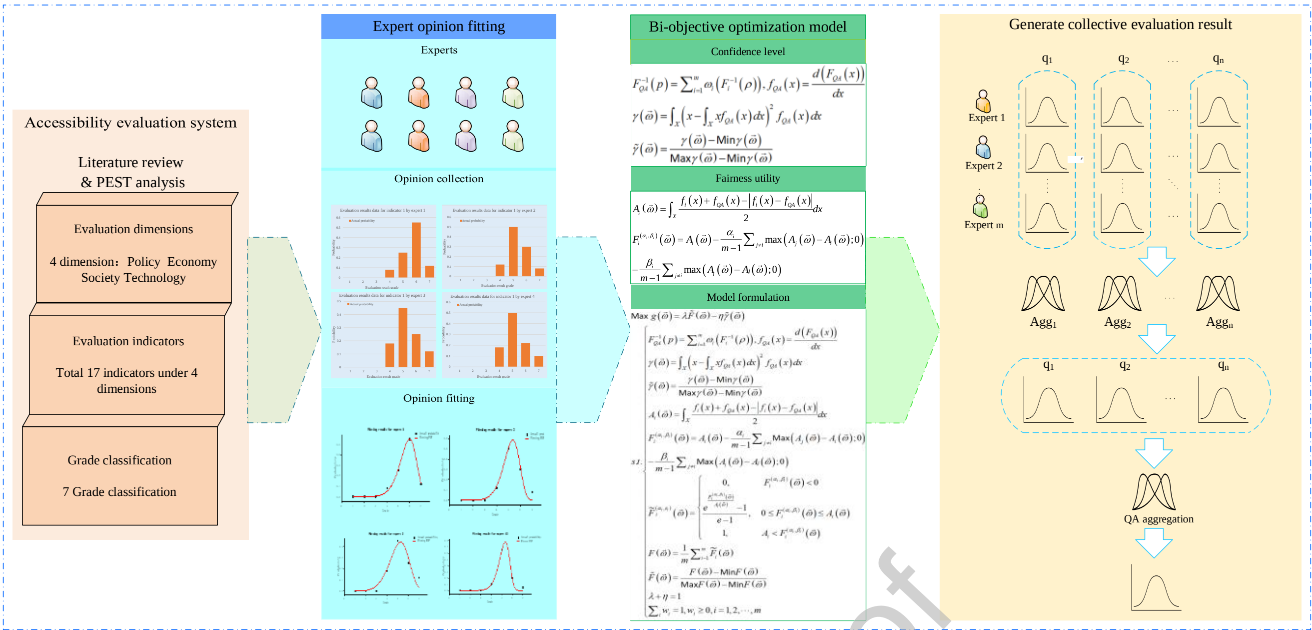

Figure 1. Procedural framework for assessing the accessibility to rail transit stations in urban areas

The subsequent sections of the paper are structured in the following manner: Section 2 reviews the definition and measurement methods of the accessibility to rail transit stations. Section 3 establishes an indicator system to evaluate the accessibility to rail transit stations in urban areas. In Section 4, a bi-objective optimization model is proposed for generating collective opinions. In Section 5, we organize a small-scale application experiment and attempt to apply the proposed approach to evaluate the accessibility to rail transit stations in *Wuchang District, Wuhan* to demonstrate the feasibility of the approach. Section 6 summarizes the research results and provides recommendations for future research.

2. Literature review

This section presents a definition of the accessibility to rail transit stations in urban areas, achieved through a review of the existing literature on the definition of accessibility. We also summarize the prevalent techniques employed for assessing the accessibility to rail transit stations. By reviewing these researches we find that prior researches have primarily concentrated on individual rail transit stations or lines, so we propose the thought of assessing the accessibility to rail transit stations in urban areas from a macro perspective. Finally, we review the literature on generating collective opinions and suggest representing individual expert evaluation results with probability distribution functions and generating the collective evaluation results using a bi-objective optimization method.

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2.1 Definition of accessibility to rail transit stations

The definition of accessibility holds significant importance in the transportation domain, as it serves as a crucial determinant of the researcher's study scope. Regrettably, accessibility has currently not been defined or measured in a consistent way [6,12].

Early definitions of reachability concerned the attractiveness of opportunities. Hansen [13] was the first academic to provide a summary of the notion of accessibility, defining it as the "potential opportunities for interaction". Subsequent researches about accessibility focused on the interaction between transportation system and land utilization. On this basis, accessibility was defined as "the ability to conveniently access any land use activity via a specific mode of transportation from the departure location" [14]; " the net benefits people derive from the interaction between the transportation system and land use" [15]. Weibull [16], El-Geneidy and Levinson [17], and Bhat et al. [18] considered the influence of individual, socioeconomic, and temporal factors in the definition of accessibility. As per Weibull's research [16], accessibility referred to an individual's freedom and capability to decide to engage in different activities. According to El-Geneidy and Levinson [17], accessibility is defined as "a measure of the performance of transportation system in serving residents". Bhat et al. [18] described accessibility as "the convenience of an Individual to conduct desired activities at a particular location, by a particular manner, and within a limited time".

Some scholars also introduced the "accessibility" concept to the public transportation field and defined accessibility from different perspectives [10,19,20]. Alan et al. [19] defined the accessibility of public transport system as "the capacity of the public transport system to efficiently move individuals from its entrance to its exit within a reasonable time". Li et al.[10] introduced the notions of attraction accessibility and radial accessibility. Attraction accessibility pertains to the level of ease in reaching a specific station from the departure location by any transportation means and radial accessibility pertains to the level of ease in reaching other stations from a particular station. Ali and Edward [6] classify public transit accessibility into three categories: The first category is the physical accessibility of the public transportation network, also known as "system accessibility" or "access to transit stops", which refers to the ease with which travelers can reach public transportation stations using different modes of travel. Research on system accessibility is important because a station is the starting point for people to use the public transportation system [21]. The second classification is referred called "system-assisted accessibility", which calculates the time/cost spent on the transportation network to measure a traveler's ability to reach the destination. The ultimate classification is referred to as "*overall accessibility*" or "*destination accessibility*", which measures the ease with which travelers can use public transportation to get from their point of origin to multiple possible destinations.

As the rail transit system is a component of the public transportation system, this study defines the accessibility to rail transit stations based on the concept of "*system accessibility*", i.e., the ease with which travelers can access the rail transit stations via various modes of transportation.

2.2 Methodology to measure the accessibility to rail transit stations

Accurately measuring accessibility has been a key research problem within the transportation domain. Geurs and van Wee [22] suggested that accessibility measures should ideally encompass four components: land use, transportation, temporal variables, and personal variables. In practical applications, researchers typically select certain components based on the purpose and object of the study [10]. Ali and Edward [6] provided a summary of commonly utilized models for measuring accessibility, which encompass distance-based, gravity-based, and utility-based models. The distance-based models measure accessibility through the enumeration of diverse opportunities within a given distance around the departure location. This approach assumes that all opportunities falling within the specified range are equally attractive [21], which is unrealistic. The gravity-based models incorporate a weighting system to assess the appeal of various opportunities and employ a decay function to devalue opportunities at locations farther from the origin [21] but ignore individuals' subjective perceptions of distinct opportunities. The utility-based models incorporate an individual's subjective assessment of the accessibility of services, and the overall usefulness of the available alternatives will impact the decision-making process of the individual [6,21].

The scholars employed diverse techniques and standards derived from these models to evaluate the availability to rail transit stations. Giannopoulos [7] proposed a gravity-based model for measuring accessibility, which considered the population residing in the vicinity of a station and the average time required for them to reach the station. Giannopoulos evaluated the impact of all existing transportation modes on accessibility and enhanced the accuracy of the measurement outcomes through the process of weight calibration for each mode. Schlossberg and Brown [8] measured the walking accessibility within 0.25-0.5 miles of a specific subway station, considering the effects of road networks, intersections, and impedance crossings. Yang et al.[9] examined the variables that impact pedestrian walking behavior through simulation experiments and questionnaires and employed *Kishi's Logit Price Sensitivity Meter* (KLP) model to determine the time and distance thresholds for individuals walking to rail transit stations. Li et al. [10] evaluated the accessibility to a specific rail transit station by measuring the time cost, fare cost and fatigue cost of different travel modes. Alfonzo et al. [11] identified the environmental factors affecting route selection and maximal walking distance for pedestrians within five station areas through questionnaires and route labeling. Bivina et al. [23] limited the study area to 800-meter around the metro station and determined the factors affecting the walking accessibility to the metro station using structural equation modeling.

2.3 Collective opinion generation

With increasing uncertainty present in the problems to be solved, the complexity of decision analysis has escalated and the resulting decisions often need to satisfy a multitude of conflicting and diverse constraints [24]. In this context, group decision making (GDM) has proven to be an efficacious mechanism for resolving significant decision-making challenges. The GDM is a specific decision process in which a group of experienced experts rank a set of options based on predefined criteria, ultimately reaching a consensus [25]. An important process of GDM is to generate a collective opinion by aggregating experts' individual opinions, and its results directly determine the success or failure of GDM.

Expert opinions are the main expression of experts' experience and knowledge and offer valuable information for forecasting, risk assessment, and decision-making [26-28], thus the adoption of expert opinions is common and often inevitable in the absence of empirical data [27-29] . The adoption of expert opinions has two main processes, namely the acquisition and aggregation of expert opinions. Expert opinion acquisition involves deliberation on the procedures for aggregating opinions and establishing guidelines for ranking, which are fairly well developed [30,31]. However, the process of aggregating expert opinions to generate collective opinions is currently in developmental stage. This process focuses on minimizing the subjectivity of individual opinions and enhance the dependability of collective opinions [25].

The expert opinion aggregation methods are categorized into mathematical and behavioral methods [28]. Behavioral aggregation methods require experts to interact to derive an acceptable collective opinion, while mathematical methods focuse on effectively integrating expert opinions utilizing rigorous mathematical models [25], with more persuasive decision outcomes. Mathematical aggregation methods are grounded in characterizing expert opinions through reliable mathematical methods, and two popular methods for expressing expert opinions in contemporary research are fuzzy theory and probability theory [32].

The fuzzy linguistic approach (FLA) utilizes linguistic variables that approximate human cognitive processes and to model linguistic information based on fuzzy theory [33], including appropriate linguistic term sets (LTS) and corresponding semantics. Rodríguez et al. [34] proposed the hesitant fuzzy LTS (HFLTS), Chen et al. [35] extended HFLTS into proportional HFLTS, Wu and Xu [36] proposed the possibility distribution of HFLTS and improved the quality of representing expert opinions by adding additional dimensions of linguistic term possibilities. Mesiar et al [37] and Jin et al [38] incorporated the reliability dimension into the linguistic evaluation and proposed a new normative formulation, basic uncertain information (BUI), which is a two-tuple containing the crisp number and its reliability degree lying in the unit interval. Herrera and Martínez [39] proposed a 2-tuple linguistic representation model, which is recognized as an effective computational method for displaying discrete linguistic items in a continuous manner. Chen et al. [33] synthesized the advantages of the BUI and the 2-tuple linguistic representation model and proposed the basic uncertain linguistic information (BULI). The probability theory approach allows experts to express confidence in their opinions through quantified probability values, which ultimately characterize expert opinions as probability distribution functions (PDFs). In general, using fuzzy theory to characterize expert opinion can only obtain a specific rank that the alternative is in and the corresponding confidence level, while using probabilistic theory can obtain the expert's confidence that the alternative is in any rank, which assists in adequately collecting expert opinions. Therefore, this study utilizes the probability theory to represent expert opinions as PDFs.

In the context of probability theory, early studies focused on axiom-based aggregation formulas [28]. Stone [40] introduced linear combination (LC), where the collective opinion is a weighted linear combination of individual expert opinions. However, this approach fails to guarantee the unimodal nature of the aggregation result, i.e., the aggregated PDF may have multiple peaks representing the existence of different collective opinions, leading to the inability to determine the optimal collective opinion. Another classical axiom-based aggregation method is logarithmic opinion pooling (LOP), which satisfies the external Bayesian principle [41] and guarantees the unimodal nature of the aggregation result. However, if an expert assigns a 0 probability to an event, the aggregation PDF ignores other experts' opinions and assigns a 0 probability to the same event [25]. Bayesian frameworks are another well-established method for collective opinion generation which requires estimating the likelihood function from past data. However, past data is typically unavailable for decision analysis [42]. Quantitative averaging (QA) aggregation is another frequently employed approach that involves computing a horizontal average of all individual distributions. QA aggregation method ensures consistency while also demonstrating favorable calibration and sharpness [43,44].

After determining the methodology for aggregating expert opinions, the impact of expert weights should also be considered. The simplest weight assignment scheme is to ignore the individual differences of experts and assign the same weight to each expert. Some scholars advocate assigning higher weights to experienced experts [45]. Some researchers suggest that expert weight assignment is not a static process and dynamic weight assignment schemes should be considered based on different weights of experts under different criteria [46].

In the group decision-making process, experts typically hold different perspectives due to differences in expertise, interests, and experience, and need to obtain the collective viewpoints that are collectively recognized through the consensus reaching process (CRP). A strict CRP requires all individuals involved in the decision-making process to reach agreement on various alternatives [47-49], which is extremely challenging in the actual decision-making process.

Consequently, the soft consensus approach has gained significant popularity, which is a strategy to establish a level of consensus satisfying a predetermined threshold [50]. Prior research typically employs distance measures to assess the consensus level, including: 1) assessing the difference between the expert's individual opinion and the collective opinion, and 2) assessing the disparity between the individual opinions of all experts [51].

CRP typically involves a feedback adjustment mechanism in which experts continuously adjust their opinions to achieve a satisfactory consensus level, coordinated by the moderator. Several studies aim to enhance CRP by reducing the cost of reaching consensus, decreasing the degree of adjustment of expert opinions, and examining the interactions between the moderator and experts. Ben-Arieh and Easton [52] proposed the minimum cost consensus model (MCCM) without considering budget constraints. Dong et al. [53] proposed the minimum adjustment consensus model (MACM), aiming to retain the initial preference information provided by experts to the greatest extent possible. Zhang et al. [54] identified a correlation between MCCM and MACM. Lu et al. [55] introduced a least-cost model that incorporates social interactions among experts using robust optimization techniques. Gong et al. [56] put out two consensus models aimed at addressing the dual link between maximizing expert gain and minimizing moderator cost. Zhang et al. [57] introduced a consensus model that incorporates soft minimum cost and maximum benefit principles, utilizing an arithmetic weighted average operator. In addition, certain scholars propose a scheme to reach consensus without feedback. Instead of iteratively adjusting the opinions, experts are required to give their opinions and determine the consensus threshold, and the moderator iteratively adjusts the expert weights to improve the consensus level [58-60]. Liu et al. [61] borrowed this idea and introduced an optimization model for aggregating experts' opinions. They defined the consensus level as the overlap region between individual PDFs and collective PDFs, and set it as the optimization objective. Based on this, Ji et al. [25] introduced confidence level and constructed a bi-objective optimization model for generating collective opinions to enhance the dependability of collective opinions. Chen et al.[62] employed the bi-objective optimization model to evaluate the maturity of building information modeling (BIM) applications in construction projects, demonstrating that the model can effectively solve the decision-making problems.

It is worth noting that although the CRP aims to increase the agreement of the members involved in decision-making with the decision outcome, it does not mean that all experts fully accept the decision outcome. The degree of acceptance of decision outcomes by experts is a post-decision evaluation issue, which is affected by various factors such as the rationality of the decision process, experts' subjective feelings about the decision process, and needs to be measured through group surveys. Due to the limitations of this study, we have not examined this aspect in depth. Moreover, reaching consensus does not imply achieving the optimal solution, as the two concepts involve different priorities and orientations. Reaching consensus involves the negotiation of members involved in decision making to increase their agreement on the decision outcome and to obtain a consensus opinion or solution. Achieving the optimal solution seeks the most effective, efficient or superior solution under given conditions and may marginalize the opinions of some members. In some cases, it may be necessary to compromise or give up some of the characteristics of the optimal solution in order to reach consensus. On the other hand, excessive pursuit of the optimal solution may lead to conflicts, as some members may not be able to accept the optimal solution because of reasonable motives (optimal cost solution can cause greater pollution). In practical GDM, the moderator and the members involved in decision making need to carefully balance these two objectives.

Contemporary research focuses on the impact of expert fairness concerns on decision-making outcomes. Adams states that human conduct is not just determined by absolute income, but is also impacted by relative income[63]. Put simply, people unconsciously compare their own earnings with those of others. In the group decision-making process, the expert's perception of the collective opinion may vary depending on differences in knowledge and experience. When the collective opinion is similar to the experts' opinions, they may feel it is fair. Conversely, if the outcome deviates from their expectations, they may consider it as unjust, so disrupting the decision-making process. Therefore, considering expert fairness concerns is significant within the context of group decision making. Fu et al. [64] assessed the fairness of criteria and alternatives in multi-criteria decision-making utilizing evidential reasoning techniques, but failed to incorporate expert fairness concerns into the decision-making process. Jing and Chao [65] investigated the effect of fairness concerns on the CRP, revealed the relationship between fairness concerns and the degree of coordination among experts, and developed an optimal response function for experts and moderators. Drawing on fairness preference theory, Du et al. [66] proposed the concepts of fairness utility function and fairness utility level, and developed a maximum fair utility consensus model. Gong et al. [67] proposed the fairness function based on the Gini coefficient and the social comparison principle, and obtained more reliable decision results through the cost-limited maximum fairness consensus model, proving that experts' fairness preferences play an important role in CRP. Zhao et al. [68] proposed a maximum utility consensus model based on 2-additive Choquet integral, aiming to find the consensus opinion with optimal group utility under limited budget. Gong et al. [50] proposed a model for reaching consensus in social network group decision making that incorporates personalized fairness perception and individual awareness of preventing manipulation.

Existing studies have examined the impact of fairness concerns on feedback-based CRP, yet few scholars consider fairness in collective opinion generation paradigms driven by optimization models. This study incorporates expert fairness concerns into the bi-objective optimization model, aiming to improve the reliability and objectivity of collective opinions.

