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Advances in Large-scale group decision making for sustainability

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The Thesis entitled *Advances in Large-scale group decision making for sustainability*, presented by Miss Shifan He to obtain the PhD degree in Computer Science, has been carried out in the Computer Science Department of the University of Jaén with the supervisors Dr. Luis Martínez López and Dr. Diego García Zamora. To be evaluated, this research memory is presented as a set of published articles, according to Article 23, point 3, Regulation of Doctoral Studies of the University of Jaén, approved in February 2012.

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Contents

Chapter 1

Introduction

In this chapter, we will provide an overview of the motivation and objectives that drive our research, as well as present the structure of our memory.

1.1. Motivation

Sustainable development refers to a concept and approach that aims to meet the needs of the present generation while ensuring that future generations can meet their own needs [63]. It recognizes the importance of pursuing economic and social development in a manner that minimizes negative impacts on the environment, making sustainability a fundamental consideration across all countries. The Sustainable Development Goals (SDGs) introduced by the Agenda 2030 [1] serve as a global blueprint for fostering peace, justice, and prosperity on a healthy planet. To drive sustainable development forward, it is essential to undertake various efforts, such as investing in renewable energy and green technologies. However, evaluating the effectiveness of sustainability projects is necessary due to their complexity, long-term implications, and inherent uncertainties. In this regard, Multi-Criteria Decision-Making (MCDM) offers a practical tool for conducting sustainability evaluations and decisions, taking into account different criteria and factors.

As decision-making situations become increasingly complex, individual decision-making in MCDM may struggle to consider all relevant information, leading to potential biases and the possibility of arriving at unreasonable and unreliable conclusions. To address this challenge, Group Decision-Making (GDM) methods have been widely studied and adopted. Such methods refer to the process of making decisions collectively, involving several individuals who come together to analyze a problem, evaluate alternatives, and make a joint decision [33, 51, 66]. However, traditional GDM primarily focuses on small groups of experts. Many real-world problems, particularly those associated with sustainability projects that hold a significant impact on economic, social, and environmental aspects, require the involvement of

[1] https://sdgs.un.org/2030agenda

multiple experts from diverse fields. Furthermore, advancements in science and technology have facilitated easier connectivity among experts. Consequently, the demand for Large-Scale Group Decision-Making (LSGDM) has become more pronounced [19, 34, 44].

In LSGDM, experts usually have different interests, knowledge backgrounds and thinking patterns, which can lead to the generation of different, conflicting, or polarized opinions [55]. To ensure the effectiveness of LSGDM, it is essential to employ a Consensus Reaching Process (CRP) before evaluating and selecting the optimal alternative for LSGDM problems. The CRP based on social networks typically encompasses the following three key steps [6] (as shown in Fig.A.1):

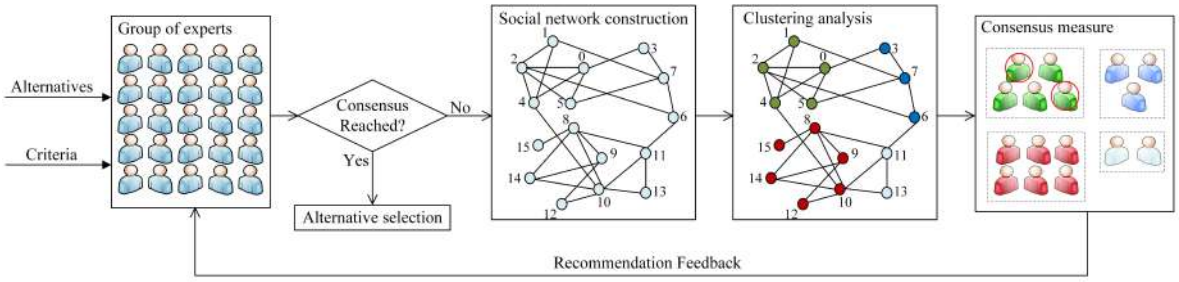

Figure 1.1: Steps in Consensus Reaching Process based on social network

- *Social network construction.* In practice, it is common for experts involved in LSGDM problems to have existing relationships as stakeholders or collaborators. This implies the presence of social connections among them [44], and it is worth noting that individuals' opinions can be influenced by their social networks or friends [72]. Consequently, LSGDM within a social network context has gained significant importance and garnered increasing attention. Preference similarity relations and trust relations are two commonly utilized foundations for constructing a social network in LSGDM [6]. However, existing researches often construct social networks solely based on either similarity [27, 50, 64] or on trust [1, 39]. To enhance the quality of social network construction in LSGDM, it is crucial to consider both preference similarity and trust relations.

- *Clustering analysis.* It allows clustering a group of experts into different classes. It can not only reduce the complexity and cost of LSGDM methodologies, but also helps to identify common patterns of opinion [59]. To date, numerous clustering methods have been proposed from various perspectives, such as alternative ranking-based clustering method [46], similarity measure-based clustering method [24], k-means clustering method [74] and so on. Among these methods, Louvain method [5] stands out as one of the most effective community discovery algorithms [37]. It demonstrates the ability to rapidly and accurately cluster large-scale networks into several distinct communities. This characteristic makes it particularly well-suited for LSGDM.

- *Consensus models construction.* Consensus, defined as the agreement reached by all experts on feasible alternatives [71], is essential to ensure that the decision results are acknowledged and accepted by all participants. Typically, consensus models involve two stages: consensus measurement and feedback recommendation. The consensus measurement stage aims to determine the level of consensus among the experts using a consensus measure [40, 84]. In this stage, a consensus threshold is predefined to evaluate whether consensus has been achieved [18]. However, these methods often classify experts' preferences into two categories: reaching consensus or not reaching consensus. It is worth noting that some experts who did not reach consensus in one iteration may reach consensus in subsequent iterations, even without adjusting their opinions.