3. Evaluation indicator system for accessibility to rail transit stations in urban areas

In this section, two commonly utilized theoretical frameworks for identifying influencing factors are indicated, namely the PEST analysis and the technology-organization-environment (TOE) framework. After comparison, PEST analysis is identified for identifying the influencing factors of the accessibility to rail transit stations in urban areas. Empirical data suggests that residents prioritize travel time over distance and cost when selecting their mode of transportation [69-71]. Therefore, our study concentrates on the political, economic, social, and technological factors that impact residents' travel time and proposes 17 evaluation indicators accordingly. The 17 accessibility evaluation indicators are allocated as below: 3 indicators $Q_1 = \{q_1, q_2, q_3\}$ of the political dimension, 3 indicators $Q_2 = \{q_4, q_5, q_6\}$ of the economic dimension, 3 indicators $Q_3 = \{q_7, q_8, q_9\}$ of the social dimension, 8 indicators $Q_4 = \{q_{10}, \cdots, q_{17}\}$ of the technological dimension. In addition, we provide a grading scheme for accessibility evaluation results and specify the specific meaning of 17 indicators at different grades.

3.1 Evaluation indicator system

The PEST analysis and the TOE framework are two effective theoretical frameworks for identifying the factors influencing the accessibility to rail transit stations. The PEST analysis focuses on the assessment of the external macro-environment in which a project or an organization is located [72] and allows the identification of political, economic, social and technological factors that may affect the operation of a project or an organization. Political factors include government intervention and political conditions under which the market operates; economic factors include market growth and economic efficiency, social factors refer to cultural characteristics and social climate, and technological factors refer to technical issues surrounding new technologies and technological trends [73]. The influencing factors identified through PEST analysis are without serious omissions and could assist organizations in analyzing the external macro-environment, which is suitable for guiding strategic decision-making [72-74]. As a theoretical framework at the organizational level, the TOE framework is commonly employed to analyze the technological, organizational, and environmental factors that influence the adoption of technological innovations by organizations [75,76]. The technological factors describes the internal and external technologies relevant to the organization, including those that exist within the organization, as well as those that are available for possible adoption by the organization. The organizational factors refer to the characteristics and assets of the organization. The environmental factors mainly describe the external conditions under which the organization conducts its business [75-77].

In reality, the survival and operation of any mode of public transportation, including urban rail transit systems, is highly dependent on a large number of external macro-factors, as they are vulnerable to government policies, drastic environmental changes, legislations that may be detrimental to their operation, changing technologies, etc.[78]. This makes the PEST analysis more suitable than the TOE framework for identifying the influencing factors on the accessibility to rail transit stations in urban areas.

In the political realm, our primary focus centers on the policy measures pertaining to rail transit that have been implemented by governments, and three distinct criteria have been identified.

1) The government's attitude toward rail transit (q_1): Since the urban transportation industry is primarily funded by government financial investment, the government's attitude towards rail transportation is directly related to the amount of government investment, which in turn affects the development of rail transportation as well as the distribution of rail transit stations.

2) The government's attitude towards shared bicycles (q_2): The shared bicycles is an alternative to public transportation in short-distance travel, effectively reducing the travel time of travelers [79,80]. The government's supportive policies towards shared bicycles are likely to attract affiliated businesses to expand their investment and enhance the supporting infrastructure, which, in turn, will meet the travel requirements of the residents and improve the accessibility to rail transport stations.

3) Traffic regulations (q_3): Effective traffic regulations can promote the secure operation of vehicles, decrease the likelihood of traffic accidents and associated delays, minimize time wastage, and enhance accessibility to urban rail transit stations. The efficacy of traffic regulations warrants evaluation by experts with expertise and practical knowledge.

In the economic sphere, our focus is on the degree of economic development of the city and the consumption capacity of its inhabitants. To this end, three distinct criteria have been identified.

1) Gross regional product (q_4): The gross regional intuitively reflects the economic status of a city and affects the government's available funds, which in turn affects the government's investment in rail transit systems and transportation infrastructure. Dense rail transit network and perfect transportation infrastructure shorten the travel

distance of residents, providing more optional travel modes for residents, thus improving the accessibility of rail transit stations.

2) Per capita disposable income (q_5): Typically, inhabitants could reach rail transit stations through five different modes of transportation: walking, cabs, shared bikes, surface transit, and private cars [81]. When making a decision about the mode of travel, individuals will take into account their consumption capacity, which is closely linked to their disposable income. A high per capita disposable income within the region means that the overall consumption capacity of the inhabitants is high, and that they are more likely to choose expensive but time-saving travel modes, as well as high accessibility to rail transit stations.

3) Urban economic development potential (q_6): The competitiveness of a city or region is significantly influenced by its development potential. Metropolitan areas exhibiting significant potential are likely to draw a substantial influx of residents and investment, thereby facilitating the progression of urban development. The assessment of a city's potential for economic development is contingent upon six key factors: the historical trajectory of its economic growth, prevailing economic policies, the level of industrial structure, degree of urbanization, human capital development, and innovation in science and technology. The measurement results of the city's development potential will be provided by a panel of experts through examining the performance of the above six factors.

The social dimension pertains to urban demographic characteristics and residents' consumption concept with three sub-indicators.

1) Resident population size (q_7): The size of the urban population plays a crucial role in the availability of human resources and contributes significantly to the economic growth of urban areas through the agglomeration economic effects [82,83]. Economic growth stimulates the development of the transportation industry, which consequently increases the accessibility to rail transit stations. However, the correlation between population size and urban economic growth is non-linear, and overpopulation instead inhibits economic development while leading to problems such as traffic congestion and insufficient public transportation, which in turn reduces rail station accessibility. Given that a majority of rail transit patrons are individuals who reside or work within the urban area for an extended period of time, it is reasonable to utilize the resident population size as an indicator for evaluating the accessibility to rail transit stations.

2) Population distribution (q_8): Individuals residing in proximity to stations have the advantage of accessing them expeditiously through walking or utilizing shared bicycles, thereby circumventing delays caused by traffic congestion

or unforeseen incidents, ultimately resulting in reduced travel time. As a result, a concentrated distribution of residents near rail transit stations will improve overall regional accessibility to rail transit stations. Conversely, a scattered distribution of residents will have an adverse effect on the accessibility to rail transit stations. Scholars commonly establish a circular locality with a radius of 800 meters surrounding a rail transit station as a neighborhood zone as 800 meters is a reasonable and customary walking distance for the majority of pedestrians [84,85].

3) Consumption concept (q_9): As previously stated, inhabitants have five distinct modes of transportation to access rail transit stations. Residents' choice of travel mode is influenced not only by their disposable income but also by their consumption perception. The consumption perception refers to the comprehensive cognitive assessment and value judgment of residents' consumption objects, consumption behavior patterns, and consumption processes when engaging in consumption activities. The present study regards taxis and private vehicles as two transportation options that are both cost-intensive yet effective, and thus categorizes them as a single entity. This study mainly examines the extent of residents' preference for expensive but time-saving travel modes such as cabs and private cars.

In the technical dimension, the focus is primarily on the present state of urban traffic development and transport infrastructure together eight specific criteria have been identified for this purpose.

1) Public bus route planning (q_{10}): Public transportation is increasingly being considered as a feasible alternative to private vehicles due to its economic viability, cost-effectiveness, energy efficiency, resource conservation, and environmental sustainability [86,87]. The design of bus routes and the allocation of bus stations have a significant impact on the public's decision to utilize public transportation and the duration of travel between drop-off stations and rail transit stations, which consequently affects the overall travel time and accessibility to rail transit stations.

2) Total number of shared bicycles (q_{11}): The total number of shared bicycles limits the number of users, forcing some residents to switch to other travel modes, which results in an increase in their travel time, thus affecting the accessibility to rail transit stations within the region.

3) Distribution of bike-sharing parking spots (q_{12}): Shared bicycles need to be rented and returned at pre-set parking spots. The duration of travel from the point of departure to the designated parking locations, as well as from the parking locations to the rail transit stations, are significant factors that impact the overall travel time. Consequently, the allocation of parking spaces has an impact on the duration of travel and, by extension, the accessibility to rail transit stations.

4) Walking Environment (q_{13}): Walking is an integral part of any commuting process. The walking environment directly affects residents' walking routes and travel time, which in turn affects the accessibility to rail transit stations. This study examines the main influencing factors of the walking environment, including the distribution of sidewalks, detour routes, the frequency of street crossings, crossing facilities, and road congestion [9], and the walking environment is evaluated by experts based on the findings.

5) Private car quantity (q_{14}): The proliferation of private vehicles in urban areas has been steadily increasing with the ongoing progress of the economy, which has contributed to a certain degree of convenience for local inhabitants in terms of transportation. However, the capacity of a city to accommodate vehicles is finite, and an overabundance of private vehicles can result in traffic congestion, prolonged travel times, and a detrimental impact on access to rail transit stations.

6) Road network (q_{15}): The configuration of the road network around the rail train stations has a direct influence on the duration of travel. A dense road network with a reasonable layout can effectively decrease the duration of travel for inhabitants. Conversely, inadequate road design or insufficient road may lead to traffic congestion, disorientation, and an escalation in travel time.

7) Traffic congestion (q_{16}): The occurrence of traffic congestion typically results in wasted time, extended travel duration, and reduced accessibility to rail transit stations. The frequency of traffic congestion in the city can be evaluated by experts based on the city's past records of traffic congestion.

8) Station coverage (q_{17}): This indicator primarily takes into account the quantity and distribution of rail transit stations. In this study, a circular region with a radius of 800 meters is designated as the sphere of influence for each station and calculates the proportion of these areas in relation to the overall urban area. A broad station coverage implies that the majority of the population can conveniently access rail transit stations.

It is pertinent to underscore that the characteristics of indicator system and the challenges of collecting data lead this study to evaluate the accessibility to rail transit stations in urban areas utilizing the collective opinion generation paradigm. The specific reasons are as follows:

(1) The delayed commencement of the rail transit system's development in China, coupled with the oversight by regulatory authorities in establishing an effective data acquisition and preservation mechanism during the initial stages of rail transit development, has led to a constrained quantity and suboptimal quality of available statistical data.

Consequently, the direct utilization of these data for assessing the accessibility of rail transit stations proves insufficient to guarantee the accuracy of measurement results.

(2) Owing to urban security considerations, certain macro data integral to the prospective city development, such as urban development plans and government investment programs, are held by government and selectively disclosed. Regrettably, we have not obtained the requisite permissions to access these pertinent datasets. Moreover, some data related to business plans of enterprises are also difficult to access directly.

(3) Within the constructed indicator system, several indicators are susceptible to the influence of multifaceted factors. For example, the assessment of the walking environment necessitates consideration of factors such as the distribution of sidewalks, detour routes, crossing frequency, crossing facilities, road congestion, among others. In this case, the survey data fail to directly embody the evaluation outcomes of the pertinent indicators, rather, they should serve as the foundation for expert judgment.

In summary, challenges in evaluating the accessibility to rail transit stations arise from the difficulties associated with obtaining sufficiently numerous and reliable empirical data, as well as the fact that certain indicators defy straightforward representation through objective data. Fortunately, extant research indicates that, in the absence of empirical data, resorting to the subjective judgment of experts stands as a prevalent and effective decision-making method [27-29]. Given the aforementioned challenges and pertinent research findings, we posit that employing expert knowledge for assessing rail transit station accessibility through a collective opinion generation paradigm represents a comparatively more precise and impartial approach, thereby holding the potential to supplant reliance on objective data.

3.2 Evaluation results grading scale

In addition to indicators, the classification of accessibility grades is imperative for quantifying the level of accessibility to railway transit stations. According to Miller [88], the utilization of a 7-point scale may enhance the likelihood of respondents providing more precise responses. Consequently, a 7-point scale has been established within this study to ensure the precision of individual viewpoints. **Table 1** outlines the various grades of accessibility to rail transit stations in urban areas. Meanwhile, **Table 2** provides a detailed description of 17 indicators under 7 distinct grades.

Table 1. Evaluation result grade and description

Grade		Description
1	Disastrous	The urban governance authorities are scaling back its rail transit network. Almost no rail transit stations exist within the areas to be examined, and the cost of reaching a rail station is so high that residents abandon using the rail system.
2	Low	The city's administration opposites to further expansion of rail transit within the city. Rail transit stations are scarce within the region, thus only residents around the stations can reach them relatively easily, but residents in other areas still have difficulty reaching rail transit stations.
3	Slightly low	The urban governance authorities do not recommend developing rail transit. Slightly fewer rail stations within the region, with certain inhabitants enjoying convenient access to such stations.
4	Ordinary	The urban governance authorities do not interfere with the development of rail transit. A certain number of rail stations exist within the region and most residents are able to reach rail transit stations relatively easily. However, a subset of residents residing in remote locales encounter challenges in accessing rail transit stations.
5	Slightly high	The urban governance authorities recommend prioritizing rail transit development. The central area is equipped with a significant number of rail transit stations which facilitates swift access for the majority of residents to the rail transit stations. The residents in isolated areas can pay an acceptable cost to reach the rail transit stations.
6	High	The urban governance authorities are improving the rail network and facilities. A large number of rail stations cover most of the city, allowing most residents to reach rail stations at low cost, and residents in isolated areas to reach rail stations quickly.
7	Excellent	The urban governance authorities have made detailed plans to expand the rail transit network while improving the existing rail transit facilities. The rail transit stations are fully covered throughout the area, and residents from any location can reach the stations with low cost, thus making rail transit the best way for residents to travel.

Table 2. Description of the evaluation results of 17 indicators

Indicator /Grade	1	2	3	4	5	6	7
q_1	Large-scale demolition of rail transit facilities	Scale back rail transit system	Not promote using rail transit	No intervention policies	Advocate residents using rail transit	Lead residents to use rail transit	Positively construct new rail lines/facilities
q_2	Prohibit residents from using shared bicycles	Restrict residents from using shared bicycles	Oppose residents using shared bicycles	No intervention policies	Advocate residents using shared bicycles	Lead residents to use shared bicycles	Complete discount policy for using shared bicycles
q_3	Serious errors exist	Numerous vulnerabilities exist	Few obvious vulnerabilities exist	No obvious vulnerabilities	Some detail omissions	Few details omissions	Clearly organized and without any omissions
q_4	Extremely poverty-stricken area	Economically backward areas	Slightly poorer economic level	Average level	Slightly developed area	Developed area	Extremely affluent area
q_5	Extremely low per capita disposable income and insecure livelihood	Low per capita disposable income and just enough for survival	Slightly lower per capita disposable income and poor consumption power	Ordinary per capita disposable income and consumption power	Slightly high per capita disposable income and certain spending power	High per capita disposable income and partial funds for consumption	Extremely high per capita disposable income and significant funds available for consumption
q_6	Extremely likely to suffer economic regression	Possible to suffer economic regression	Slight probability to suffer economic regression	The economic level remains the same	Slight probability to occur economic growth	Possible to occur economic growth	Extremely likely to occur economic growth
q_7	Extremely sparse or severely exceeds the urban load limit	Sparse or exceeds the urban load limit	The population is relatively small or slightly exceeds the urban load limit	Reach the urban load limit	Below the urban load limit but far from the optimal size	Close to optimal population size	Optimal population size
q_8	All residents are located away from rail transit stations	Most residents are located away from rail transit stations	Partial residents are located away from rail transit stations	All residents are located within acceptable distance boundaries	Some residents are located around rail train stations	Most residents are located around rail train stations	All residents are located around rail train stations
q_9	Extremely conservative	Significantly conservative	Slightly conservative	Normal	Slightly enlightened	Significantly enlightened	Choose the appropriate travel mode according to the situation

q_{10}	No access to any rail station via public bus	Few rail transit stations can be reached by public bus	Partial rail transit stations can be reached via public bus	Most rail transit stations can be reached by public bus	Access to most rail transit stations via public bus in an acceptable time frame	Access to any rail transit station via public bus in an acceptable time frame	Access to any rail transit station via public bus in a short time frame
q_{11}	No shared bicycles	Extremely rare	Below is the demanded quantity	Meets usage needs	Above demand quantity	Have some spare vehicles	Spare vehicles are available for unexpected situations
q_{12}	No parking lots for shared bicycles	Few parking lots for shared bicycles	Fewer in number and far from rail transit stations	Basically, meets usage needs	High quantity and close to some rail transit stations	Parking lots for shared bicycles are available near most transit rail stations	Parking lots for shared bicycles are available near any rail transit station
q_{13}	No walking facilities	Few walking facilities and dangerous to walk	Inadequate walking facilities and walking danger exists in some areas	Basically meet walking needs and ensure walking safety	Adequate walking facilities but walking obstacles exist in some areas	Relatively complete walking facilities with few walking obstacles	Perfect walking facilities without any walking obstacles
q_{14}	No private car	Few or severely exceed the urban load limit	Relatively few or slightly exceeds the urban load limit	Reach the urban load limit	Below the urban load limit but far from the optimal quantity	Close to the optimal quantity	Optimal quantity
q_{15}	No road network near most rail transit stations	A low density of road network near most rail stations	A low density of road network near partial rail stations	A low density of road network near specific rail transit stations	Road network near partially rail transit stations	A dense road network near most rail transit stations	A dense road network near all rail transit stations
q_{16}	Traffic congestion persists in any area and at any times	Traffic congestion persists in most areas and at most times	Traffic congestion occurs frequently in most areas and at most times	Traffic congestion persists on special roads and during peak periods	Congestion occurs frequently on special roads and during peak periods	Traffic congestion exists in few areas and at few times	No traffic congestion ever
q_{17}	No rail transit stations	Covers only tiny areas	Covers some central areas	Covers central areas	Covers central areas and some peripheral areas	Covers most urban areas	Complete covers urban areas

4. Collective opinion generation paradigm driven by a bi-objective optimization model

Within this section, the expert opinions are depicted as PDFs and subsequently aggregated to produce collective opinions through the utilization of a bi-objective optimization model. By setting two optimization objectives, collective fair utility, and confidence, the objectivity and reliability of collective opinion improved.

4.1 Expert opinion aggregation based on probability distribution

Human opinions or judgments are inherently imprecise [89], and uncertain information is also present in the expert opinions. The present article employs probability theory as a means of articulating expert opinion, a widely accepted approach for conveying uncertain information [32], and also furnishes a theoretical foundation for the process of aggregating opinions [25]. In the probabilistic approach, PDFs are applied to express experts' individual opinions, and the expert opinion aggregation process is thus transformed into an aggregation of PDFs that can be computed mathematically.

For any one evaluation indicator, assuming that m experts are involved in the evaluation process, x represents the evaluation result, the PDF and cumulative distribution function (CDF) of expert i are denoted as $f_i(x)$ and $F_i(x)$, $i=1,2,\cdots m$. The goal of expert opinion aggregation is to generate a collective opinion from individual opinions, i.e., to generate an aggregated PDF from individual PDFs, so the aggregated PDF $f(x)$ is a function of the individual PDFs $f_i(x)$, $i=1,2,\cdots m$:

$$f(x)=\phi\left(f_1(x), f_2(x),\cdots f_m(x)\right) \tag{1}$$

where ϕ is a mapping $R^m \to R^+$, and $f(x)$ satisfies the consistency condition $\int_{-\infty}^{+\infty} f(x)dx=1$.

To ensure that the collective opinion is acceptable to the majority of experts, the aggregated PDF should be as close as possible to each individual PDF. In other words, the crucial task of expert opinion aggregation is to find the operator ϕ that minimizes $\sum_{i=1}^{m}\|f-f_i\|$, where $\|\bullet\|$ denotes the generalized distance between f and f_i.

In Section 2.3, we referred that QA aggregation is a reliable aggregation method, therefore, this paper employs QA aggregation to obtain the aggregated PDF $f_{QA}(x)$ and aggregated CDF $F_{QA}(x)$ through the following computational procedure:

$$F_{QA}(x)=\left(\sum_{i=1}^{n}\lambda_i F_i^{-1}(\rho)\right)^{-1},\ f_{QA}(x)=\frac{d\left(F_{QA}(x)\right)}{dx} \tag{2}$$

where $\rho = F_i(x)$, $\rho \in [0,1]$, and $F_i^{-1}(\rho)$ is the inverse function of $F_i(x)$, ω_i refers the weight assigned to expert i, satisfying $\omega_i \in [0,1]$ and $\sum_{i=1}^{m} \omega_i = 1$. The weights of all experts form an expert weight vector $\boldsymbol{\omega} = (\omega_1, \omega_2, \cdots \omega_m)^T$.

According to Equation (2), the properties of the aggregated PDF $f_{QA}(x)$ are contingent upon expert weight vector $\boldsymbol{\omega} = (\omega_1, \omega_2, \cdots \omega_m)^T$, when the experts' individual PDFs have been established. The simplest weight assignment scheme is to assign equal weights to each expert, but this approach disregards variations among the experts. Some scholars advocate assigning weights based on the experience of experts, i.e., more experienced experts will be assigned higher weights [45]. Liu et al.[61] transformed the expert opinion aggregation problem into an optimization problem, and they set the expert weight as the only variable to generate collective opinions by setting appropriate optimization objectives. Ji et al. [25] constructed a bi-objective optimization model for generating collective opinions with the objectives of consensus level and confidence level. In this study, based on [25] , a bi-objective optimization model containing two optimization objectives of collective fair utility and confidence level is built for generating collective opinions.

4.2 Individual fairness utility and collective fairness utility

Existing research has considered the impact of experts' fairness concerns about the decision-making process on decision outcomes. The existing theories regarding fairness concerns can be categorized into three types: (1) the income distribution model (F-S model) [90], (2) reciprocal fairness preferences [91], and (3) hybrid models that integrate income distribution and reciprocity psychology. The F-S model states that individuals are not solely concerned with their own income, but also with the income of others. Reciprocal fairness preferences suggest that individuals tend to consider the underlying motivations behind others' behavior. However, reciprocal fairness preferences can only handle two-person static games, but cannot handle multi-person dynamic games. Moreover, the hybrid model that combines income distribution and reciprocity psychology exhibits a multitude of parameters, intricate structure, and limited capacity for behavioral prediction, causing it to be inapplicable in a majority of cases [66]. The F-S model emphasizes only the fairness of income distribution, exhibits parsimony in its parameterization, and demonstrates robust predictive efficacy with respect to human behavior. Consequently, the present investigation employs the F-S model as a means of assessing the degree of fairness in the aggregation procedure.

According to the F-S model, individuals assess fairness by making comparisons between their respective incomes.

The emotion of jealousy may manifest when an individual perceives a discrepancy in their earnings compared to others, whereas the emotion of pride may arise when an individual perceives higher earnings compared to others. The mathematical expression of the F-S model is as follows:

$$u_i = x_i - \frac{\alpha_i}{n-1}\sum_{j\neq i}\mathrm{Max}\left(x_j - x_i;0\right) - \frac{\beta_i}{n-1}\sum_{j\neq i}\mathrm{Max}\left(x_i - x_j;0\right) \tag{3}$$

where $0 \le \alpha_i \le 1$, $-1 < \beta_i < 1$. u_i is the fairness utility of participant i, x_i is the absolute gain of participant i. α_i is the jealousy preference coefficient, β_i is the pride preference coefficient ($-1 < \beta_i < 0$) or sympathy preference coefficient ($0 \le \beta_i < 1$) of participant i. In general, $\alpha_i \ge \beta_i$, which means that the participant is more averse to an "unfavorable unfair allocation" than to a "favorable unfair allocation". Thus, a participant's fairness utility is composed of three components: absolute income utility, negative utility of jealousy preference, negative utility of sympathy preference or positive utility of pride preference.

In the aggregation process, the "absolute gain" of expert i is the area of the overlap region between the individual PDF $f_i(x)$ and the aggregated PDF $f_{QA}(x)$, denoted as A_i, which represents the agreement level between the individual opinion of expert i and the collective opinion. Obviously, $A_i \ge 0$ and the larger the A_i values, the closer the expert's opinion is to the collective opinion. A_i is calculated as:

$$A_i = \int_X \mathrm{Min}\left\{f_i(x), f_{QA}(x)\right\}dx = \int_X \frac{f_i(x) + f_{QA}(x) - \left|f_i(x) - f_{QA}(x)\right|}{2}dx \tag{4}$$

In the case that all individual opinions $f_i(x)$ are determined, according to Equation (4), the value of A_i depends only on $f_{QA}(x)$, and according to Equation (2), the nature of $f_{QA}(x)$ depends only on the expert weight vector $\boldsymbol{\omega} = (\omega_1, \omega_2, \cdots \omega_m)^T$, and therefore the value of A_i depends only on the expert weight vector $\boldsymbol{\omega} = (\omega_1, \omega_2, \cdots \omega_m)^T$. Equation (3) can be further converted into:

$$A_i(\boldsymbol{\omega}) = \int_X \mathrm{Min}\left\{f_i(x), f_{QA}(x)\right\}dx = \int_X \frac{f_i(x) + f_{QA}(x) - \left|f_i(x) - f_{QA}(x)\right|}{2}dx \tag{5}$$

Replacing the absolute income utility in Equation (3) with $A_i(\boldsymbol{\omega})$, the individual fairness utility of the expert i, denoted as $F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})$, can be expressed as follows:

$$F_i^{(\alpha_i,\beta_i)}(\omega) = A_i(\omega) - \frac{\alpha_i}{m-1}\sum_{j\neq i}\mathrm{Max}\left(A_j(\omega) - A_i(\omega);0\right) - \frac{\beta_i}{m-1}\sum_{j\neq i}\mathrm{Max}\left(A_i(\omega) - A_j(\omega);0\right) \quad (6)$$

Without specification, this study takes $\alpha_i = 0.2$ and $\beta_i = -0.2$ for calculation purposes. The proposed individual fairness utility follows the following theorem:

Theorem 1. Let $A_i(\omega)$ denote the area of the overlap region between the PDF of the ith expert and the aggregated PDF, if $A_i(\omega) < F_i^{(\alpha_i,\beta_i)}(\omega)$, then $-1 < \beta_i \leq 0$.

The proof of **Theorem 1** is not presented in this context owing to its straightforwardness. **Theorem 1** states that if the expert's individual fairness utility surpasses the absolute income utility, it is imperative that the expert possesses a preference for pride. However, if the expert exhibits a preference for pride, his or her fairness utility may not necessarily exceed the absolute income utility. In other words, $A_i(\omega) < F_i^{(\alpha_i,\beta_i)}(\omega)$ is a sufficient and unnecessary condition for $-1 < \beta_i \leq 0$.

The individual fairness utility $F_i^{(\alpha_i,\beta_i)}(\omega)$ represents the absolute fairness utility, which is not bounded and thus cannot be applied directly for fairness measurement and needs to be modified. In the case that $0 < A_i(\omega) < F_i^{(\alpha_i,\beta_i)}(\omega)$, the pursuit of excessive fairness does not increase an individual's marginal fairness utility, thus the individual fairness utility reaches its maximum level. Moreover, experts exhibit a heightened sensitivity of alterations in their perceptions of fairness, and their satisfaction with fairness experiences a steep decline in a non-linear fashion as the gap between their own viewpoints and those of other experts widens. Consequently, linear utility functions are inadequate for modeling shifts in the perspectives of experts. The exponential utility function is a frequently utilized function that exhibits a high degree of flexibility in representing a diverse array of preferences and its parsimony and invertibility further enhance the feasibility of conducting analyses [92].

Definition 1. Let $A_i(\omega)$ denote the absolute benefit of the ith expert and $F_i^{(\alpha_i,\beta_i)}(\omega)$ denote the individual fairness utility of expert i. Then the exponential individual fairness utility function of expert i can be defined as follows.

$$F_i^{(\alpha_i,\beta_i)}(\omega) = \begin{cases} 0, & F_i^{(\alpha_i,\beta_i)}(\omega) < 0, \\ \dfrac{e^{\frac{F_i^{(\alpha_i,\beta_i)}(\omega)}{A_i(\omega)}} - 1}{e-1}, & 0 \leq F_i^{(\alpha_i,\beta_i)}(\omega) \leq A_i(\omega), \\ 1, & A_i(\omega) < F_i^{(\alpha_i,\beta_i)}(\omega). \end{cases} \quad (7)$$

The individual fairness utility function $\frac{e^{\frac{F_i^{(\alpha_i,\beta_i)}(\omega)}{A_i(\omega)}}-1}{e-1}$ is obtained by extending one of the underlying forms of the exponential utility function $u_i(x)=K_i-B_i e^{x_i RT_i}$ [92], where K_i and B_i are essentially proportionality constants, RT_i is the risk tolerance of the experts, who are usually asked to determine the values of the above parameters.

Several critical properties of $F_i^{(\alpha_i,\beta_i)}(\omega)$ are stated as follows:

Theorem 2. Let $A_i(\omega)$ be defined as above, for $0\le F_i^{(\alpha_i,\beta_i)}(\omega)\le A_i(\omega)$, $0\le\alpha_i\le 1$, $-1<\beta_i<1$, if $A_1(\omega)\le A_2(\omega)\le\cdots\le A_i(\omega)\le\cdots\le A_m(\omega)$, then we have

(1) When $-1<\beta_i\le 0$, $F_i^{(\alpha_i,\beta_i)}(\omega)$ is an increasing function on $A_i(\omega)$.

(2) When $0<\beta_i<1$, and $\frac{\alpha_i}{\beta_i}>\frac{\sum_{j=1}^{i-1}A_j(\omega)}{\sum_{j=i+1}^{m}A_j(\omega)}$, $F_i^{(\alpha_i,\beta_i)}(\omega)$ is an increasing function with respect to $A_i(\omega)$.

(3) When $0<\beta_i<1$, and $\frac{\alpha_i}{\beta_i}<\frac{\sum_{j=1}^{i-1}A_j(\omega)}{\sum_{j=i+1}^{m}A_j(\omega)}$, $F_i^{(\alpha_i,\beta_i)}(\omega)$ is a decreasing function with respect to $A_i(\omega)$.

Proof. Without loss of generality, assuming that $A_i(\omega)\ge 0$ and $A_1(\omega)\le A_2(\omega)\le\cdots\le A_i(\omega)\le\cdots\le A_m(\omega)$, $i=1,2,\cdots m$, such that we have $F_i^{(\alpha_i,\beta_i)}(\omega)=\frac{e^{\frac{F_i^{(\alpha_i,\beta_i)}(\omega)}{A_i(\omega)}}-1}{e-1}=\frac{e^{1-\frac{\alpha_i}{m-1}\sum_{j\neq i}\text{Max}\left(\frac{A_j(\omega)}{A_i(\omega)}-1,0\right)-\frac{\beta_i}{m-1}\sum_{j\neq i}\text{Max}\left(1-\frac{A_j(\omega)}{A_i(\omega)},0\right)}-1}{e-1}$,

then we need to calculate the derivative function of $F_i^{(\alpha_i,\beta_i)}(\omega)$:

$$\frac{\partial F_i^{(\alpha_i,\beta_i)}(\omega)}{\partial A_i(\omega)}=\frac{e^{1-\frac{\alpha_i}{m-1}\sum_{j\neq i}\text{Max}\left(\frac{A_j(\omega)}{A_i(\omega)}-1,0\right)-\frac{\beta_i}{m-1}\sum_{j\neq i}\text{Max}\left(1-\frac{A_j(\omega)}{A_i(\omega)},0\right)}}{e-1}*\frac{-\frac{\alpha_i}{m-1}\sum_{j\neq i}\text{Max}\begin{Bmatrix}-\frac{A_j(\omega)}{(A_i(\omega))^2}, & A_i(\omega)<A_j(\omega)\\ 0, & A_i(\omega)>A_j(\omega)\end{Bmatrix}-\frac{\beta_i}{m-1}\sum_{j\neq i}\text{Max}\begin{Bmatrix}0, & A_i(\omega)<A_j(\omega)\\ \frac{A_j(\omega)}{(A_i(\omega))^2}, & A_i(\omega)>A_j(\omega)\end{Bmatrix}}{e-1},$$

such that

$$\frac{\partial F_i^{(\alpha_i,\beta_i)}(\omega)}{\partial A_i(\omega)}=\frac{e^{1-\frac{\alpha_i}{m-1}\sum_{j\neq i}\text{Max}\left(\frac{A_j(\omega)}{A_i(\omega)}-1,0\right)-\frac{\beta_i}{m-1}\sum_{j\neq i}\text{Max}\left(1-\frac{A_j(\omega)}{A_i(\omega)},0\right)}}{e-1}*\frac{\frac{\alpha_i}{(A_i(\omega))^2(m-1)}\sum_{j=i+1}^{m}A_j(\omega)-\frac{\beta_i}{(A_i(\omega))^2(m-1)}\sum_{j=1}^{i-1}A_j(\omega)}{e-1}.$$

Since $e^{1-\frac{\alpha_i}{m-1}\sum_{j\neq i}\text{Max}\left(\frac{A_j(\omega)}{A_i(\omega)}-1,0\right)-\frac{\beta_i}{m-1}\sum_{j\neq i}\text{Max}\left(1-\frac{A_j(\omega)}{A_i(\omega)},0\right)}>0$ always holds, we only need to determine whether $\frac{\alpha_i}{(A_i(\omega))^2(m-1)}\sum_{j=i+1}^{m}A_j(\omega)-\frac{\beta_i}{(A_i(\omega))^2(m-1)}\sum_{j=1}^{i-1}A_j(\omega)$ is negative or positive. Since $A_j(\omega)\ge 0$,

$0 \le \alpha_i \le 1$, if $-1 < \beta_i \le 0$, we can easily obtain $\frac{\partial F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})}{\partial A_i(\boldsymbol{\omega})} \ge 0$, that is, $F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})$ is an increasing function with respect to $A_i(\boldsymbol{\omega})$; if $0 < \beta_i \le 1$ and $\frac{\alpha_i}{\beta_i} > \frac{\sum_{j=1}^{i-1} A_j(\boldsymbol{\omega})}{\sum_{j=i+1}^{m} A_j(\boldsymbol{\omega})}$, then $\frac{\partial F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})}{\partial A_i(\boldsymbol{\omega})} > 0$, $F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})$ is an increasing function with respect to $A_i(\boldsymbol{\omega})$; if $0 < \beta_i \le 1$ and $\frac{\alpha_i}{\beta_i} < \frac{\sum_{j=1}^{i-1} A_j(\boldsymbol{\omega})}{\sum_{j=i+1}^{m} A_j(\boldsymbol{\omega})}$, then $\frac{\partial F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})}{\partial A_i(\boldsymbol{\omega})} < 0$, $F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})$ is a decreasing function with respect to $A_i(\boldsymbol{\omega})$.

The F-S model delineates the condition of $\alpha_i \ge \beta_i$. The individual fairness utility, as proposed in this paper, aligns with this assumption of the F-S model. Therefore, when $0 < \beta_i < 1$, $\frac{\alpha_i}{\beta_i} \ge 1$ constantly holds; at the same time, according to the assumption $A_1(\boldsymbol{\omega}) \le A_2(\boldsymbol{\omega}) \le \cdots \le A_i(\boldsymbol{\omega}) \le \cdots \le A_m(\boldsymbol{\omega})$ in **Theorem 2**, we can get $\frac{\sum_{j=1}^{i-1} A_j(\boldsymbol{\omega})}{\sum_{j=i+1}^{m} A_j(\boldsymbol{\omega})} \le 1$ constantly holds, so the case $\frac{\alpha_i}{\beta_i} > \frac{\sum_{j=1}^{i-1} A_j(\boldsymbol{\omega})}{\sum_{j=i+1}^{m} A_j(\boldsymbol{\omega})}$ actually does not exist. That is, the exponential individual fairness utility function $F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})$ is an increasing function with respect to $A_i(\boldsymbol{\omega})$ in all cases.

Theorem 2 establishes a direct correlation between the fairness preferences of experts and their individual utility with regard to fairness. Although experts may exhibit similar fairness preference behavior, variations in fairness perceptions can arise as a result of differing levels of preference.