With the proliferation of Web 2.0, the preference information of LSGDM could not only be obtained by experts' subjective judgements, but also be automatically collected from online reviews. Over recent years, Web 2.0 technologies have changed the way of how people access and disseminate information. Not only does it offer users a platform to retrieve information, but it also empowers them to generate a vast array of online reviews. These online reviews obtained from the web contain information from real-world users/experts in large scale mode, which can significantly aid in decision-making processes. Consequently, Online Reviews-based Decision-Making (ORDM) has garnered increasing attention [8, 15, 47]. Generally speaking, ORDM encompasses three phases, as illustrated in Fig. A.2:

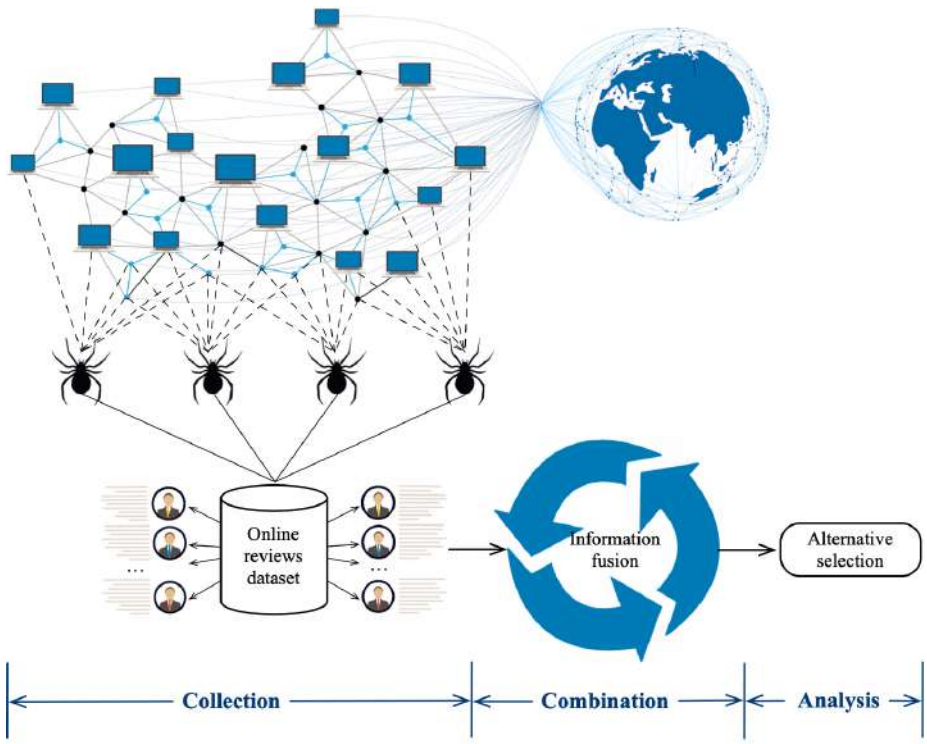

Figure 1.2: General scheme of ORDM

- *Collection.* Online reviews encompass heterogeneous information, that could include text, images, videos, ratings and so on. Among these forms, online rating reviews and online textual reviews are the most commonly used types, and extensive efforts have been dedicated to utilizing them. Online rating reviews typically employ a simple five-star rating system to evaluate products, services, or events, providing a straightforward and user-friendly approach [85]. On the other hand, online textual reviews allow users to express their opinions in greater detail through written text [26]. Previous studies have primarily focused on utilizing either online rating reviews [16] or online textual reviews [12]. However, it is important to note that online rating reviews may limit users' freedom of speech and lack specific comment details about the reviewed items; while online textual reviews can sometimes excessively emphasize specific aspects that users like or dislike, leading to a potential deviation between their expressed views and their true opinions.

- *Combination.* The qualitative and massive nature of online reviews presents challenges in utilizing them directly for decision-making. Therefore, it is necessary to combine online reviews into a single collective preference that summarizes the reviews of all individual users. Fuzzy sets theory [30] is commonly employed to address this need, such as transforming online reviews into probabilistic linguistic term sets [45], picture fuzzy sets [28], discrete percentage distribution [16], linguistic assessments [85] and so on. However, two key problems remain un-solved. First, due to differences in users' educational backgrounds, experiences, and habits, not all comments provided are complete. Unfortunately, existing methods often overlook the incompleteness of the collected reviews. Second, the extant methods primarily rely on statistical techniques, potentially neglecting the opinions of individual users.

- *Analysis.* When it comes to managing online reviews, decision-makers often pay special attention to certain criteria. Therefore, it is crucial to incorporate MCDM methods into the analysis phase of ORDM processes. These methods facilitate the evaluation of alternatives based on various criteria and aid in identifying the most suitable option [25]. Several analysis methods are employed in ORDM. For instance, Liang et al. [42] utilized a fuzzy synthesis operator for comprehensive evaluation, while Liu et al. [48] ranked alternatives using the intuitionistic fuzzy weighted average operator. Liu and Teng [44] proposed the probabilistic linguistic TODIM method for comparing alternatives, and Fan et al. [16] employed the PROMETHEE-II method to determine the ranking of candidate products. However, fuzzy operator-based MCDM methods often lack theoretical or practical justification [54], while other existing MCDM methods used in ORDM researches face challenges in effectively handling uncertain and incomplete information.

In summary, this research aims to utilize several MCDM methods to drive sustainable

development, particularly through the application of the LSGDM framework. As shown in Fig.A.3, although the inclusion of more experts has the potential to enhance the accuracy of sustainability evaluation, it also introduces new characteristics and challenges that must be carefully managed. The research aims to address these emerging characteristics associated with large-scale group experts, develop effective strategies for managing them appropriately, and employ the proposed methods to promote sustainability.

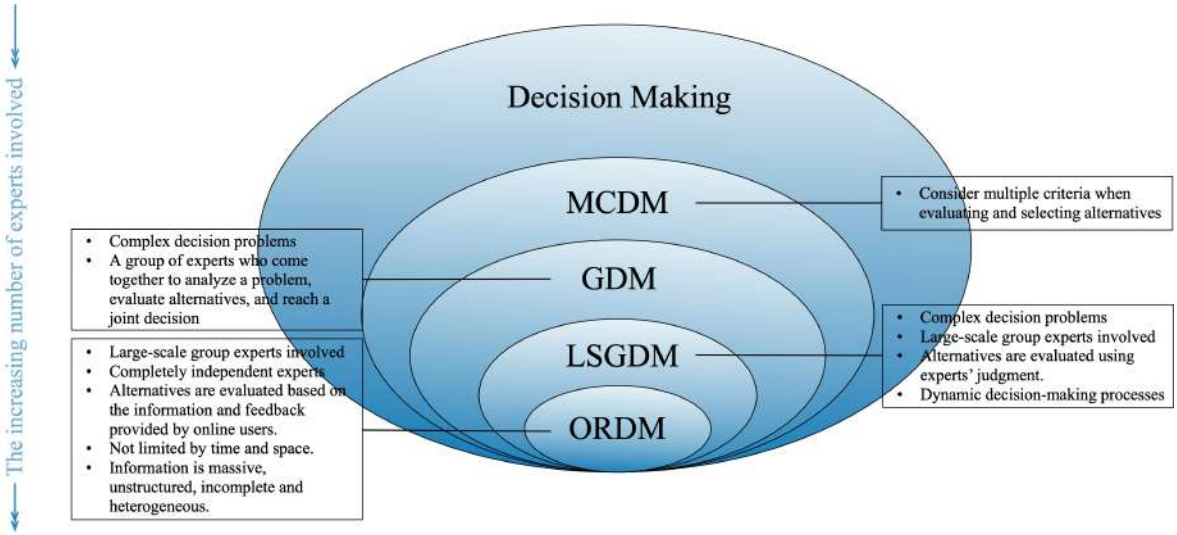

Figure 1.3: Classification of GDM according to the number of experts involved

1.2. Objectives

Considering the inherent limitations in current researches as discussed in the previous section and the goal of promoting sustainable development, the main aim of this doctoral thesis is to utilize some MCDM methods to enhance sustainable development. Specifically, the main aim is developed by three specific objectives:

1. **To consider the bounded rationality of decision-makers in sustainability evaluation**: This objective aims to consider the bounded rational behavior of decision-makers in sustainability evaluation. It is important to acknowledge that humans exhibit bounded rationality, particularly when faced with risk and uncertainty. In the context of sustainability evaluation, decision-makers may not have access to complete information, possess limited cognitive capacity, or face time constraints, all of which can impact their decision-making process. By acknowledging and considering these constraints, a more realistic and effective approach to sustainability evaluation can be developed, leading to well-grounded and reasonable decisions in complex and uncertain sustainability contexts.

2. **To propose a novel CRP for LSGDM in sustainability evaluation**: This objective aims to propose a novel CRP model within LSGDM framework to solve sustainability decision problems. One limitation of most existing CRP models is that they only classify experts into two opposing groups, potentially resulting in over-adjustment. To overcome this limitation, we will propose a novel CRP model based on three-way decision. This model includes acceptance decision (opinions that do not require adjustment), rejection decision (opinions that need adjustment), and non-commitment decision (opinions that do not require adjustment in the current round). By incorporating non-commitment decision-making, our proposed CRP model enhances decision utility and provides improved flexibility compared to other existing methods.

3. **To employ online reviews in sustainability evaluation**: This objective aims to study online reviews-driven decision processes for solving sustainability decision problems. As a form of electronic 'word-of-mouth' communication, online reviews can provide genuine evaluations, experiences, and opinions from a large number of users. Due to their independent and credible characteristics, online reviews are often regarded as a more reliable source of information compared to traditional sources of information. However, the massive, incomplete, heterogeneous nature of online reviews presents challenges when attempting to utilize them directly for decision-making. To handle these challenges, this research explores how to effectively incorporate online reviews into the decision-making process.

1.3. Structure

In compliance with Article 25, point 2, of the current regulations of the Doctoral Studies at the University of Jaén (RD. 99/2011), this doctoral thesis will consist of a collection of articles published or submitted by the PhD student. These articles are intended to fulfill the objectives outlined in the previous section. Specifically, this research comprises four articles, three of which have been published in internationally recognized journals indexed in the Journal Citation Reports (JCR) database, while the remaining one has been submitted to an international journal also indexed in the JCR database.

The structure of this research memory consists of the following chapters:

- Chapter 2: Fundamental concepts related to the doctoral thesis research are presented in this chapter, including the introduction of LSGDM and CRP, a detailed discussion on information form of online reviews, and an explanation of various methods and models that will be used in the doctoral thesis.

- Chapter 3: This chapter will provide a summary of the main proposals presented in this research memory, emphasizing the results and conclusions derived from each of them.

- Chapter 4: The four articles previously mentioned are included in this chapter, along with detailed information about the journals in which they have been published or submitted.
- Chapter 5: The main conclusions of the doctoral thesis have been summarized, and promising future research is introduced.

Chapter 2

Basics Concepts and Methods

The evaluation of sustainability projects plays an important role in the pursuit of SDGs introduced by the Agenda 2030 [1]. Given the intricate nature, long-term consequences, and inherent uncertainties associated with sustainability evaluation, an individual decision-maker or small groups of decision-makers may struggle to comprehensively consider all relevant information related to this type of evaluation. This can potentially introduce biases and yield unreasonable or unreliable decision outcomes. To tackle this challenge, LSGDM presents a valuable approach, involving large number of experts who collaborate to analyze problems and reach decisions [19]. With the widespread adoption of Web 2.0 and the ubiquity of portable devices, decision-related information for sustainability evaluations within LSGDM can now not only rely on subjective judgments from experts but can also be automatically gathered from online reviews. The integration of online reviews into sustainability evaluation decisions can substantially reduce decision costs, enhance decision accuracy, and streamline decision-making processes, all of which contribute significantly to the achievement of SDGs. Additionally, MCDM methods prove to be an invaluable tool for conducting sustainability evaluations. They enable decision-makers to systematically evaluate, compare, and prioritize alternatives based on multiple criteria, a crucial aspect in attaining SDGs and making well-informed and equitable decisions within complex sustainability-related contexts.

Hence, in this chapter, we will provide an introduction to the key concepts and methods that will be used in this doctoral thesis. Firstly, we will introduce the fundamental concepts of LSGDM and Minimum Cost Consensus models. Subsequently, a comprehensive exploration of the information form of online reviews is described. Finally, we will revise several concepts, methods and models, including prospect theory, the TOPSIS method, the evidential reasoning algorithm, and the three-way decision that will be used in our proposals.

[1] https://sdgs.un.org/2030agenda

2.1. Large-Scale Group Decision-Making

As previously mentioned, LSGDM proves to be a valuable tool for sustainability project evaluations. It offers a structured approach to effectively incorporate the individual preferences of a large group of experts when evaluating several alternatives based on multiple criteria [19]. The primary objective is to facilitate the identification of a preferred solution that is acceptable to all involved parties. LSGDM methods exhibit superiorities in several key aspects. Firstly, they enable the inclusion of diverse perspectives, resulting in more comprehensive and informed decisions [57]. Secondly, they enhance the acceptance of decisions as group members feel valued and heard in the decision-making process [75]. Thirdly, LSGDM leverages the collective wisdom of the crowd, leading to enhance performance and better outcomes [60]. Lastly, in the face of increasing complexity in organizations and societies, involving a larger number of experts in decision-making becomes imperative to ensure a comprehensive consideration of all perspectives and interests [58].

Formally, an LSGDM problem consists of:

- a set of experts, $E = \{e_1, \ldots, e_k, \ldots, e_K\}$, who will express their preferences on alternatives under each criterion.
- a set of alternatives, $A = \{a_1, \ldots, a_i, \ldots, a_m\}$, which are possible solutions for the decision problem.
- a set of criteria, $C = \{c_1, \ldots, c_j, \ldots, c_n\}$, which is used to measure the performance of alternatives.