The aim of generating collective opinions is to optimize the expert fairness utility at a collective level, rather than solely focusing on individual fairness utility. Hence, the construction of the collective fairness utility is achieved through the utilization of an aggregation function, with the individual fairness utility serving as the independent variable. This approach guarantees a flexible and manageable representation of the experts' perception of collective fairness. This study adopts the approach of aggregating the arithmetic mean of the individual fairness utility scores of multiple experts to derive the collective fairness utility metric. That is,

$$U(\boldsymbol{\omega}) = \frac{1}{m} \sum_{i-1}^{m} F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega}), \tag{8}$$

where $U(\boldsymbol{\omega})$ is the collective fairness utility, $F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})$ is the exponential individual fairness utility of expert i.

4.3 Bi-objective optimization model with fairness utility

The utilization of optimization as a means to generate collective opinions has proven to be efficacious. Ji et al.'s bi-objective optimization model, as presented in [25], serves as an exemplar of the application of optimization in this context. The process of obtaining aggregated PDFs involves the utilization of QA aggregation and the two optimization objectives that are established for this process are the consensus level $A(\boldsymbol{\omega})=\sum_{i=1}^{m} A_i(\boldsymbol{\omega})$ and the confidence level $\gamma(\boldsymbol{\omega})$. The consensus level pertains to the overlap area between the individual expert PDF and the aggregated PDF, while the confidence level pertains to the variance of the aggregated PDF. The bi-objective optimization model is structured in a specific manner as outlined below:

Model 1:

$$\text{Max}\left(A(\boldsymbol{\omega}),-\gamma(\boldsymbol{\omega})\right)$$

$$s.t.\begin{cases} F_{QA}(x)=\left(\sum_{i=1}^{n}\lambda_i F_i^{-1}(\rho)\right)^{-1} \\ f_{QA}(x)=\dfrac{d\left(F_{QA}(x)\right)}{dx} \\ A_i(\boldsymbol{\omega})=\int_X \dfrac{f_i(x)+f_{QA}(x)-\left|f_i(x)-f_{QA}(x)\right|}{2}dx \\ A(\boldsymbol{\omega})=\sum_{i=1}^{m} A_i(\boldsymbol{\omega}) \\ \gamma(\boldsymbol{\omega})=\int_X\left(x-\int_X x f_{QA}(x)dx\right)^2 f_{QA}(x)dx \\ \sum_i \omega_i=1,\omega_i\geq 0, i=1,2,\cdots,m \end{cases}$$

Whilst the aforementioned bi-objective optimization model is proficient in producing collective viewpoints that exhibit acceptable levels of consensus and confidence, it is not suitable for the representation of behavioral traits. As delineated in Section 4.2, experts often prioritize the fairness of the decision-making procedure over the mathematical expression of the combined probability density function with conspicuous representation. The perspective of the perceived fairness of experts should be given greater importance in the collective opinion generation framework, rather than solely focusing on the tradeoff between objectivity and reliability of the aggregated PDF. In fact, the objectives of maximizing consensus level and collective fairness utility are aligned in terms of enhancing consensus, whereby the collective fair utility experiences an upsurge with an increase in consensus level. Consequently, it is possible to eliminate the objective at the consensus level, integrate the maximization of the collective fairness utility level into the optimization objective, and restructure the bi-objective optimization model utilized for producing the collective opinion. The improved bi-objective optimization model exhibits a distinct structure that can be described as follows:

Model 2:

$$\mathrm{Max}\left(U(\boldsymbol{\omega}),-\gamma(\boldsymbol{\omega})\right)$$

$$s.t.\begin{cases} F_{QA}(x)=\left(\sum_{i=1}^{n}\lambda_i F_i^{-1}(\rho)\right)^{-1} \\ f_{QA}(x)=\dfrac{d\left(F_{QA}(x)\right)}{dx} \\ A_i(\boldsymbol{\omega})=\int_X \dfrac{f_i(x)+f_{QA}(x)-\left|f_i(x)-f_{QA}(x)\right|}{2}dx \\ \gamma(\boldsymbol{\omega})=\int_X\left(x-\int_X xf_{QA}(x)dx\right)^2 f_{QA}(x)dx \\ F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})=A_i(\boldsymbol{\omega})-\dfrac{\alpha_i}{m-1}\sum_{j\neq i}\mathrm{Max}\left(A_j(\boldsymbol{\omega})-A_i(\boldsymbol{\omega});0\right)-\dfrac{\beta_i}{m-1}\sum_{j\neq i}\mathrm{Max}\left(A_i(\boldsymbol{\omega})-A_j(\boldsymbol{\omega});0\right) \\ \overline{F_i^{(\alpha_i,\beta_i)}}(\boldsymbol{\omega})=\begin{cases} 0, & F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})<0 \\ \dfrac{e^{\frac{F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})}{A_i(\boldsymbol{\omega})}}-1}{e-1}, & 0\leq F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})\leq A_i(\boldsymbol{\omega}) \\ 1, & A_i<F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega}) \end{cases} \\ U(\boldsymbol{\omega})=\dfrac{1}{m}\sum_{i=1}^{m}\overline{F_i^{(\alpha_i,\beta_i)}}(\boldsymbol{\omega}) \\ \sum_i \omega_i=1,\omega_i\geq 0, i=1,2,\cdots,m \end{cases}$$

In contemporary research, there exist two prevalent approaches for addressing multi-objective optimization problems [93]. The first involves amalgamating all objectives into a singular objective, while the second entails identifying the Pareto optimal solution set. The present study addresses the optimization dilemma through the amalgamation of two objectives into a singular objective via weighted summation. The optimization objectives exhibit distinct dimensions, thereby necessitating the normalization process to mitigate the impact of dimensionality. This normalization process transforms the optimization objectives into the normalized collective fairness utility $U(\boldsymbol{\omega})$ and the normalized confidence level $\tilde{\gamma}(\boldsymbol{\omega})$, which are calculated as follows:

$$U(\boldsymbol{\omega})=\frac{U(\boldsymbol{\omega})-\mathrm{Min}U(\boldsymbol{\omega})}{\mathrm{Max}U(\boldsymbol{\omega})-\mathrm{Min}U(\boldsymbol{\omega})} \tag{9}$$

$$\tilde{\gamma}(\boldsymbol{\omega})=\frac{\gamma(\boldsymbol{\omega})-\mathrm{Min}\gamma(\boldsymbol{\omega})}{\mathrm{Max}\gamma(\boldsymbol{\omega})-\mathrm{Min}\gamma(\boldsymbol{\omega})} \tag{10}$$

To achieve normalization, it is necessary to utilize the boundaries of both objectives. The bounds of the collective fairness utility $U(\boldsymbol{\omega})$ can be acquired through a constrained nonlinear optimization model as follows.

Model 3:

$$\text{Max / Min}(U(\boldsymbol{\omega}))$$

$$s.t.\begin{cases} F_{QA}(x) = \left(\sum_{i=1}^{n} \lambda_i F_i^{-1}(\rho)\right)^{-1} \\ f_{QA}(x) = \dfrac{d\left(F_{QA}(x)\right)}{dx} \\ A_i(\boldsymbol{\omega}) = \int_X \dfrac{f_i(x) + f_{QA}(x) - \left|f_i(x) - f_{QA}(x)\right|}{2} dx \\ F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega}) = A_i(\boldsymbol{\omega}) - \dfrac{\alpha_i}{m-1}\sum_{j\neq i} \text{Max}\left(A_j(\boldsymbol{\omega}) - A_i(\boldsymbol{\omega}); 0\right) - \dfrac{\beta_i}{m-1}\sum_{j\neq i} \text{Max}\left(A_i(\boldsymbol{\omega}) - A_j(\boldsymbol{\omega}); 0\right) \\ \overline{F_i^{(\alpha_i,\beta_i)}}(\boldsymbol{\omega}) = \begin{cases} 0, & F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega}) < 0 \\ \dfrac{e^{\frac{F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})}{A_i(\boldsymbol{\omega})}} - 1}{e-1}, & 0 \le F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega}) \le A_i(\boldsymbol{\omega}) \\ 1, & A_i < F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega}) \end{cases} \\ U(\boldsymbol{\omega}) = \dfrac{1}{m}\sum_{i-1}^{m} \overline{F_i^{(\alpha_i,\beta_i)}}(\boldsymbol{\omega}) \\ \sum_i \omega_i = 1, \omega_i \ge 0, i = 1, 2, \cdots, m \end{cases}$$

As per the definition of confidence level, it is possible to establish the lower bound as zero, given that the variance is a non-negative quantity. The theorem presented below provides a means of obtaining the upper bound of the confidence level.

Theorem 3. Assume $F_i(x)(i = 1, 2 \cdots m; x \in X)$ be the CDFs of individual experts, and μ_i, γ_i corresponding expectation value and variance of the $F_i(x)$. If the aggregated PDF is obtained by the QA formula, the expectation value μ_{QA} and the variance γ_{QA} of the aggregated CDF $F_{QA}(x)$ satisfy $\mu_{QA} = \sum_{i=1}^{m} \omega_i \mu_i$ and $\gamma_{QA} \le \text{Max}\{\gamma_i \mid i = 1, 2, \cdots, m\}$.

The demonstration of **Theorem 3** has been presented in the work of Ji et al. [25] and, as a result, has been excluded from this manuscript. The clarification of the Min-Max normalization of the two objectives can be achieved through the utilization of Models 2 and **Theorem 3**.

Following the application of min-max normalization, the objective of **Model 2** undergoes a transformation resulting in the attainment of $\text{Max}\left(U(\boldsymbol{\omega}), -\tilde{\gamma}(\boldsymbol{\omega})\right)$. Given that the two objectives can be assigned varying weights, the optimization objective function of **Model 3** can be modified as follows: $\text{Max} g(\boldsymbol{\omega}) = \lambda U(\boldsymbol{\omega}) - \eta\tilde{\gamma}(\boldsymbol{\omega})$, where the parameters λ and η represent the relative significance of the two objectives and satisfy the constraint $\lambda+\eta=1$. In the absence of additional information, the Laplace decision criterion will accord equal weight to both objectives, as they are deemed equally critical in yielding a logical resolution. Thus, the second model is ultimately transformed into the subsequent generalized single-objective optimization model.

Model 4:

$$\text{Max } g(\boldsymbol{\omega})=\lambda U(\boldsymbol{\omega})-\eta\tilde{\gamma}(\boldsymbol{\omega})$$

$$\text{s.t.}\begin{cases}F_{QA}(x)=\left(\sum_{i=1}^{n}\lambda_i F_i^{-1}(\rho)\right)^{-1}\\ f_{QA}(x)=\dfrac{d\left(F_{QA}(x)\right)}{dx}\\ \gamma(\boldsymbol{\omega})=\int_X\left(x-\int_X xf_{QA}(x)dx\right)^2 f_{QA}(x)dx\\ \tilde{\gamma}(\boldsymbol{\omega})=\dfrac{\gamma(\boldsymbol{\omega})-\text{Min}\gamma(\boldsymbol{\omega})}{\text{Max}\gamma(\boldsymbol{\omega})-\text{Min}\gamma(\boldsymbol{\omega})}\\ A_i(\boldsymbol{\omega})=\int_X\dfrac{f_i(x)+f_{QA}(x)-\left|f_i(x)-f_{QA}(x)\right|}{2}dx\\ F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})=A_i(\boldsymbol{\omega})-\dfrac{\alpha_i}{m-1}\sum_{j\neq i}\text{Max}\left(A_j(\boldsymbol{\omega})-A_i(\boldsymbol{\omega});0\right)-\dfrac{\beta_i}{m-1}\sum_{j\neq i}\text{Max}\left(A_i(\boldsymbol{\omega})-A_j(\boldsymbol{\omega});0\right)\\ \overline{F_i^{(\alpha_i,\beta_i)}}(\boldsymbol{\omega})=\begin{cases}0, & F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})<0\\ \dfrac{e^{\frac{F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})}{A_i(\boldsymbol{\omega})}}-1}{e-1}, & 0\le F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})\le A_i(\boldsymbol{\omega})\\ 1, & A_i<F_i^{(\alpha_i,\beta_i)}(\boldsymbol{\omega})\end{cases}\\ U(\boldsymbol{\omega})=\dfrac{1}{m}\sum_{i-1}^{m}\overline{F_i^{(\alpha_i,\beta_i)}}(\boldsymbol{\omega})\\ \widetilde{U(\boldsymbol{\omega})}=\dfrac{U(\boldsymbol{\omega})-\text{Min}U(\boldsymbol{\omega})}{\text{Max}U(\boldsymbol{\omega})-\text{Min}U(\boldsymbol{\omega})}\\ \lambda+\eta=1\\ \sum_i\omega_i=1,\omega_i\ge 0,i=1,2,\cdots,m\end{cases}$$

The initial step in the optimization procedure involves the estimation of the fairness function/variance function range in **Model 3**. The genetic algorithm was employed to produce fair function/variable function range evaluation results through the utilization of MATLAB R2020b's global optimization toolbox. Subsequently the constrained nonlinear solver fmincon in MATLAB is used to solve the objective function in **Model 4**. Upon receiving the collective evaluation outcomes for each indicator, we proceed to assign equal weight to all indicators. Subsequently, the QA aggregation technique is utilized to consolidate the results and derive a comprehensive evaluation of the accessibility to rail transit stations in urban areas.

5. Case study

In this section, we design a small-scale application experiment attempting to evaluate the accessibility to rail transit stations in *Wuchang District, Wuhan* with the proposed approach in order to demonstrate the feasibility of the approach.

5.1 Basic status of rail transit in Wuchang District, Wuhan City

Wuhan serves as the administrative center of Hubei Province and is situated in the central region of China, as well as an important industrial and transportation hub in China. Wuhan is comprised of 13 administrative districts and 6 functional districts. The present study focuses specifically on the *Wuchang District*, which is situated in the southeastern region of Wuhan City and is the seat of the CPC Hubei Provincial Committee and Provincial People's Government. The rail transit system in *Wuhan* comprises a total of 11 operational metro lines and three tram lines, as illustrated in **Figure 2**. However, the rail transit system in *Wuchang District* solely comprises the metro system, which offers access to residents via metro lines 2, 4, 5, 7, and 8, with 35 metro stations dispersed throughout the district.

5.1.1 Political environment

Since the intra-regional rail transit system is planned and constructed by the Wuhan Municipal Government, this section aims to provide a succinct overview of the Wuhan Municipal Government's attitude towards the intra-regional rail transit system. The Wuhan Municipal Government regards rail transit as a rapid, effective, and ecologically sound form of urban public transportation. The expeditious development of rail transit holds significant implications for enhancing the urban framework and advancing sustainable economic and social progress. The Wuhan Municipal Government has expressed its dedication to the development of the "Wuhan Metropolitan Area on the Rail". As part of this initiative, the construction of rail transit systems will be progressively expanded from the city's central region to its periphery. It is anticipated that the Wuhan Metropolitan Area will establish a comprehensive urban rail transit system comprising 32 lines spanning a total distance of 1600 km by the year 2035[2]. Furthermore, the Wuhan municipal administration has collaborated with multiple financial institutions, including China Construction Bank and China Communication Bank, to implement favorable measures for subway transportation, with the aim of promoting the utilization of the rail transit system among local inhabitants.

[2] *http://www.hubei.gov.cn/hbfb/rdgz/202007/t20200714_2672220.shtml*

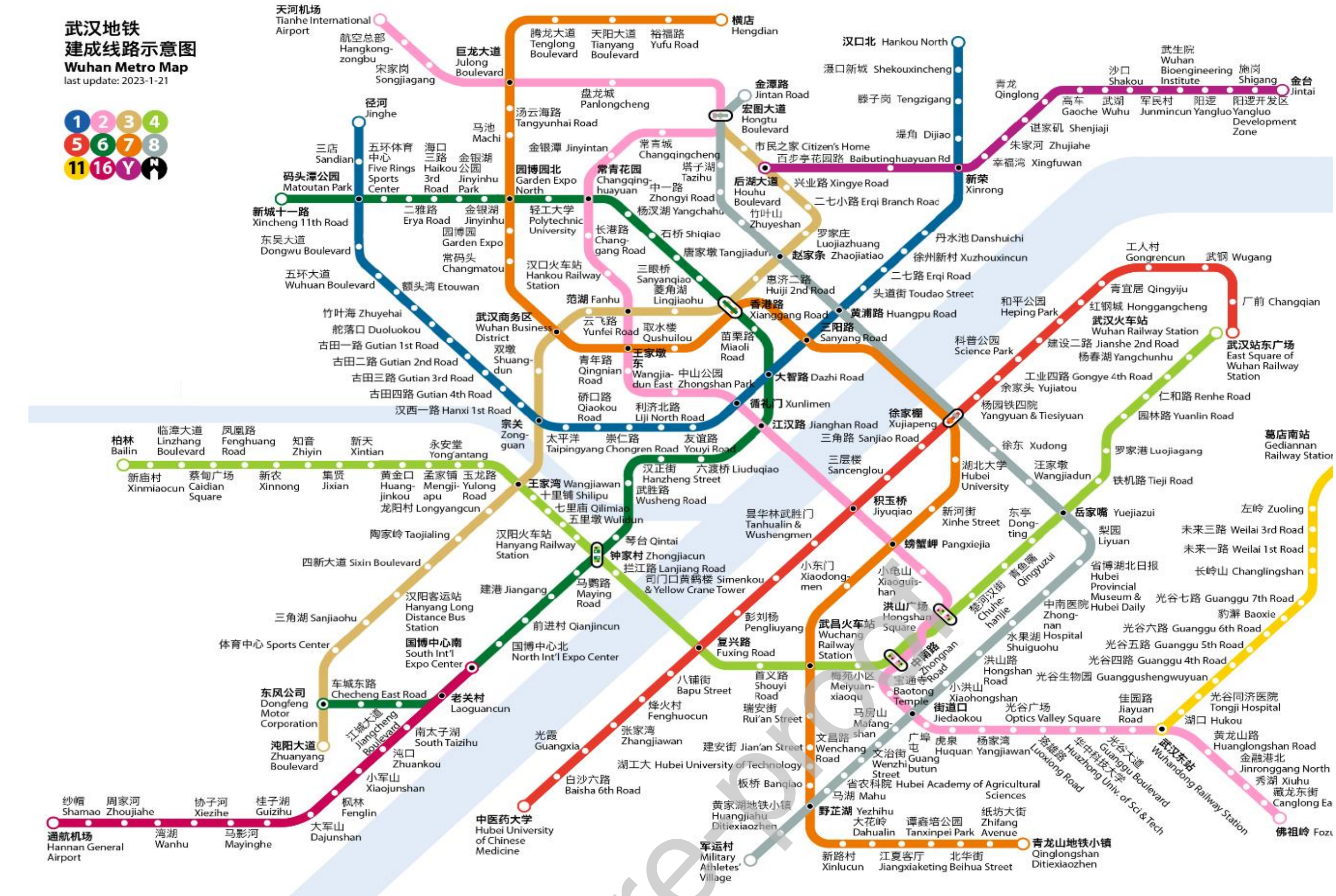


Figure 2. Wuhan metro line map

Source: Wikipedia (https://en.wikipedia.org/wiki/Wuhan_Metro)

5.1.2 Economic environment

In recent years, the *Wuchang District* has experienced consistent growth in its economic development. According to the data presented in **Figure 3 (a)**, the gross regional product of *Wuchang District* in 2021 amounted to CNY 166.444 billion, reflecting a year-on-year increase of 10.4% at comparable prices[3]. The secondary industry exhibited a value added of CNY 18.414 billion, indicating a 6.2% year-on-year increase at comparable prices. Similarly, the tertiary industry demonstrated a value added of CNY 148.030 billion, signifying a 10.9% year-on-year increase at comparable prices[3]. According to the data presented in **Figure 3 (b)**, the per capita disposable income of urban residents in *Wuchang District* in the year 2021 amounted to CNY 63258, indicating a growth of 10.8% in comparison to the preceding year[3].

Nevertheless, there are certain possible drawbacks that may hinder the economic progress of *Wuchang District*, which are outlined below: 1)The tax revenue is excessively dependent on the financial industry and real estate industry,

[3] *Wuhan Wuchang District Economic and Social Development Statistics for 2021*

which is subject to the influence of national policies and controls, and has a large uncertainty. 2)The industrial structure in *Wuchang District* is characterized by a significant presence of state-owned enterprises and a high proportion of traditional industries, which poses challenges for expediting the process of industrial transformation and upgrading. 3) Insufficient implementation of specialized support policies for emerging industries with rapid growth.

5.1.3 Social environment

As of the conclusion of 2021, the populace residing within *Wuchang District* has attained a numerical count of 1.27 million individuals, with a subset of 1,054,900 individuals possessing household registration[4]. The *Wuchang District* encompasses a total area of 107.76 km^2, of which 60.96 km^2 is comprised of land. Based on the land area and household registration population, the population density is calculated to be 17,295 individuals per square kilometer. The jurisdiction of *Wuchang District* encompasses 14 subdistricts, and **Table 3** shows the number of household registration populations and population density of all sub-districts. As presented in **Table 3,** Zhongnanlu subdistrict boasts the highest population count, with 205,100 individuals, while the Zhonghualu subdistrict exhibits the greatest population density, with 34,778 people per square kilometer. In 2021, the per capita consumption expenditure of residents in *Wuchang District* has risen by 14.50% compared to the preceding year, amounting to CNY42,367 [3]. In 2021, the *Wuchang District* Bureau of Statistics conducted a sample survey by selecting 329 residents, and the survey results provided in **Table 4** show that approximately 66% of the disposable income of the residents was allocated to consumption. Notably, transportation and communication accounted for approximately 10% of the total expenditure, while education, culture, and entertainment accounted for approximately 12% of the total expenditure.

5.1.4 Technical environment

1) The transportation infrastructure in *Wuchang District* is undergoing significant expansion, with a current count of over 80 bus routes servicing the area. However, the current bus line layout cannot well meet the travel needs of the public, while the bus ride experience is poor, residents prefer to use private cars to travel.

2) In recent years, the *Wuchang District* government has focused on the standardized management of shared bicycles and strictly enforced the shared bicycles access policy. The relevant departments reduce the number of shared bicycles in the district by specifying the number of bicycles to be placed, synchronizing the scrapping data, and setting up no-parking zones. The government also entrusted relevant enterprises with the responsibility of standardized bicycle parking and transfer, as shown in **Figure 3(c)**.

3) The overall walking environment in *Wuchang District* is general, and it represents a significant constraint on the

[4] *Wuchang Statistical Yearbook in 2021*

expansion of rail transit in the area. The inadequate early planning and geographical constraints have resulted in the presence of narrow sidewalks and the lack of supporting facilities such as underground passages in certain areas, thereby compromising the safety of residents during travel. **Figure 3 (d)** shows the walking environment of some sections of Donghu South Road in *Wuchang District*, which is adjacent to Wuhan University in the west and East Lake in the east, with a large flow of people, but the sidewalks are too narrow and inconvenient for pedestrians to pass.

4)According to the survey conducted by the *Wuchang District* Bureau of Statistics in 2021, there is an average of 62.73 private cars per 100 households in the district. The *Wuchang District Government* has proposed the addition of 10,000 new parking spaces to accommodate the increasing number of private cars.

5) *Wuchang District* has a dense road network, with a total road area of 7,181,300 square meters in 2021[4]. Simultaneously, the *Wuchang District Government* is proactively constructing the microcirculation system of regional traffic and adopting a small neighborhood, dense road network planning model for the ground road system. Furthermore, the government is also promoting the transformation of the old community road network and enhancing the slow-walking system network to increase the proportion of slow-moving traffic trips[5].

6) Wuhan has severe traffic congestion, with an average city congestion factor of 1.641 in 2022, ranking 10th among major Chinese cities[6]. *Wuchang District* is the area with more serious traffic congestion in Wuhan. Among the 10 long-term congested areas identified by Wuhan Public Security Traffic Administration in 2022, Dingziqiao Road and Shuiguo Lake are situated in the *Wuchang District*. Additionally, two of the 10 phased congestion areas are also located in *Wuchang District*, with peak congestion times concentrated in the morning from 7-9 a.m. and in the evening from 5-7 p.m.[7]. **Figure 3 (e)** shows the traffic congestion during the early morning peak in the Shuiguo Lake area

7)The distribution of rail transit stations in *Wuchang District* is depicted in **Figure 3 (f),** revealing 35 rail transit stations dispersed throughout the district, effectively covering a significant portion of the area.

[5] *Wuchang District National Economic and Social Development 14th Five-Year Plan and 2035 Visionary Goals Outline Task*

[6] *2022 Annual China Urban Transportation Report*

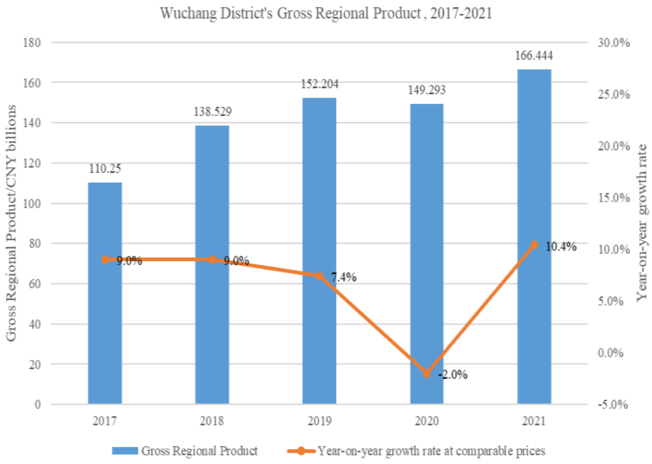
[7] *10 + 10 + N traffic congestion point governance list in 2022*

Table 3. Household registration population and population density of each sub-district in *Wuchang District*

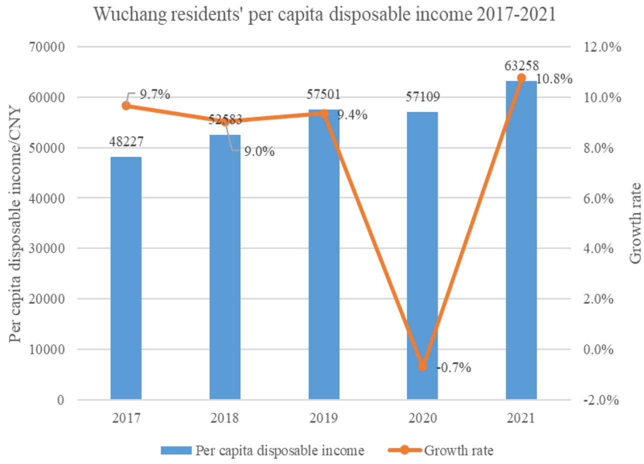
Subdistrict	Household registration population	Population Density(people/km^2)
Jiyuqiao Subdistrict	65461	17303
Yngyuan Subdistrict	89632	17131
Xujiapeng Subdistrict	108373	13859
Liangdao Subdistrict	54645	30582
Zhonghualu Subdistrict	36108	34778
Huanghelou Subdistrict	49900	25183
Ziyang Subdistrict	46465	17894
Baishazhou Subdistrict	53995	9078
Shouyilu Subdistrict	55923	18064
Zhongnanlu Subdistrict	205107	25724
Shuiguohu Subdistrict	185247	19478
Luojiashan Subdistrict	36389	10141
Shidong Subdistrict	6172	1498
Nanhu Subdistrict	62489	24197
Total	1054900	17295

Table 4. 2021 *Wuchang District* Residents' expenditure survey

Indicator		Survey Result/CNY
Per capita disposable income of urban permanent residents		63258.00
Consumption expenditure	Food, Tobacco, and Alcohol	11243.14
	Clothes	2043.09
	Residence	13502.88
	Living Goods & Services	2114.55
	Traffic Communication	4036.60
	Education, Culture, and Entertainment	5269.42
	Healthcare	3101.94
	Other Supplies & Services	1055.38



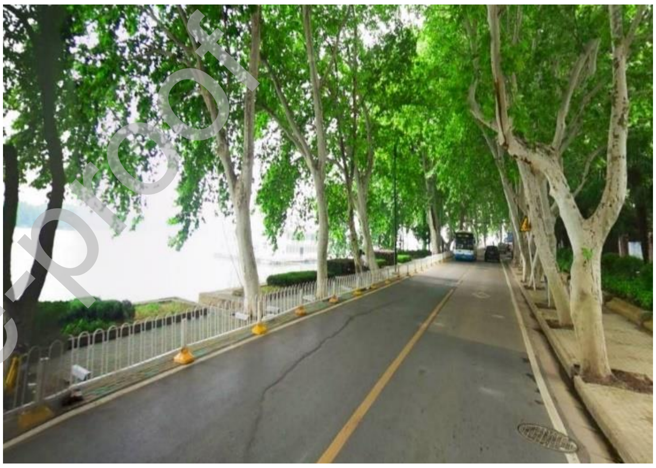
(a) Gross regional product of *Wuchang District*, 2017-2021



(b) Per capita disposable income of the residents in *Wuchang District*,2017-2021

(c) Staff are sorting out shared bicycles

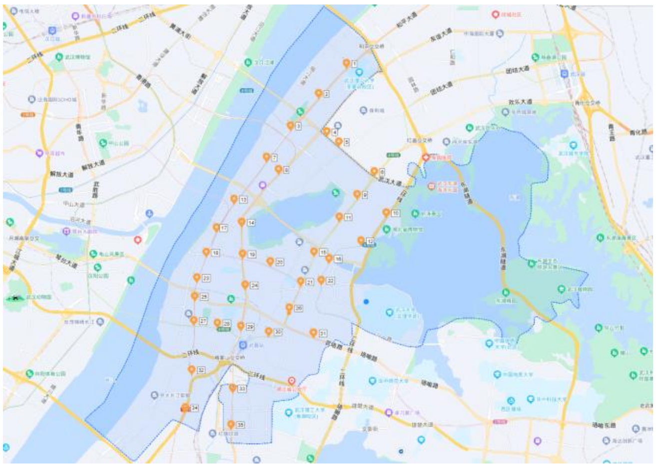
Source:https://new.qq.com/rain/a/20211106A04JFB00



(d) Donghu south road walking environment

(e) Traffic congestion scene in the Shuiguo Lake area

Source: Traffic congestion in the Shuiguo Lake area



(f) Distribution of rail transit stations in *Wuchang District*

Figure 3. Economic and technical environment influencing accessibility to rail transit stations in *Wuchang District*

5.2 Expert evaluation results acquisition and fitting

A group of twelve professionals specializing in urban transportation has been extended an invitation to assess the accessibility to rail transit stations in the *Wuchang District.* The experts should provide a subjective probability for each grade under which each indicator falls. It must be recognized that accessibility measurement is a large-scale survey issue, and 12 experts are clearly insufficient to capture the diverse perspectives of all city residents. However, the goal of this section is to validate the feasibility of the proposed methodology through a small-scale experiment to lay the foundation for a subsequent large-scale group survey. Therefore, a decision-making panel of 12 experts can fulfill the requirements of this study's empirical research.

In the process of fitting expert opinions with PDFs, it is typically imperative to impose some structure on the probability distribution rather than simply assuming that the PDFs are uniformly continuous. In practical applications, it is customary to employ distributions belonging to a certain family of distributions characterized by specific parameters to model expert opinions. The commonly used families of distributions include the normal, Weibull, beta, and uniform distributions[25,94]. The present investigation employs the generalized two-parameter Weibull distribution to model expert opinions due to the following reasons: 1) each expert allocates a positive probability to three or more assessment results; 2) the distribution exhibits a unimodal trend; 3) the generalized two-parameter distribution exhibits commendable characteristics for characterizing the predictors' opinions by adapting the column and shape parameters. The structure of the generalized two-parameter Weibull distribution can be expressed as follows:

$$f\left(x,a,b\right)=\begin{cases}\dfrac{a}{b}\left(\dfrac{x}{b}\right)^{a-1}e^{-\left(\frac{x}{b}\right)^{a}} & x\geq 0\\ 0 & x<0\end{cases}, \tag{11}$$

where x is the random variable, which is the expert evaluation result in this study. a is the shape parameter, and b is the scale parameter, and a, b satisfy respectively $a>0$, $b>0$.

The Origin software is utilized to perform fitting of the expert evaluation outcomes. In consideration of the substantial volume of data, solely the first evaluation indicator, namely "government attitude toward rail transit," is presented as an illustration to demonstrate the effectiveness of the fitting process. **Table 5** provides the fitting parameters utilized to fit the expert evaluation outcomes with the Weibull distribution. Meanwhile, **Figure 4** displays the actual probability distribution and fitting the PDF of the expert evaluation results. **Table 5** and **Figure 4** together provide evidence of the sufficiency of the fitting.

Table 5. Fitting parameters for Weibull distribution

Fitting parameters	The government's attitude toward rail transit			
	a	b	SSE	R^2
expert 1	9.00	6.07	0.00	0.99
expert 2	8.59	5.43	0.01	0.96
expert 3	6.35	5.41	0.01	0.90
expert 4	7.63	5.29	0.01	0.93
expert 5	7.51	5.31	0.00	0.98
expert 6	10.70	5.37	0.01	0.95
expert 7	8.92	5.42	0.02	0.90
expert 8	8.11	5.95	0.00	1.00
expert 9	9.43	5.29	0.00	0.98
expert 10	7.51	5.31	0.00	0.98
expert 11	10.05	6.12	0.01	0.98
expert 12	11.27	5.37	0.00	0.99

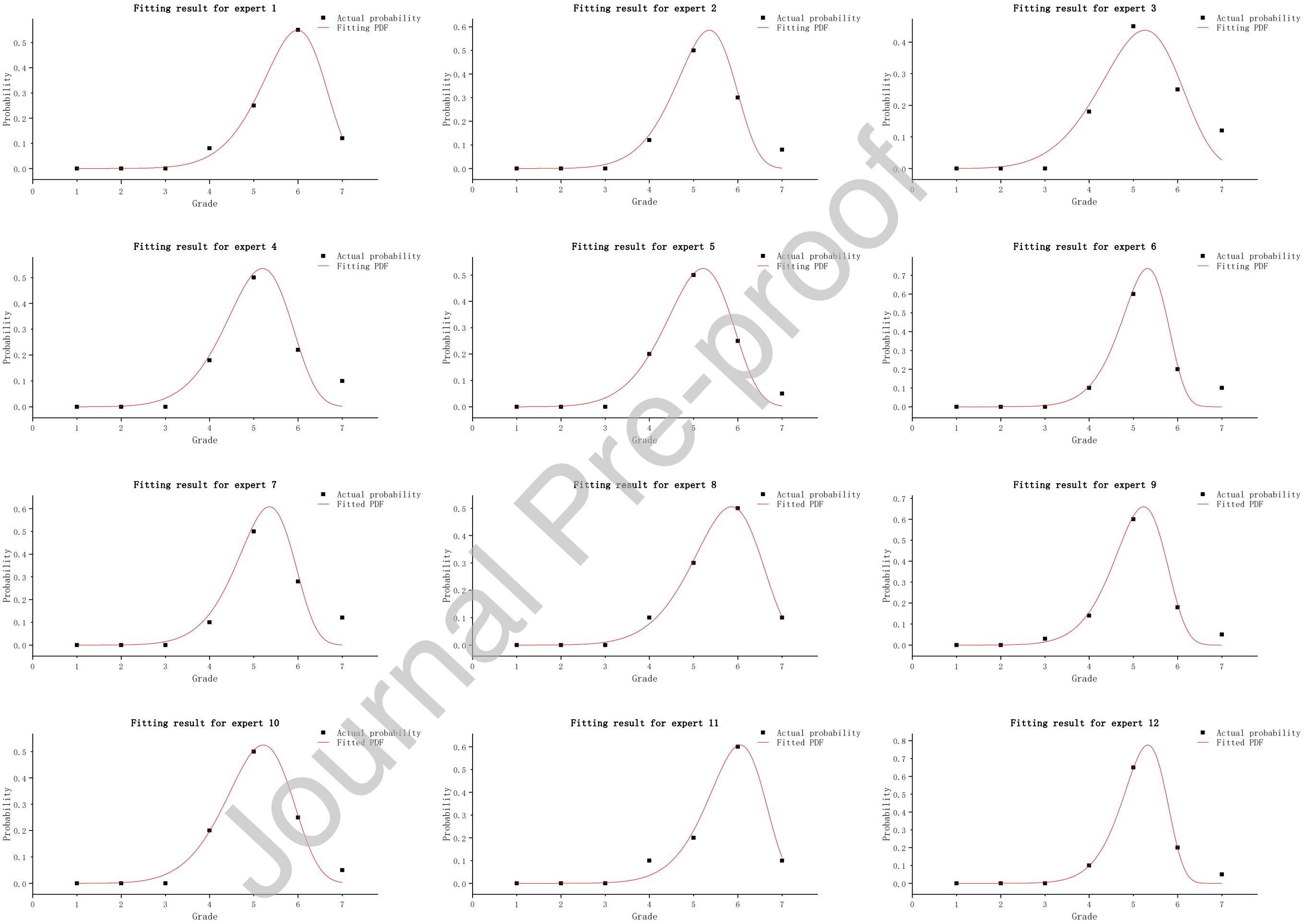
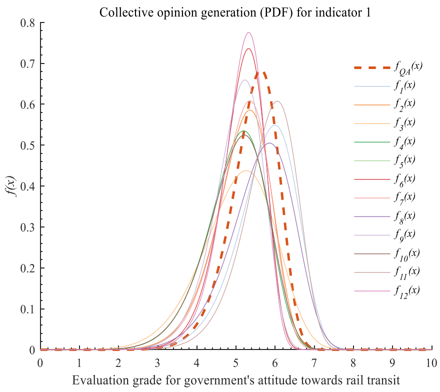