LSGDM is particularly applicable in complex decision-making situations that entail a substantial number of experts, each offering their distinct perspectives, preferences, and interests. This approach has found widespread application in various domains, including public policy-making [65], strategic planning [90], public transportation [88], and environmental impact assessments [49], and so on. The general scheme of LSGDM is depicted in Fig.2.1 [7]. Given the involvement of a large number of experts, LSGDM faces new challenges in the decision-making process compared to traditional group decision-making [59, 19]. These challenges include: (1) Dimension reduction. This aspect aims to reduce the complexity and cost associated with LSGDM problems. (2) Consensus. As the number of participants in LSGDM grows, so does the potential for disagreement. Hence, it becomes crucial to measure consensus among large groups to facilitate reaching mutually agreed-upon solutions. (3) Behavior management. LSGDM needs mechanisms to handle non-cooperative experts and mitigate disharmonious relationships among them, ensuring productive collaboration. (4) Social network analysis. This approach considers the relationships between experts, such as trust, which can influence the decision process. (5) Weighting and aggregation. These aspects pertain to effectively gauging the significance of the experts engaged in the decision-making

process and efficiently fusing their opinions. (6) Cost management. The interaction between experts and the moderator consumes considerable time and resources, requiring careful cost management within LSGDM frameworks.

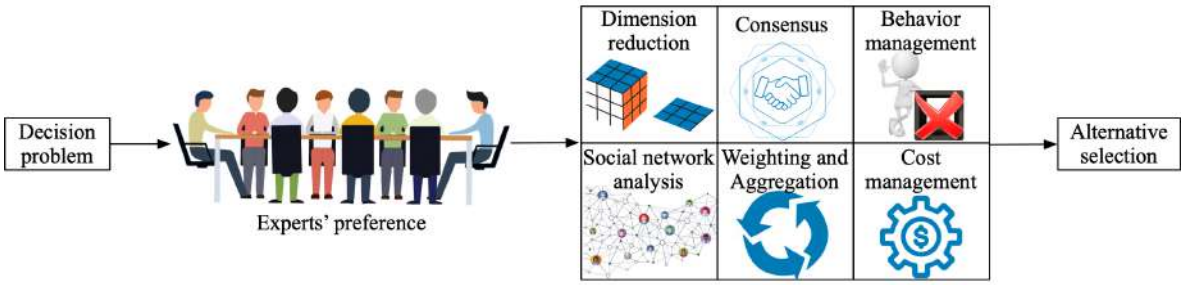

Figure 2.1: General scheme of LSGDM

2.2. Consensus Reaching Processes

Of note, in LSGDM, experts may provide different, conflicting, or polarized opinions due to their different interests, knowledge background, and thinking patterns, especially in the face of critical decisions such as sustainability evaluation [55]. To ensure acceptance of decisions in a LSGDM problem, it is common to incorporate a CRP that aims to mitigate conflicts among participants and soften the differences between their individual opinions [19]. As depicted in Fig.2.2, this process entails a series of interactions and negotiations among experts, facilitated by a moderator. The moderator plays a crucial role in persuading experts to adjust their opinions, which may require investments such as time, resources, or effort [9].

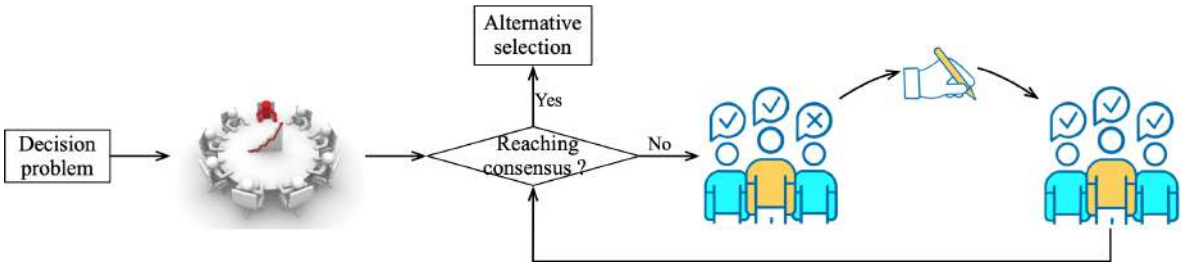

Figure 2.2: General process of CRP

To facilitate consensus reaching processes within LSGDM, moderators often deem it necessary to provide some forms of compensation to the participating experts as a means to encourage them to adjust their opinions [22]. In this endeavor, the coordinator strives to achieve consensus while minimizing associated costs [43]. Besides, in a decision situation in which a large number of experts are involved in a decision-making process, expecting them

to reach a consensus through a discussion process becomes time-consuming, costly and even unrealistic. In such cases, automatic CRP models offer a solution or a guide to a solution by providing a collective opinion automatically.

Among various automatic CRP models, the Minimum Cost Consensus (MCC) models [4] stand out as particularly suitable for solving LSGDM problems. This model offers the advantage of reformulating the consensus process as an optimization problem, enabling the attainment of an agreed solution within a few seconds [20].

Definition 1 ([4]) *Let $E = \{e_1, \ldots, e_K\}$ represent the set of K experts, $O = \{o_1, \ldots, o_K\}$ denote their original assessments, $X = \{x_1, \ldots, x_K\}$ indicate the adjusted assessments, and $C = \{c_1, \ldots, c_K\}$ signify the unit consensus cost associated with adjusting each expert's opinion. Then, the MCC model is defined as follows:*

$$\begin{aligned} &\min \sum_{k=1}^{m} c_k |x_k - o_k| \\ &s.t.\ |x_k - g| \leq \varepsilon, k = 1, \ldots, m. \end{aligned} \tag{2.1}$$

where g represents the group collective opinion and $\varepsilon > 0$ is the maximum acceptable distance of each expert to the collective opinion.

The classic MCC model has been extended in various ways. For example, Zhang et al. [86] investigated the impact of different aggregation operators used to derive the collective opinion on the solution of the optimization problem. Labella et al. [35] explored the inclusion of an additional constraint related to the satisfaction of a specific consensus measurement. More recently, a fuzzy-based formulation for MCC models [21] has emerged as a versatile framework that enables the incorporation of additional constraints and diverse preference structures into MCC models. In general, when experts modify their initial opinions, there are two possible adjustment directions: upward adjustment and downward adjustment. Based on this idea, Cheng et al. [10] proposed a MCC model under the context of asymmetric adjustment costs, where consensus costs are categorized into upward or downward adjustment directions. Furthermore, the MCC model has been integrated with other theories. Zhang et al. [83] conducted a study based on game theory on consensus mechanisms with maximum return modification and minimum cost feedback. Du et al. [14] combined minimum cost conflict risk mitigation with probabilistic linguistic information and developed an innovative failure mode and effect analysis model for risk assessment. Gong et al. [23] introduced a consensus model that operates within a transaction and interaction framework, employing the Choquet integral in conjunction with the MCC model.

2.3. Online reviews as input information in LSGDM

Online reviews provides a valuable information source for sustainability evaluation and LSGDM. Compared with traditional information collection methods which mainly rely on the

subjective judgements of experts in LSGDM. Online reviews present numerous advantages, notably lower cost and enhanced accuracy. The lower cost stems from their ready accessibility on the Internet, which is not constrained by factors like time and space. The enhanced accuracy arises from the freedom they afford users to express their viewpoints, opinions, and recommendations across a wide range of subjects and content, reflecting true opinions based on the large number of reviewers' experience. Additionally, online reviews contribute to the achievement of SDGs from various perspectives. For instance, policymakers can gain insights into the nationwide impact of policy implementation by examining comments from the public in online communities. Similarly, government agencies and electric vehicle manufacturers can understand consumers' perspectives on electric vehicles by analyzing feedback from consumers on automotive review websites.

When it comes to decision-making, online rating reviews and textual reviews emerge as the most frequently utilized sources of information [16, 28, 45]. As depicted in Fig.2.3, when gathering feedback based on specific criteria, one can choose to use either rating reviews or textual reviews. The distinct characteristics of these two information forms are elaborated upon in the subsequent sections.

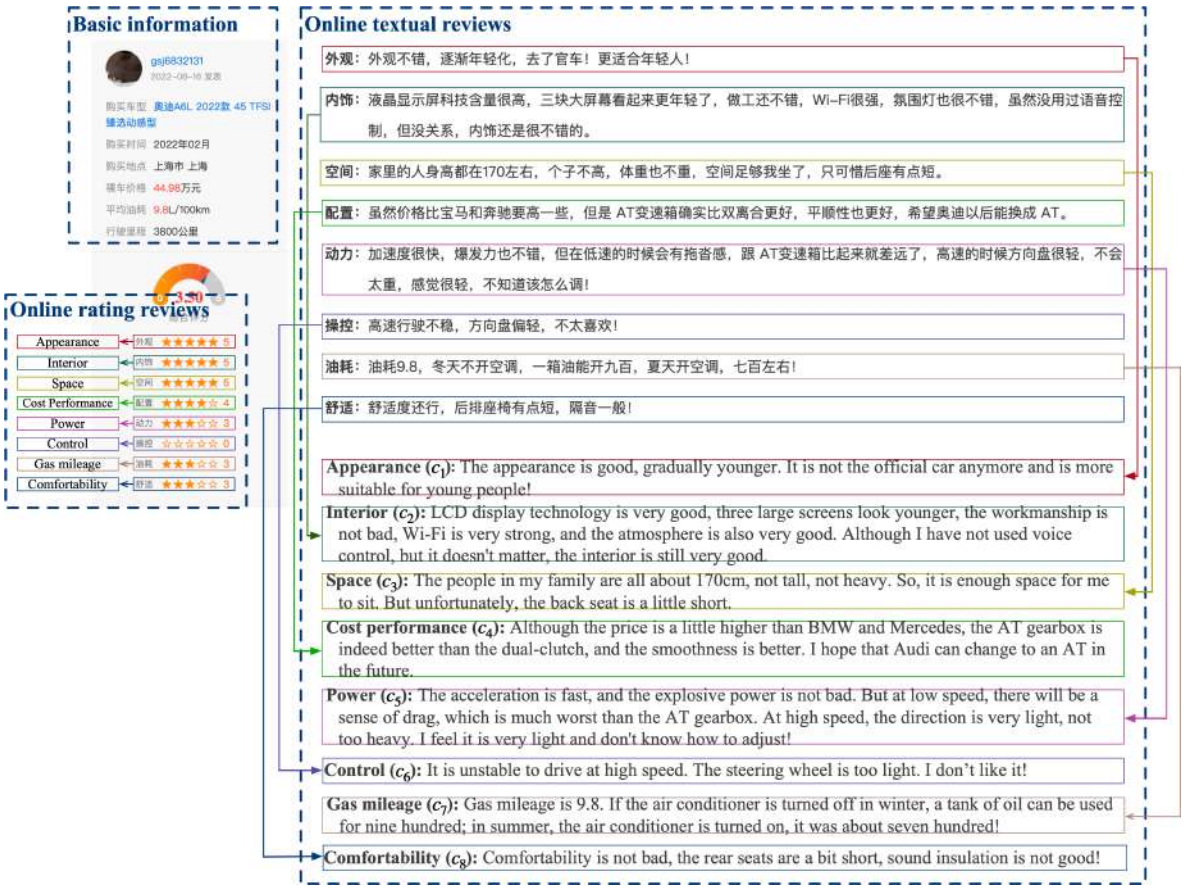

Figure 2.3: An example of online review

2.3.1. Online rating reviews

Online rating reviews are a prevalent form of online review information. They typically employ a Likert five-point scale (as depicted in Fig.2.4), allowing users to rate products, services, or other content on a scale of 1-5 stars based on their personal perceptions and experiences. In this scale, 1 star represents "very dissatisfied", 2 stars signify "slightly dissatisfied", 3 stars denote "neutral", 4 stars indicate "slightly satisfied", and 5 stars represent "very satisfied". A higher rating value signifies better product or service quality, indicating greater satisfaction among reviewers, and vice versa. This straightforward and easily comprehensible form of online rating review information simplifies the collection and analysis process, making it widely employed in e-commerce [16], tourism [85], and various other fields.

Figure 2.4: An example of online rating reviews

2.3.2. Online textual reviews

While online rating reviews offer valuable insights, they have several limitations: (1) The use of a 1-5 star scale in online rating reviews restricts users' freedom of expression. Sometimes, reviewers' true opinions may fall between three and four stars, and this nuance is not

effectively captured. (2) Online rating reviews lack detailed review content, providing only a numerical rating without further elaboration. (3) Not all products or services can be adequately evaluated through online rating review information. While it may be suitable for simple and standardized products or services, it does not offer comprehensive or accurate assessments for complex or highly personalized products or services. To address these limitations and provide further detailed and comprehensive information, the study of online textual reviews becomes crucial. Online textual reviews offer a wealth of detailed content, including users' specific evaluations, strengths and weaknesses, usage experiences, and personal sentiments. This information better reflects users' true thoughts and provides decision-makers with more valuable references and suggestions.

However, it is important to acknowledge that online textual reviews may occasionally be incomplete. This can occur when comments on specific criteria are missing (as depicted in Fig.2.5) or when the sentiment orientation cannot be identified (as depicted in Fig.2.6). In this case, these reviews are still valid, and simply ignoring this information will lead to inaccurate evaluation results.