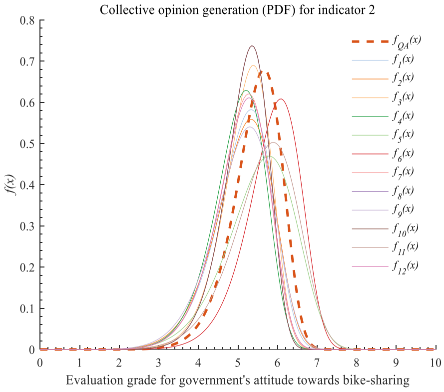
Figure 3. Fitting PDF (solid line) and actual probability distribution (point)

Table 6. Intermediate results of evaluation results aggregation of indicators at the political level

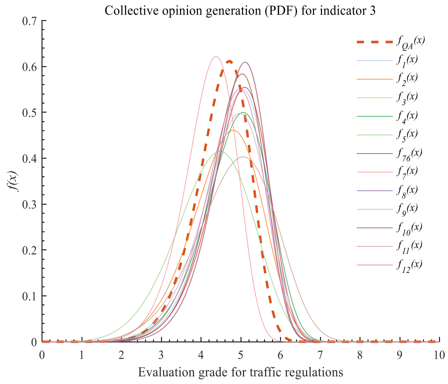
Indicator	Parameters		Fairness utility			Variance				Weights											
	a	b	Min	Max	Obj	Min	Max	Std.	Obj	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Exp10	Exp11	Exp12
Indicator 1	10.5359	5.6904	0.0000	1.0000	0.9958	0.0000	0.8581	0.4498	0.3860	0.0120	0.0063	0.0025	0.0039	0.0038	0.0346	0.0074	0.0058	0.0092	0.0038	0.3988	0.5120
Indicator 2	10.4456	5.6746	0.0000	1.0000	0.9029	0.0000	0.7701	0.5063	0.3899	0.0042	0.0035	0.0183	0.0052	0.0026	0.3428	0.0053	0.3032	0.0030	0.3032	0.0037	0.0049
Indicator 3	7.8973	4.7910	0.0000	1.0000	0.9199	0.0000	0.9878	0.4642	0.4585	0.0075	0.0025	0.1926	0.0038	0.0017	0.0083	0.5541	0.2003	0.0037	0.0163	0.0016	0.0075
Indicator 4	9.2562	5.6955	0.0000	1.0000	0.9182	0.0000	0.8605	0.5675	0.4883	0.0198	0.0037	0.0020	0.0036	0.0025	0.0019	0.2150	0.0055	0.3855	0.0146	0.0048	0.3413
Indicator 5	8.6953	5.6040	0.0000	1.0000	0.9242	0.0000	0.9822	0.5382	0.5287	0.6022	0.0007	0.0016	0.0005	0.0007	0.0008	0.0007	0.0024	0.0008	0.0024	0.3864	0.0009
Indicator 6	8.8582	4.7644	0.0000	1.0000	0.9768	0.0000	0.7196	0.5137	0.3697	0.0028	0.0024	0.0174	0.0028	0.0028	0.0029	0.0050	0.6480	0.0043	0.0092	0.2980	0.0043
Indicator 7	9.4972	5.5424	0.0000	1.0000	0.8636	0.0000	0.9909	0.4456	0.4416	0.0100	0.1256	0.0113	0.0169	0.0053	0.0084	0.0191	0.0204	0.0165	0.6395	0.1158	0.0112
Indicator 8	7.8984	4.8028	0.0000	1.0000	0.9904	0.0000	1.1301	0.4076	0.4607	0.0066	0.0464	0.0899	0.0067	0.0023	0.1414	0.0066	0.1635	0.4167	0.0984	0.0065	0.0149
Indicator 9	9.4408	5.6409	0.0000	1.0000	0.9126	0.0000	0.7973	0.5799	0.4623	0.0031	0.0037	0.0052	0.5467	0.0021	0.0024	0.3424	0.0058	0.0276	0.0052	0.0507	0.0051
Indicator 10	7.5206	4.8022	0.0000	1.0000	0.9539	0.0000	1.1368	0.4417	0.5022	0.0013	0.0026	0.0137	0.0025	0.0010	0.0047	0.0021	0.0151	0.0074	0.0017	0.4172	0.5307
Indicator 11	6.6930	4.6120	0.0000	1.0000	0.9751	0.0000	0.9654	0.5887	0.5684	0.0074	0.0055	0.0294	0.0059	0.0300	0.0148	0.3281	0.4143	0.0074	0.0165	0.1095	0.0312
Indicator 12	7.0153	4.5976	0.0000	1.0000	0.9218	0.0000	0.7903	0.6582	0.5202	0.0166	0.0030	0.0044	0.0044	0.0700	0.4740	0.3441	0.0022	0.0054	0.0040	0.0700	0.0019
Indicator 13	6.7630	4.5417	0.0000	1.0000	0.9900	0.0000	0.9758	0.5547	0.5412	0.0077	0.5608	0.0093	0.0179	0.3644	0.0141	0.0039	0.0065	0.0061	0.0018	0.0027	0.0047
Indicator 14	7.5781	4.8566	0.0000	1.0000	0.9153	0.0000	0.8746	0.5794	0.5068	0.0032	0.0033	0.0196	0.0035	0.0040	0.0074	0.0040	0.4633	0.4798	0.0064	0.0026	0.0028
Indicator 15	8.0375	4.6900	0.0000	1.0000	0.9341	0.0000	0.9713	0.4385	0.4259	0.0033	0.0043	0.0025	0.0019	0.0037	0.3399	0.0055	0.0084	0.0274	0.5908	0.0028	0.0095
Indicator 16	7.4186	4.6336	0.0000	1.0000	0.9981	0.0000	1.0805	0.4432	0.4789	0.4092	0.0117	0.0066	0.0130	0.0198	0.0199	0.0151	0.0153	0.0140	0.0117	0.4590	0.0047
Indicator 17	10.3263	5.5385	0.0000	1.0000	0.9382	0.0000	0.6622	0.5727	0.3792	0.0374	0.0444	0.0510	0.4174	0.0762	0.0409	0.0764	0.0635	0.0399	0.0477	0.0690	0.0363



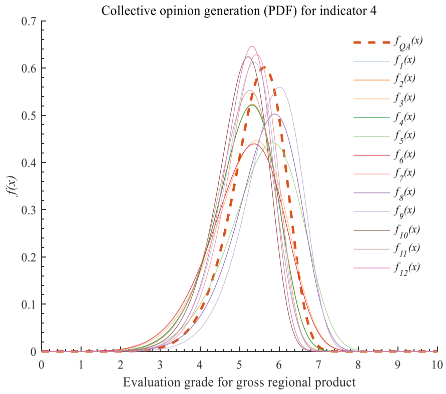
(a) Collective evaluation result for government's attitude toward rail transit



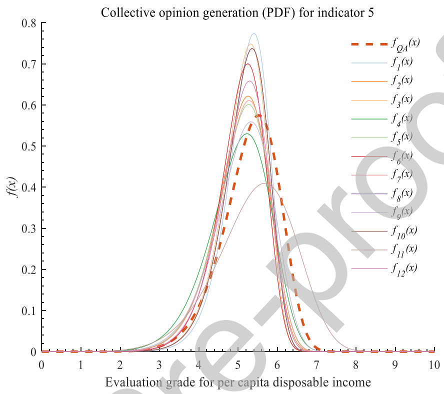
(b) Collective evaluation result for the government's attitude towards bike-sharing:



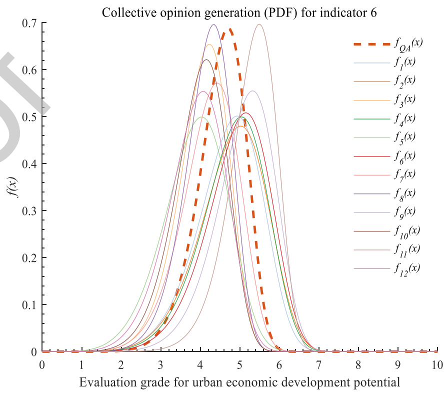
(c) Collective evaluation result for traffic regulations



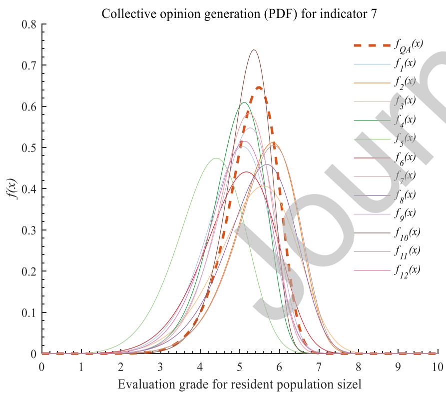
(d) Collective evaluation result for gross regional product



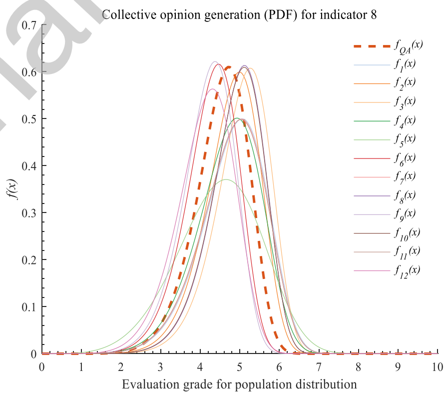
(e) Collective evaluation result for per capita disposable income



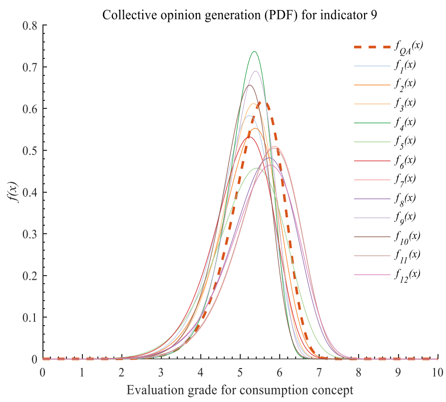
(f) Collective evaluation result for urban economic development potential



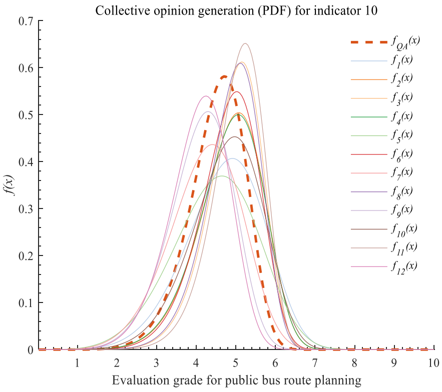
(g) Collective evaluation result for resident population size



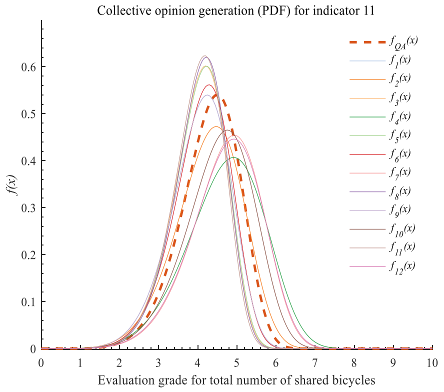
(h) Collective evaluation result for population distribution



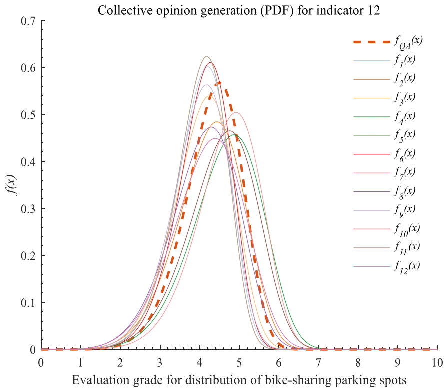
(i) Collective evaluation result for consumption concept



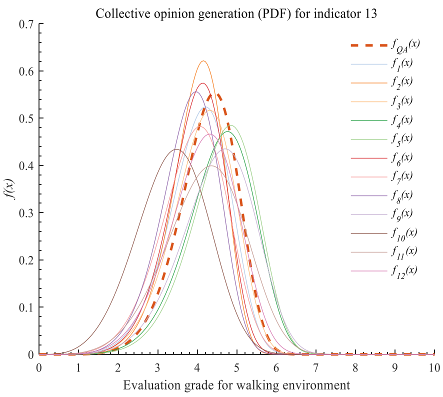
(j) Collective evaluation result for public bus route planning



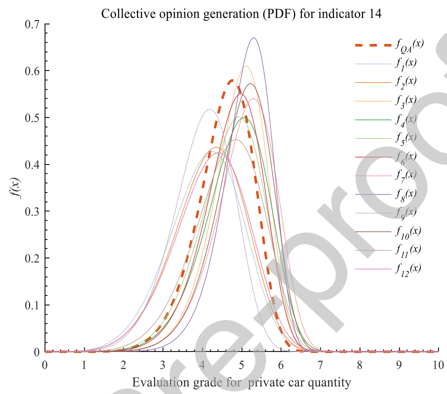
(k) Collective evaluation result for the total number of shared bicycles



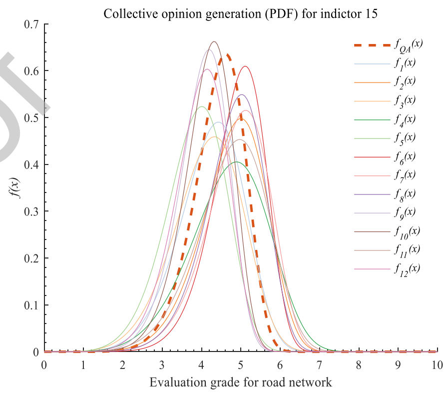
(l) Collective evaluation result for Distribution of bike-sharing parking spots



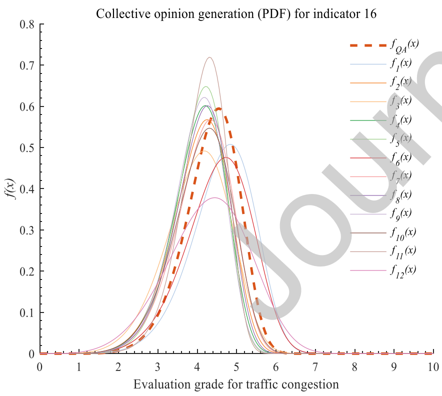
(m) Collective evaluation result for walking environment



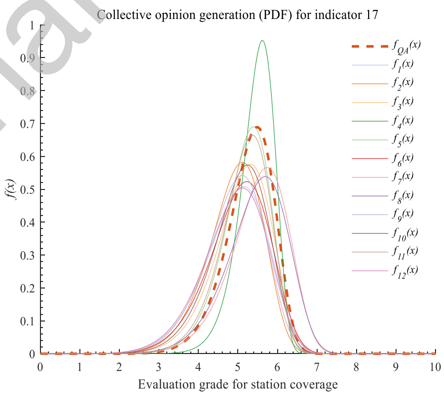
(n) Collective evaluation result for private car quantity