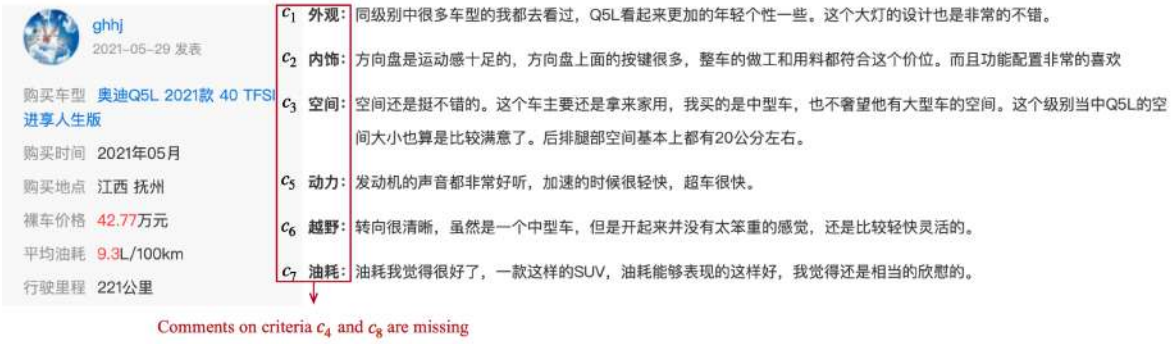

Figure 2.5: Incomplete online textual review caused by missing information

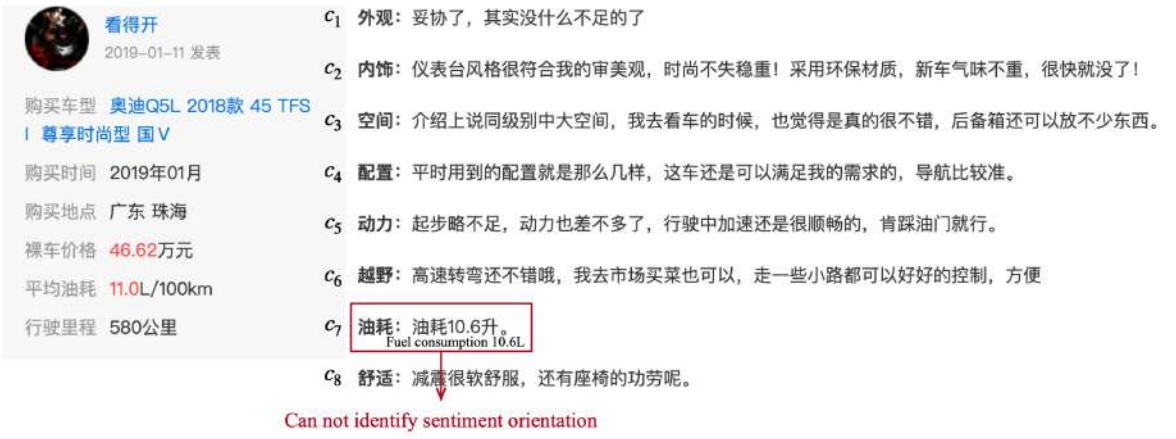

Figure 2.6: Incomplete online textual review caused by unidentified sentiment orientation

In summary, existing research [16, 42, 45, 85] on online reviews-based decision-making faces two significant limitations:

1. Ignoring the incompleteness of online textual reviews. As mentioned above, online textual reviews can be incomplete due to missing information or unidentified sentiment orientation. However, it is crucial to acknowledge that even in these cases, these reviews still hold value and should not be disregarded. Neglecting them can lead to inaccurate evaluation results.

2. Neglecting the utilization of hybrid online reviews: Current researches mainly focuses on either online rating reviews or online textual reviews separately. However, it is important to recognize that both types have their limitations. Online rating reviews may restrict users' freedom of expression and lack specific details about the reviewed items, while online textual reviews can sometimes overly emphasize specific aspects, potentially deviating from users' true opinions. To obtain a more comprehensive understanding of users' perspectives, it is advantageous to utilize hybrid online review information that combines both online rating reviews and online textual reviews simultaneously.

2.4. Methods and models

In this section, we will revise several methods and models that are relevant to our research, including prospect theory, the TOPSIS method, the Evidential Reasoning (ER) algorithm, the three-way decision. These methods and models will assist in sustainability evaluation from the perspective of considering the bounded rational behavior of decision-makers, improving the objectivity of decision results, fusing uncertain information and mitigating the decision-related risk.

2.4.1. Prospect theory

Sustainability projects are extensive, long-term initiatives designed to tackle environmental, social, and economic challenges while fostering sustainable development. The process of sustainability evaluation is crucial for optimizing the benefits and selecting the most appropriate projects. A misjudgment can lead to not only financial losses but also hamper the progress toward achieving SDGs. Hence, these evaluations inherently involve risks. Human beings often exhibit bounded rationality, particularly in the context of risk assessment [31, 87]. To describe this bounded rationality, Kahneman and Tversky [32] developed prospect theory, a behavioral decision theory that builds based on utility theory. It provides a framework for understanding the psychological behavior of decision-makers and has been widely employed to explain the decision behavior of people when facing risk. The main idea of prospect theory is that people's decision is influenced not only by objective outcomes but also by subjective factors. The theory consists of two main stages: the editing phase and the evaluation phase.

In the editing phase, individuals categorize potential outcomes based on reference points they establish and classify them as either "gains" or "losses". Alternatives are evaluated relative to this reference point, and their outcomes are framed as gains or losses. In the evaluation phase, a value function is used to calculate the prospect values. This value function captures individuals' subjective evaluations of gains and losses, which is defined as follows:

$$v(x) = \begin{cases} x^{\alpha}, & x \geqslant 0 \\ -\varepsilon \cdot (-x)^{\beta}, & x < 0 \end{cases} \tag{2.2}$$

where α and β are risk coefficients, satisfying $0 \leqslant \alpha, \beta \leqslant 1$, ε is the risk aversion coefficient, $\varepsilon > 1$, x denotes the gains or losses the decision-makers perceived, $x \geqslant 0$ denotes gain while $x < 0$ means loss. Kahneman and Tversky testified that when $\alpha = \beta = 0.88$ and $\varepsilon = 2.25$, the results obtained are more consistent with empirical data [62]. The image of this function can be seen in Fig.2.7.

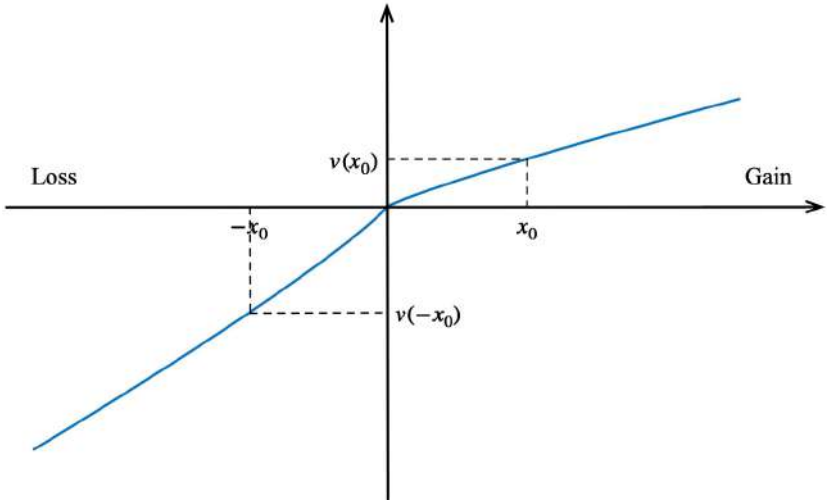

Figure 2.7: The S-shaped function of prospect theory(here $\alpha = \beta = 0.88$ and $\varepsilon = 2.25$)

Prospect theory mainly includes three important features:

- *Reference point independence.* Reference point independence highlights the significance of reference points in decision-making. People's responses to new outcomes are often influenced by their existing possessions, future expectations, or comparisons with others [69]. For instance, if a junior programmer receives a salary increase of 500 dollars, he may feel very satisfied. However, if a senior programmer receives the same salary increase, his degree of satisfaction will not be the same. In other words, the evaluation of gains or losses is determined by the deviation from a specific reference point.

- *Diminishing sensitivity.* Individuals exhibit higher sensitivity to relatively small potential losses or gains compared to larger ones. This means that the perceived difference in psychological impact between gains or losses decreases as their magnitude increases.

For instance, receiving a gift worth 100 may increase one's happiness by 3 points, while receiving a gift worth 200 may only increase it by 5 points, rather than the expected 6 points (2×3).

- *Loss aversion.* Loss aversion refers to the phenomenon where individuals exhibit a stronger psychological response to losses compared to equivalent gains. For instance, if someone loses 100 dollars, they are likely to feel a sense of sadness, whereas if they earn 100 dollars, they might experience happiness. However, the intensity of the sadness felt from the loss is usually greater than the happiness derived from the gain [53].

In recent years, prospect theory has gained significant attraction across various domains. For instance, in the insurance industry, prospect theory is utilized to explain consumer decision-making. In practice, consumers select a higher premium service in exchange for a lower deductible, even in situations where the annualized claim rate is minimal. This phenomenon is usually modeled by prospect theory since individuals exhibit higher sensitivity to losses than gains [2, 56]. In Economics, prospect theory is applied to explain how economic agents subjectively perceive and frame outcomes or transactions, which in turn influences the utility that they anticipate or derive [61]. Additionally, in emergency decisions, the prospect theory is used to deal with vague and uncertain decision information and to describe bounded rationality in emergency situations [13].

2.4.2. TOPSIS method

Sustainability evaluation often entails the consideration of diverse criteria spanning environmental, social, and economic dimensions. Moreover, it frequently involves subjective judgments and qualitative data, particularly when addressing social aspects. In such complex scenarios, the utilization of MCDM methods is not only suitable but highly beneficial. Among the array of MCDM approaches [17], the TOPSIS method stands out for sustainability evaluation due to its well-established reputation for simplicity, flexibility, and effectiveness [29, 36]. These qualities make TOPSIS particularly well-suited for resolving intricate, multiple criteria decision problems involving large-scale experts. The objective of TOPSIS method is to identify the optimal option from a given set of alternatives by considering multiple criteria and incorporating both positive and negative aspects of each alternative. TOPSIS methods employ a geometric approach to compute the distances between the alternatives and the ideal solutions, enabling the ranking of alternatives based on their relative closeness to the ideal solutions. In essence, TOPSIS methodologically enhances the objectivity of decision results by introducing a structured and quantitative framework, which is especially valuable in sustainability evaluation scenarios where subjective biases and qualitative data can introduce uncertainties and complexities that need to be rigorously addressed.

Consider a MCDM problem that involves the evaluation of alternatives z_i $(i = 1, \ldots, m)$ with respect to criteria c_j $(j = 1, \ldots, n)$. Let x_{ij} denote the assessment value for alternative

z_i under criterion c_j, and let w_j represent the weight assigned to criterion c_j. To address this problem using the TOPSIS method, the following key steps are typically followed [3].

Step 1: Normalize the decision matrix and obtain $\bar{x}_{ij}$.

$$\bar{x}_{ij} = x_{ij} / \sqrt{\sum_{j=1}^{n} x_{ij}^2}, i = 1, \ldots, m, j = 1, \ldots, n \tag{2.3}$$

Step 2: Compute the weighted normalized decision matrix nx_{ij}.

$$nx_{ij} = w_j \cdot \bar{x}_{ij} \tag{2.4}$$

Step 3: Determine the positive ideal solution nx_j^+ and the negative ideal solution nx_j^- for each criterion.

$$nx_j^+ = \begin{cases} \max\limits_i \{nx_{ij}\}, & \text{if } c_j \text{ is benefit criterion} \\ \min\limits_i \{nx_{ij}\}, & \text{if } c_j \text{ is cost criterion} \end{cases} \tag{2.5}$$

$$nx_j^- = \begin{cases} \min\limits_i \{nx_{ij}\}, & \text{if } c_j \text{ is benefit criterion} \\ \max\limits_i \{nx_{ij}\}, & \text{if } c_j \text{ is cost criterion} \end{cases} \tag{2.6}$$

Step 4: Calculate the distances between alternatives and the positive ideal solution D_i^+, and the negative ideal solution D_i^-, respectively.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (nx_{ij} - nx_j^+)^2} \tag{2.7}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (nx_{ij} - nx_j^-)^2} \tag{2.8}$$

Step 5: Obtain the closeness coefficient CD_i of each alternative

$$CD_i = \frac{D_i^+}{D_i^+ + D_i^-}, i = 1, \ldots, m \tag{2.9}$$

and rank the alternatives according to the closeness coefficients.

2.4.3. Evidential Reasoning algorithm

The information used in sustainability evaluation often contains uncertainty arising from the complexity of sustainability issues, the long-term nature of the impacts, and the presence of inherent variability, among other factors. Consequently, when performing information fusion in sustainability evaluation, it becomes crucial to carefully address this uncertainty. The ER algorithm has been widely acknowledged as a powerful tool for information fusion in uncertain situations [26, 68, 79], which makes it suitable for solving sustainability evaluation.

The ER algorithm [79] is developed based on the Dempster-Shafer theory of evidence, which allows decision-makers to incorporate and manage uncertain or incomplete information effectively [77]. Moreover, ER algorithm offers strategies for conflict management, essential for addressing inconsistencies between sources of evidence [79]. While the original recursive ER algorithm introduced by Yang et al. [78] systematically combines evidence one by one, its practical application may suffer from inefficiency and time-consumption. To address this issue, Wang et al. [68] proposed an analytical ER algorithm that enables the simultaneous combination of all evidence, thereby offering to provide greater flexibility in incorporating a large number of criteria.

Consider a MCDM problem that involves m alternatives denoted as $z_i (i = 1, \ldots, m)$, and n basic criteria represented by $c_j (j = 1, \ldots, n)$. Each criterion c_j is assigned a relative weight w_j, satisfying $0 \leq w_j \leq 1$ and $\sum_{j=1}^{n} w_j = 1$. To analyze the problem, let us introduce $N \in \mathbb{N}$ as the number of classes or grades and define the frame of discernment $H = \{H_1, \ldots, H_N\}$. Consequently, each alternative z_i is evaluated with a grade H_k concerning criterion c_j, with a belief degree denoted as $\beta_{k,j}(z_i)$, where $\beta_{k,j}(z_i) \in [0, 1]$. This evaluation can be represented as $S(c_j(z_i)) = \{(H_k, \beta_{k,j}(z_i)) | k = 1, \ldots, N\}$. The utilization of the analytical ER algorithm predominantly involves the following steps.

Step 1: Convert the belief degrees into Basic Probability Assignments (BPAs) [68] using the following equations:

$$m_{k,j} = w_j \beta_{k,j}, k = 1, \ldots, K, j = 1, \ldots, n \tag{2.10}$$

$$m_{H,j} = 1 - \sum_{j=1}^{n} m_{k,j} = 1 - w_j \sum_{j=1}^{n} \beta_{k,j}, k = 1, \ldots, K, j = 1, \ldots, n \tag{2.11}$$

$$\bar{m}_{H,j} = 1 - w_j, j = 1, \ldots, n \tag{2.12}$$

$$\tilde{m}_{H,j} = w_j (1 - \sum_{k=1}^{K} \beta_{k,j}), j = 1, \ldots, n \tag{2.13}$$

Here, $m_{k,j}$ represents the probability of assigning criterion c_j to grade H_k, while $m_{H,j}$ indicates the probability mass of criterion c_j not allocated to any specific grade. In accordance with the original ER theory, $m_{H,j}$ is computed as the sum of $\bar{m}_{H,j}$ and $\tilde{m}_{H,j}$. Here, $\bar{m}_{H,j}$ quantifies the influence of other criteria, whereas $\tilde{m}_{H,j}$ denotes the incompleteness in assessing criterion c_j for alternative z_i.

Step 2: Utilize the analytical ER algorithm to integrate the assessment of each criterion

into the form of BPAs:

$$m_k = \rho[\prod_{j=1}^{n}(m_{k,j} + \bar{m}_{H,j} + \tilde{m}_{H,j}) - \prod_{j=1}^{n}(\bar{m}_{H,j} + \tilde{m}_{H,j})], k = 1, \ldots, K \tag{2.14}$$

$$\tilde{m}_H = \rho[\prod_{j=1}^{n}(\bar{m}_{H,j} + \tilde{m}_{H,j}) - \prod_{j=1}^{n}\bar{m}_{H,j}] \tag{2.15}$$

$$\bar{m}_H = \rho[\prod_{j=1}^{n}\bar{m}_{H,j}] \tag{2.16}$$

$$\rho = [\sum_{k=1}^{K}\prod_{j=1}^{n}(m_{k,j} + \bar{m}_{H,j} + \tilde{m}_{H,j}) - (K-1)\prod_{j=1}^{n}(\bar{m}_{H,j} + \tilde{m}_{H,j})]^{-1} \tag{2.17}$$

Here, the normalization factor ρ is the reciprocal of the sum of BPAs assigned to all non-empty sets.

Step 3: Normalized the aggregated BPAs obtained in Step 2 to the belief structure using the following equation:

$$p_k = \frac{m_k}{1 - \bar{m}_H} \tag{2.18}$$

$$p_H = \frac{\tilde{m}_k}{1 - \bar{m}_H} \tag{2.19}$$

By utilizing the analytical ER algorithm, the aggregated distributed assignments can be obtained as $S(z_i) = \{H_k, p_k(z_i)|k = 1, \ldots, N\}$, providing a comprehensive evaluation of alternative z_i.

2.4.4. Three-Way Decision

As aforementioned, sustainability evaluation normaly involves risk. Three-way decision theory offers an effective means to mitigate these risks by introducing a delayed decision strategy. This strategy enables individuals to carefully evaluate potential risks and benefits, make more precise trade-offs, and effectively navigate complex decision environments. Hence, the concept of three-way decision theory aligns well with people's cognitive and behavioral characteristics, contributing significantly to the reduction of risks associated with sustainability evaluation.

The three-way decision theory, initially proposed by Yao [80, 81, 82], subdivides the decision-making process into three distinct regions: the positive region (POS), the negative region (NEG), and the boundary region (BND), providing a more detailed and specific approach to decision-making. Each region employs different decision strategies that align with people's cognitive and behavioral tendencies in various situations. Specifically, when individuals encounter deterministic events, where have sufficient understanding of the events, they tend to make prompt decisions by accepting or rejecting. Conversely, when faced with uncertain events characterized by a lack of information or knowledge, they tend to employ a

strategy of deferring decisions, in order to gather more information to support their decision-making process [67].

The three-way decision employs conditional probability and Bayesian minimum risk decision rules to calculate the expected loss of the three actions. The object's belongingness is represented by the set $\Omega = \{X, \neg X\}$, indicating whether the object belongs to X. The set $\{a_P, a_B, a_N\}$ represents the actions corresponding to each state, where a_P, a_B and a_N mean $x \in POS(X)$, $x \in BND(X)$ and $x \in NEG(X)$, respectively. The loss function for each action in a given state is represented by a matrix, as shown in Table 2.1:

Table 2.1: The loss functions

	X	$\neg X$
a_P	λ_{PP}	λ_{PN}
a_B	λ_{BP}	λ_{BN}
a_N	λ_{NP}	λ_{NN}

In Table 2.1, λ_{PP}, λ_{BP}, and λ_{NP} denote the losses incurred when taking actions a_P, a_B, and a_N, respectively, under the condition that the object belongs to X. Likewise, λ_{PN}, λ_{BN}, and λ_{NN} represent the losses associated with actions a_P, a_B, and a_N, respectively, when the object does not belong to X.

On the basis of loss functions, we can calculate the expected loss $R(a_v|[x])$ associated with taking different actions $a_v (v \in P, B, N)$ for objects in $[x]$ by the following equations [80].

$$R(a_P|[x]) = \lambda_{PP} Pr(X|[x]) + \lambda_{PN} Pr(\neg X|[x]) \tag{2.20}$$

$$R(a_B|[x]) = \lambda_{BP} Pr(X|[x]) + \lambda_{BN} Pr(\neg X|[