(o) Collective evaluation result for road network

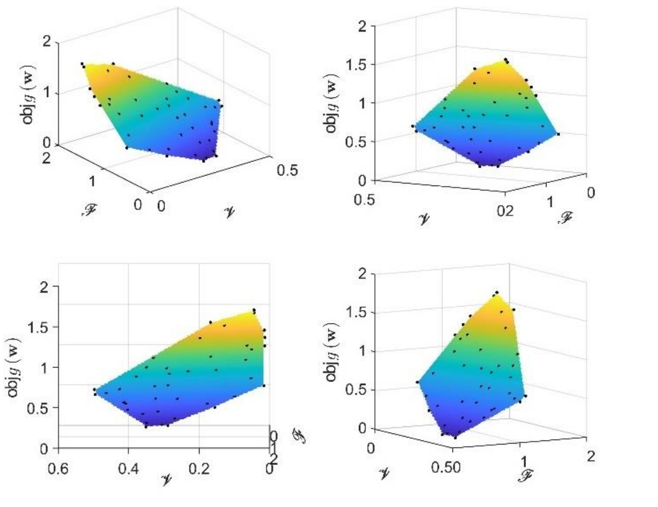


(p) Collective evaluation result for traffic congestion

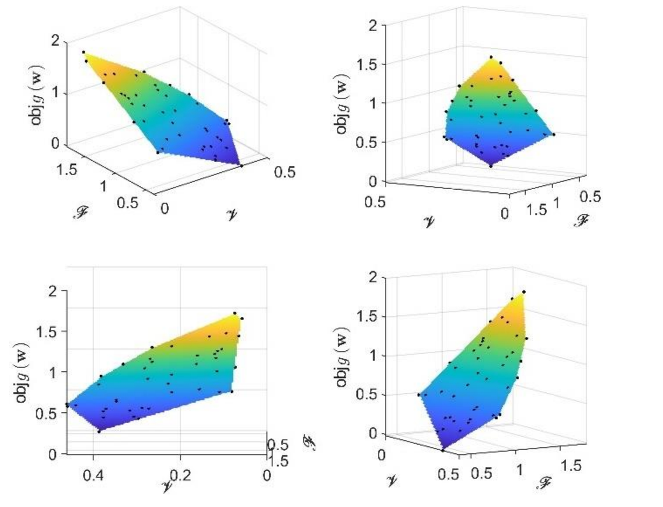


(q) Collective evaluation result for station coverage

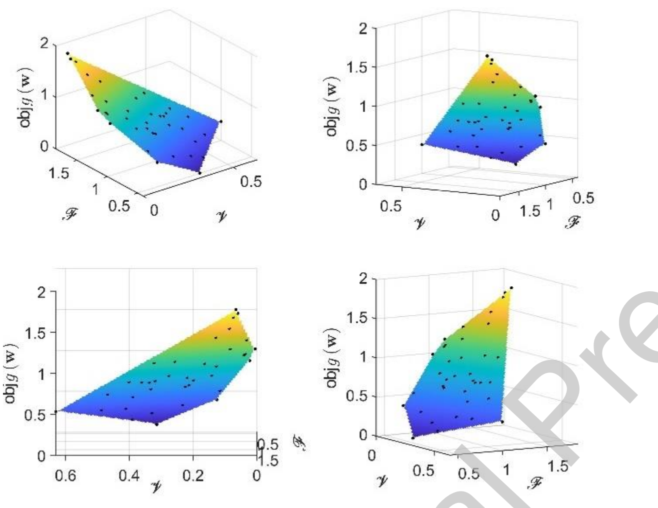
Figure 5. Collective evaluation result for each indicator under the Weibull distribution



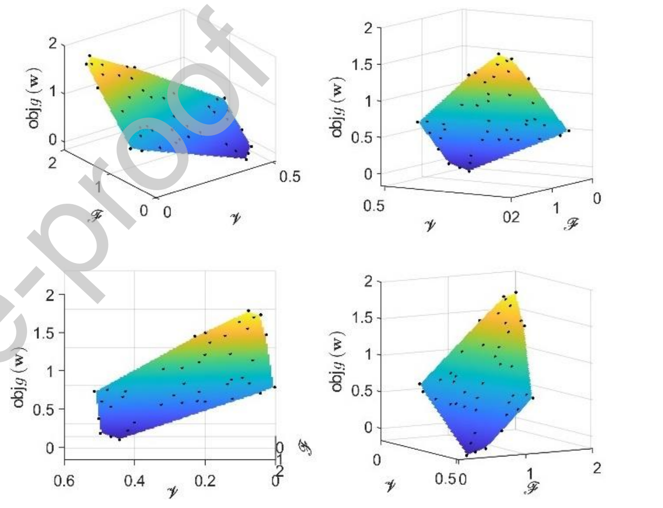
(a) Aggregation for government's attitude toward rail transit



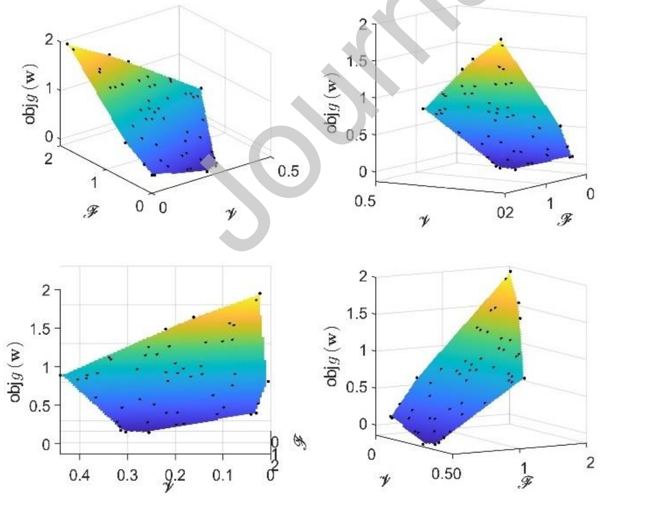
(b) Aggregation for government's attitude towards bike-sharing



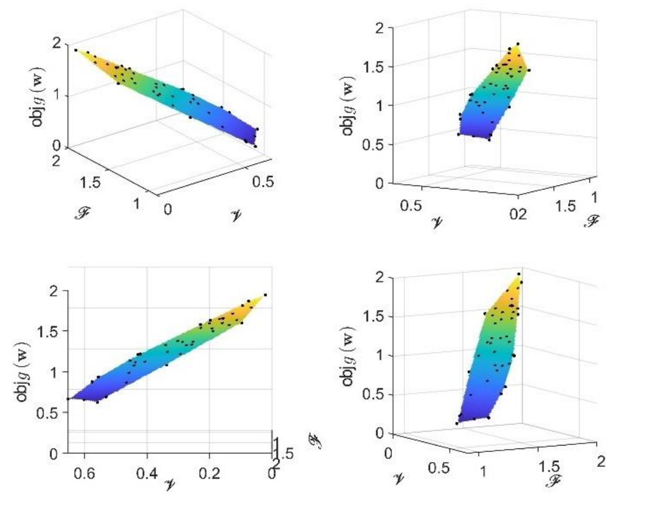
(c) Aggregation for traffic regulations



(d) Aggregation for gross regional product



(e) Aggregation for per capita disposable income



(f) Aggregation for urban economic development potential

Figure 6. Search space for the proposed model in evaluating indicators of political and economic dimensions

5.3 Aggregating expert opinions to generate collective opinions

After obtaining all the fitted PDFs representing the expert opinions, it is required to generate the collective opinion by aggregating the expert opinions utilizing Model 4.

According to the Laplace decision criterion, the two objectives in **Model 4** $U(\boldsymbol{\omega})$ and $\tilde{\gamma}(\boldsymbol{\omega})$ have equal importance. The optimal solution is then obtained using MATLAB R2022a software. **Table 6** presents the intermediary outcomes of the aggregation of evaluation results for all indicators. The aggregated PDFs for all indicators are presented in **Figure 5**. For the 6 indicators under the technical and economic dimensions, the ideal search space for the two optimization objectives in the aggregation process of their evaluation results is shown in **Figure 6.**

It can be observed in **Table 6** that the collective fairness utility exhibits a high value, signifying that a majority of experts deem the collective evaluation outcomes to be equitable. Additionally, the aggregated PDF displays a relatively small variance, representing the relative concentration of the collective opinion. Collective fairness utility and the confidence level jointly demonstrate the validity of the model. As depicted in Figure 6, it is evident that the model efficiently attains the optimal solution following multiple iterations, signifying its efficacy in facilitating large-scale opinion aggregation. For the purpose of brevity and efficiency, we refrain from providing an exhaustive account of the PDFs and search spaces for all objectives that arise during the evaluation of all indicators. But these materials are available from the corresponding authors upon reasonable request.

After obtaining the collective evaluation results for all indicators, the same weights are assigned to the 17 indicators, and the QA aggregation technique is employed to aggregate the collective evaluation results for all indicators. Through these two processes, the comprehensive evaluation result concerning the accessibility to rail transit stations in *Wuchang District* has been obtained, as depicted in **Figure 7**. The ultimate assessment outcome is also represented as a Weibull distribution function, wherein the shape parameter $a = 8.384$ and the scale parameter $b = 5.0861$. The Weibull distribution's expectation E is utilized to denote the assessment grade, while the variance Var is employed to indicate the degree of concentration. The expectation is calculated as $E = b\Gamma(1+\frac{1}{a})$, while the variance is computed using $Var = b^2 * \left\{\Gamma(1+\frac{2}{a}) - [\Gamma(1+\frac{1}{a})]^2\right\}$. Where Γ is the gamma function and $\Gamma(x) = \int_0^{+\infty} t^{x-1}e^{-t}dt,\ (x>0)$. **Table 7** presents the expectation and variances of the aggregated PDFs for all indicators, as well as the expectation and variance of the ultimate evaluation outcome.

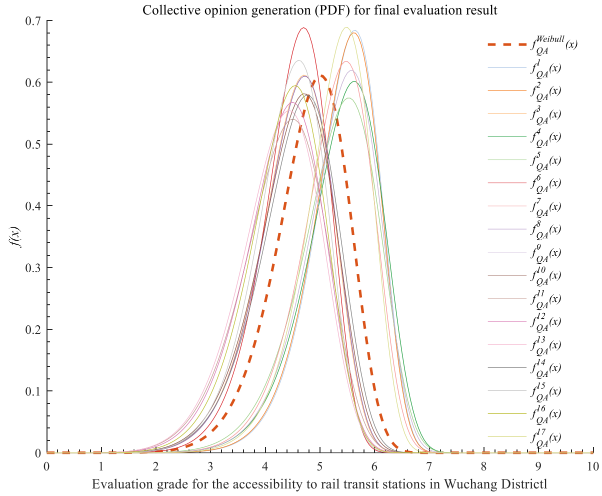


Figure 7. Collective evaluation result for the accessibility to rail transit stations in *Wuchang District*

Table 7. Expectation and variance of aggregated PDF under each indicator and of the final evaluation result

Parameter/Indicator	a	b	Expectation	Variance
Indicator 1	10.5359	5.6904	5.4253	0.3860
Indicator 2	10.4456	5.6746	5.4084	0.3899
Indicator 3	7.8973	4.7910	4.5090	0.4585
Indicator 4	9.2562	5.6955	5.4003	0.4883
Indicator 5	8.6953	5.6040	5.2984	0.5287
Indicator 6	8.8582	4.7644	4.5085	0.3697
Indicator 7	9.4972	5.5424	5.2611	0.4416
Indicator 8	7.8984	4.8028	4.5202	0.4607
Indicator 9	9.4408	5.6409	5.3531	0.4623
Indicator 10	7.5206	4.8022	4.5086	0.5022
Indicator 11	6.6930	4.6120	4.3040	0.5684
Indicator 12	7.0153	4.5976	4.3012	0.5202
Indicator 13	6.7630	4.5417	4.2408	0.5412
Indicator 14	7.5781	4.8566	4.5615	0.5068
Indicator 15	8.0375	4.6900	4.4178	0.4259
Indicator 16	7.4186	4.6336	4.3473	0.4789
Indicator 17	10.3263	5.5385	5.2762	0.3792
Final	8.384	5.0861	4.8006	0.4647

5.4 Discussion

A collection of indicators was acquired to assess the accessibility to rail transit stations in *Wuchang District* utilizing a PEST framework. The collective opinion generation model based on bi-objective optimization is used to evaluate the performance of each indicator, and QA aggregation is used to generate the final evaluation results. **Table 7** displays that the assessment outcomes for all indicators are situated within the range of grade 4 to grade 6. The "gross regional product" indicator exhibits the best performance, while the "pedestrian environment" indicator demonstrates the worst performance. **Table 7** also indicates that the accessibility to rail transit stations within *Wuchang District* ranges from grade 4 to grade 5.

In general, the accessibility to rail transit stations in *Wuchang District* is at an acceptable level, but not satisfactory, and much space exists for improvement. The favorable social and economic conditions in *Wuchang District* provide a conducive environment for the development of rail transit and the government has undertaken efforts to construct and promote the rail transit system. However, the government appears to lack attention towards the construction and updating of infrastructure and access tools that are necessary for the efficient functioning of the rail transit system. As a result, residents continue to face difficulties in accessing the rail transit stations. Consequently, it is recommended that the *Wuchang District* shift its urban planning priorities from constructing novel rail routes to enhancing and modernizing pre-existing fundamental transportation infrastructure，such as improving the pedestrian environment and improving the quality of roads.

It is worth noting that assessing the accessibility to rail transit stations is a complex endeavor that currently lacks universally accepted standard measurement procedures and methods. Existing studies on the accessibility to rail transit stations, including this study, differ in terms of data sources, measurement indicators, and measurement time points, and the measurements vary as a result. Therefore, direct comparison of the strengths and weaknesses of the measurement results becomes challenging, as exemplified in the subsequent aspects：

(1) *Diverse sources of data*: The quantification of the accessibility to rail transit stations is contingent upon the use of data obtained from diverse sources, including transit agencies, geographic databases, census data, and surveys. Discrepancies in measurements collected through different methods might arise due to variations in data sources, data quality, and data gathering processes, so impacting their comparability.

(2) *Different indicators measured*: Various studies have different focuses and identify different indicators for evaluating the accessibility to rail transit stations. For example, Giannopoulos [7] considered the average time required

for residents to reach a station via all available modes of transportation, while Schlossberg and Brown [8] limited travel modes to walking, and Li et al. [10] focused on the time cost, fare cost, and fatigue cost of all travel modes. Differences in measurement indicators pose a challenge in directly comparing measurements, as they cover different aspects of the accessibility to rail transit stations.

(3) *Different measurement time points*: The accessibility to rail transit stations in urban areas is subject to temporal variations influenced by variables such as enhancements in transportation infrastructure, modifications in transit services, fluctuations in population density, and urban growth. If the two measurement procedures were executed at distinct points in time, their outcomes would only reflect the accessibility to rail transit stations at their respective time points, thus diminishing the significance of the direct comparison.

Even though, it is impossible to visually compare the strengths and weaknesses of the measurements of different studies, compared with the existing research, the evaluation method for the accessibility to rail transit stations proposed in this study has obvious advantages, which are reflected in the following:

(1) Previous research focuses on examining the micro-factors affecting the accessibility to rail transit stations, including transportation infrastructure, travel modes, and traveler characteristics, etc. However, it must be recognized that the accessibility to rail transit stations within urban areas is also influenced at the macro level by a wider range of external forces, such as government policies and resident consumption concepts. This study identifies the factors influencing the accessibility to rail transit systems through the PEST analysis, and accordingly establishes a comprehensive indicator system for assessing the accessibility to rail transit stations in urban areas. The findings may help urban managers to comprehensively understand the influence of macro external factors on the accessibility to rail transit stations.

(2) Existing research mainly concerns individual rail transit stations or lines, and the findings can help urban managers optimize the layout of specific stations. In fact, when planning the construction of rail transit, urban managers are required to consider the overall situation of the rail transit network within the region, rather than limiting their attention to individual stations or specific lines. This study evaluates the comprehensive accessibility to rail transit stations within urban areas, which can provide valuable insights for urban managers to understand the current status of rail transit development within the region, thus facilitating the formulation of targeted development plans.

(3) Existing measurements of the accessibility to rail transit stations depend on the quality of the survey data, and the data collection process directly affects the accuracy of the measurement results. In this study, we introduce a

collective opinion generation paradigm that utilizes expert knowledge to avoid the impact of insufficient and low-quality objective data on measurement results. In addition, we employ PDFs to characterize expert opinions to reduce their inherent imprecision and incorporate fairness concerns into the collective opinion generation paradigm to reduce the likelihood of experts undermining decisions due to perceived unfairness. Together, these two measures improve the reliability and accuracy of the final measurements.

6. Conclusion

The urban rail transit system is an effective tool for solving urban transport problems, but it works effectively only if enough commuters utilize it. The accessibility to rail transit stations is a key factor in determining whether residents choose to use the rail transit system. This study identifies and determines the impact factors of the accessibility to rail transit stations in urban areas through PEST analysis and constructs an evaluation indicator system. We introduce the collective opinion generation paradigm, and construct a bi-objective optimization model for aggregating expert opinions based on the consideration of expert fairness concerns, to obtain the collective evaluation results of each indicator, followed by QA aggregation to generate the accessibility evaluation results.A small-scale empirical study is conducted to demonstrate the feasibility of the proposed methodology by applying it to assess the accessibility to rail transit stations in the *Wuchang district* of *Wuhan*. The assessment results indicate that the accessibility to rail transit stations in *Wuchang District* is between "average" and "slightly high", and also suggest that improving transportation infrastructure is a more effective way to improve the accessibility to rail transit stations in *Wuchang District* than building new rail transit lines.

The contributions of the article can be summarized as follows:

(1) Identifying the external influences on the accessibility to rail transit stations in urban areas from a macroscopic perspective through the PEST analysis, which bridges the gap of existing studies focusing on micro factors while ignoring the macroscopic external environment.

(2) Innovatively adopting the collective opinion generation paradigm to assess the accessibility to rail transit stations, which effectively solves the challenge of insufficient objective data.

(3) Incorporating experts' fairness concerns about the decision-making process into the collective opinion generation paradigm to improve the objectivity and reliability of collective opinions.

(4) The results of the small-scale exploratory empirical study can provide a reference for urban managers in Wuchang District, Wuhan, to formulate rail transit development plans.

The limitations of the proposed approach in this study include:

(1) The computational process of the bi-objective optimization model is complex and requires certain programming knowledge, which may affect the widespread application of the method.

(2) All expert opinions are assumed to remain fixed, but in reality expert opinions may change over time.

(3) Only considering the impact of expert fairness concerns on decision making, ignoring the impact of other behavioral factors.

(4) The setting of optimization objectives leads to a reduction in the solution space, and the resulting collective opinion may deviate from the optimal solution.

Our forthcoming efforts will be centered on the following aspects:

(1) Conducting a large-scale public survey to further validate the effectiveness of using the collective opinion generation paradigm to measure the accessibility to rail transit stations.

(2) Deeply analyzing the conflict between reaching consensus and realizing the optimal solution, and searching for a suitable trade-off solution.

(3) Attempting to construct a dynamic collective opinion generation framework to cope with the change of expert opinions over time.

(4) Considering the influence of other behavioral factors on the decision-making process.

Acknowledgements

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References

[1] L. Zhao, L. Shen, The impacts of rail transit on future urban land use development: A case study in Wuhan, China, *Transport Policy* 81 (2019) 396-405.

[2] J.P. Chang, Z.S. Chen, Z.J. Wang, L. Jin, W. Pedrycz, L. Martínez, M.J. Skibniewski, Assessing spatial synergy between integrated urban rail transit system and urban form: A BULI-based MCLSGA model with the wisdom of crowds, *IEEE Transactions on Fuzzy Systems* 31 (2) (2023) 434-448.

[3] S. Kirtonia, Y. Sun, Evaluating rail transit's comparative advantages in travel cost and time over taxi with open data in two U.S. cities, *Transport Policy* 115 (2022) 75-87.

[4] Q. Du, Y. Zhou, Y. Huang, Y. Wang, L. Bai, Spatiotemporal exploration of the non-linear impacts of accessibility on metro ridership, *Journal of Transport Geography* 102 (2022) 103380.

[5] H.-W. Wu, J. Zhen, J. Zhang, Urban rail transit operation safety evaluation based on an improved CRITIC method and cloud model, *Journal of Rail Transport Planning & Managemen*t 16 (2020) 100206.

[6] A. Malekzadeh, E. Chung, A review of transit accessibility models: Challenges in developing transit accessibility models, *International Journal of Sustainable Transportation* 14 (10) (2019) 733-748.

[7] G.A. Giannopoulos, G.A. Boulougaris, Definition of accessibility for railway stations and its impact on railway passenger demand, *Transportation Planning and Technology* 13 (2) (1989) 111-120.

[8] M. Schlossberg, N. Brown, Comparing transit-oriented development sites by walkability indicators, *Transportation Research Record* 1887 (1) (2004) 34-42.

[9] R. Yang, H. Yan, W. Xiong, T. Liu, The study of pedestrian accessibility to rail transit stations based on KLP model, *Procedia - Social and Behavioral Sciences* 96 (2013) 714-722.

[10] L. Li, H. Ren, S. Zhao, Z. Duan, Y. Zhang, A. Zhang, Two dimensional accessibility analysis of metro stations in Xi'an, China, *Transportation Research Part A: Policy and Practice* 106 (2017) 414-426.

[11] M. Alfonzo, M.G. Boarnet, K. Day, T. McMillan, C.L. Anderson, The relationship of neighbourhood built environment features and adult parents' walking, *Journal of Urban Design* 13 (1) (2008) 29-51.

[12] S. Bree, D. Fuller, E. Diab, Access to transit? Validating local transit accessibility measures using transit ridership, *Transportation Research Part A: Policy and Practice* 141 (2020) 430-442.

[13] W.G. Hansen, How Accessibility Shapes Land Use, *Journal of the American Institute of Planners* 25 (2) (1959) 73-76.

[14] M.Q. Dalvi, K.M. Martin, The measurement of accessibility: Some preliminary results, *Transportation* 5 (1) (1976) 17-42.

[15] G. Leonardi, Optimum facility location by accessibility maximizing, *Environment and Planning A: Economy and Space* 10 (11) (1978) 1287-1305.

[16] J.W. Weibull, On the numerical measurement of accessibility, *Environment and Planning A: Economy and Space* 12 (1) (1980) 53-67.

[17] A.M. El-Geneidy, Levinson, D. M. , Access to destinations： Development of accessibility measures, Retrieved from *the University of Minnesota Digital Conservancy* MN/RC-2006-16 (2006) 1-124.

[18] C. Bhat, S. Handy, K. Kockelman, H. Mahmassani, Q. Chen, L. Weston, Development of an urban accessibility index: Literature review, (2000).

[19] A.T. Murray, R. Davis, R.J. Stimson, L. Ferreira, Public transportation access, *Transportation Research Part D: Transport and Environment* 3 (5) (1998) 319-328.

[20] M.A. Foda, A.O. Osman, Using GIS for measuring transit stop accessibility considering actual pedestrian road network, *Journal of Public Transportation* 13 (4) (2010) 23-40.

[21] M.S. Hasnine, A. Graovac, F. Camargo, K.N. Habib, A random utility maximization (RUM) based measure of accessibility to transit: Accurate capturing of the first-mile issue in urban transit, *Journal of Transport Geography* 74 (2019) 313-320.

[22] K.T. Geurs, B. van Wee, Accessibility evaluation of land-use and transport strategies: review and research directions, *Journal of Transport Geography* 12 (2) (2004) 127-140.

[23] G.R. Bivina, A. Gupta, M. Parida, Walk accessibility to metro stations: An analysis based on Meso- or Micro-scale built environment factors, *Sustainable Cities and Society* 55 (2020).

[24] Z.-S. Chen, Z. Zhu, Z.-J. Wang, Y. Tsang, Fairness-aware large-scale collective opinion generation paradigm: A case study of evaluating blockchain adoption barriers in medical supply chain, *Information Sciences* 635 (2023) 257-278.

[25] C. Ji, X. Lu, W. Zhang, A biobjective optimization model for expert opinions aggregation and its application in group decision making, *IEEE Systems Journal* 15 (2) (2021) 2834-2844.

[26] C. Zuheros, E. Martinez-Camara, E. Herrera-Viedma, F. Herrera, Crowd decision making: Sparse representation guided by sentiment analysis for leveraging the wisdom of the crowd, *IEEE Transactions on Systems, Man, and Cybernetics: Systems* (2022) 1-11.

[27] C. Sáenz-Royo, F. Chiclana, E. Herrera-Viedma, Intentional bounded rationality methodology to assess the quality of decision-making approaches with latent alternative performances, *Information Fusion* 89 (2023) 254-266.

[28] R.T. Clemen, R.L. Winkler, Combining probability distributions from experts in risk analysis, *Risk Analysis* 19 (2) (1999) 187-203.

[29] H.J. Einhorn, Expert judgment: Some necessary conditions and an example, *Journal of applied psychology* 59 (5) (1974) 562.

[30] A. O’Hagan, Expert knowledge elicitation: Subjective but scientific, *The American Statistician* 73 (sup1) (2019)

69-81.

[31] M. Kynn, The ‘heuristics and biases’ bias in expert elicitation, *Journal of the Royal Statistical Society*: Series A (Statistics in Society) 171 (1) (2008) 239-264.

[32] S. McClean, B. Scotney, M. Shapcott, Aggregation of imprecise and uncertain information in databases, *IEEE Transactions on Knowledge and Data Engineering* 13 (6) (2001) 902-912.

[33] Z.-S. Chen, L. Martínez, J.-P. Chang, X.-J. Wang, S.-H. Xionge, K.-S. Chin, Sustainable building material selection: A QFD- and ELECTRE III-embedded hybrid MCGDM approach with consensus building, *Engineering Applications of Artificial Intelligence* 85 (2019) 783-807.

[34] R.M. Rodriguez, L. Martinez, F. Herrera, Hesitant fuzzy linguistic term sets for decision making, *IEEE Transactions on Fuzzy Systems* 20 (1) (2012) 109-119.

[35] Z.-S. Chen, K.-S. Chin, Y.-L. Li, Y. Yang, Proportional hesitant fuzzy linguistic term set for multiple criteria group decision making, *Information Sciences* 357 (2016) 61-87.

[36] Z. Wu, J. Xu, Possibility distribution-based approach for MAGDM with hesitant fuzzy linguistic information, *IEEE Transactions on Cybernetics* 46 (3) (2016) 694-705.

[37] R. Mesiar, S. Borkotokey, L. Jin, M. Kalina, Aggregation under uncertainty, *IEEE Transactions on Fuzzy Systems* 26 (4) (2018) 2475-2478.

[38] L. Jin, R. Mesiar, S. Borkotokey, M. Kalina, Certainty aggregation and the certainty fuzzy measures, *International Journal of Intelligent Systems* 33 (4) (2018) 759-770.

[39] F. Herrera, L. Martinez, A 2-tuple fuzzy linguistic representation model for computing with words, *IEEE Transactions on Fuzzy Systems* 8 (6) (2000) 746-752.

[40] M. Stone, The opinion pool, *The Annals of Mathematical Statistics* 32 (4) (1961) 1339-1342.

[41] C. Genest, J.V. Zidek, Combining probability distributions: A critique and an annotated bibliography, *Statistical Science* 1 (1) (1986) 114-135.

[42] Z.-S. Chen, Z. Zhu, X.-J. Wang, F. Chiclana, E. Herrera-Viedma, M.J. Skibniewski, Multiobjective optimization-based collective opinion generation with fairness concern, *IEEE Transactions on Systems, Man, and Cybernetics: Systems 53(9)* (2023) 5729-5741.

[43] E.A.C. Thomas, B.H. Ross, On appropriate procedures for combining probability distributions within the same family, *Journal of Mathematical Psychology* 21 (2) (1980) 136-152.

[44] K.C. Lichtendahl, Y. Grushka-Cockayne, R.L. Winkler, Is it better to average probabilities or quantiles?, *Management Science* 59 (7) (2013) 1594-1611.

[45] R.L. Winkler, The consensus of subjective probability distributions, *Management Science* 15 (2) (1968) B61-B75.

[46] Y. Ju, A new method for multiple criteria group decision making with incomplete weight information under linguistic environment, *Applied Mathematical Modelling* 38 (21) (2014) 5256-5268.

[47] J.C. Bezdek, B. Spillman, R. Spillman, A fuzzy relation space for group decision theory, *Fuzzy Sets and Systems* 1 (4) (1978) 255-268.

[48] B. Spillman, R. Spillman, J. Bezdek, A fuzzy analysis of consensus in small groups, *Fuzzy sets: Theory and applications to policy analysis and information systems, Springer*, 1980, pp. 291-308.

[49] J. Kacprzyk, M. Fedrizzi, A 'human-consistent' degree of consensus based on fuzzy login with linguistic quantifiers, *Mathematical Social Sciences* 18 (3) (1989) 275-290.

[50] G. Gong, X. Zhou, Q. Zha, Managing fairness and consensus based on individual consciousness of preventing manipulation, *Information Fusion* (2023) 102047.

[51] Y. Dong, J. Xu, Dong, Consensus building in group decision making, *Springer*, 2015.

[52] D. Ben-Arieh, T. Easton, Multi-criteria group consensus under linear cost opinion elasticity, *Decision Support Systems* 43 (3) (2007) 713-721.

[53] Y. Dong, Y. Xu, H. Li, B. Feng, The OWA-based consensus operator under linguistic representation models using position indexes, *European Journal of Operational Research* 203 (2) (2010) 455-463.

[54] G. Zhang, Y. Dong, Y. Xu, H. Li, Minimum-cost consensus models under aggregation operators, *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 41 (6) (2011) 1253-1261.

[55] Y. Lu, Y. Xu, E. Herrera-Viedma, Y. Han, Consensus of large-scale group decision making in social network: the minimum cost model based on robust optimization, *Information Sciences* 547 (2021) 910-930.

[56] Z. Gong, H. Zhang, J. Forrest, L. Li, X. Xu, Two consensus models based on the minimum cost and maximum return regarding either all individuals or one individual, *European Journal of Operational Research* 240 (1) (2015) 183-192.

[57] H. Zhang, G. Kou, Y. Peng, Soft consensus cost models for group decision making and economic interpretations, *European Journal of Operational Research* 277 (3) (2019) 964-980.

[58] H.-S. Lee, Optimal consensus of fuzzy opinions under group decision making environment, *Fuzzy Sets and*

Systems 132 (3) (2002) 303-315.

[59] H. Hsi-Mei, C. Chen-Tung, Aggregation of fuzzy opinions under group decision making, *Fuzzy Sets and Systems 79 (3) (1996) 279-285*.

[60] D. Ben-Arieh, C. Zhifeng, Linguistic-labels aggregation and consensus measure for autocratic decision making using group recommendations, *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 36 (3) (2006) 558-568.

[61] X. Liu, A. Ghorpade, Y.L. Tu, W.J. Zhang, A novel approach to probability distribution aggregation, *Information Sciences* 188 (2012) 269-275.

[62] Z.-S. Chen, M.-D. Zhou, K.-S. Chin, A. Darko, X.-J. Wang, W. Pedrycz, Optimized decision support for BIM maturity assessment, *Automation in Construction* 149 (2023) 104808.

[63] J.S. Adams, Inequity in social exchange, in *Advances in experimental social psychology*, 2 (1965) 267-299

[64] C. Fu, K. Zhou, M. Xue, Fair framework for multiple criteria decision making, *Computers & Industrial Engineering* 124 (2018) 379-392.

[65] F. Jing, X. Chao, Fairness concern: An equilibrium mechanism for consensus-reaching game in group decision-making, *Information Fusion* 72 (2021) 147-160.

[66] J. Du, S. Liu, Y. Liu, A limited cost consensus approach with fairness concern and its application, *European Journal of Operational Research* 298 (1) (2022) 261-275.

[67] G. Gong, K. Li, Q. Zha, A maximum fairness consensus model with limited cost in group decision making, *Computers & Industrial Engineering* 175 (2023).

[68] Y. Zhao, Z. Gong, G. Wei, R. Słowiński, Consensus modeling with interactive utility and partial preorder of decision-makers, involving fairness and tolerant behavior, *Information Sciences* 638 (2023).

[69] S. Mavoa, K. Witten, T. McCreanor, D. O'Sullivan, GIS based destination accessibility via public transit and walking in Auckland, New Zealand, *Journal of Transport Geography* 20 (1) (2012) 15-22.

[70] D. Salon, Neighborhoods, cars, and commuting in New York City: A discrete choice approach, *Transportation Research Part A: Policy and Practice* 43 (2) (2009) 180-196.

[71] L. Frank, M. Bradley, S. Kavage, J. Chapman, T.K. Lawton, Urban form, travel time, and cost relationships with tour complexity and mode choice, *Transportation* 35 (1) (2008) 37-54.

[72] E. Iacovidou, J. Busch, J. Hahladakis, H. Baxter, K. Ng, B. Herbert, A parameter selection framework for

sustainability assessment, *Sustainability* 9 (9) (2017) 1497.

[73] S.-G. Lee, S.H. Chae, K.M. Cho, Drivers and inhibitors of SaaS adoption in Korea, *International Journal of Information Management* 33 (3) (2013) 429-440.

[74] J. Cox, The higher education environment driving academic library strategy: A political, economic, social and technological (PEST) analysis, *The Journal of Academic Librarianship* 47 (1) (2021) 102219.

[75] J. Cho, Y. Cheon, J.W. Jun, S. Lee, Digital advertising policy acceptance by out-of-home advertising firms: a combination of TAM and TOE framework, *International Journal of Advertising* 41 (3) (2022) 500-518.

[76] H.O. Awa, O. Ukoha, B.C. Emecheta, Using T-O-E theoretical framework to study the adoption of ERP solution, *Cogent Business & Management* 3 (1) (2016) 1196571.

[77] F. Cruz-Jesus, A. Pinheiro, T. Oliveira, Understanding CRM adoption stages: empirical analysis building on the TOE framework, *Computers in Industry* 109 (2019) 1-13.

[78] M.G. Sobhani, M.N. Imtiyaz, M.S. Azam, M. Hossain, A framework for analyzing the competitiveness of unconventional modes of transportation in developing cities, *Transportation Research Part A: Policy and Practice* 137 (2020) 504-518.

[79] J. Wang, M.-P. Kwan, W. Cao, Y. Gong, L. Guo, Y. Liu, Assessing changes in job accessibility and commuting time under bike-sharing scenarios, *Transportmetrica A: Transport Science* (2022) 1-17.

[80] L. Li, X. Li, S. Yu, X. Li, J. Dai, Unbalanced usage of free-floating bike sharing connecting with metro stations, *Physica A: Statistical Mechanics and its Applications* 608 (2022) 128245.

[81] M. Meng, P. Koh, Y. Wong, Influence of socio-demography and operating streetscape on last-mile mode choice, *Journal of Public Transportation* 19 (2) (2016) 38-54.

[82] R.E. Baldwin, P. Martin, Chapter 60 - Agglomeration and regional growth, in *Handbook of Regional and Urban Economics*, 4, (2004) 2671-2711.

[83] S. Sarkar, P. Phibbs, R. Simpson, S. Wasnik, The scaling of income distribution in Australia: Possible relationships between urban allometry, city size, and economic inequality, *Environment and Planning B: Urban Analytics and City Science* 45 (4) (2016) 603-622.

[84] O.D. Cardozo, J.C. García-Palomares, J. Gutiérrez, Application of geographically weighted regression to the direct forecasting of transit ridership at station-level, *Applied Geography* 34 (2012) 548-558.

[85] S. Li, D. Lyu, X. Liu, Z. Tan, F. Gao, G. Huang, Z. Wu, The varying patterns of rail transit ridership and their

relationships with fine-scale built environment factors: Big data analytics from Guangzhou, *Cities* 99 (2020) 102580.

[86] L. Redman, M. Friman, T. Gärling, T. Hartig, Quality attributes of public transport that attract car users: A research review, *Transport Policy* 25 (2013) 119-127.

[87] C.P. Tribby, P.A. Zandbergen, High-resolution spatio-temporal modeling of public transit accessibility, *Applied Geography* 34 (2012) 345-355.

[88] G.A. Miller, The magical number seven, plus or minus two: Some limits on our capacity for processing information, *Psychological Review* 63 (1956) 81-97.

[89] R. Lipshitz, O. Strauss, Coping with uncertainty: A naturalistic decision-making analysis, *Organizational Behavior and Human Decision Processes* 69 (2) (1997) 149-163.

[90] E. Fehr, K.M. Schmidt, A theory of fairness, competition, and cooperation, *The Quarterly Journal of Economics* 114 (3) (1999) 817-868.

[91] M. Rabin, Incorporating fairness into game theory and economics, *The American Economic Review* 83 (5) (1993) 1281-1302.

[92] J. Butler, D.J. Morrice, P.W. Mullarkey, A multiple attribute utility theory approach to ranking and selection, *Management Science* 47 (6) (2001) 800-816.

[93] A. Konak, D.W. Coit, A.E. Smith, Multi-objective optimization using genetic algorithms: A tutorial, *Reliability Engineering & System Safety* 91 (9) (2006) 992-1007.

[94] M. Cai, Y. Lin, B. Han, C. Liu, W. Zhang, On a simple and efficient approach to probability distribution function aggregation, *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 47 (9) (2016) 2444-2453.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: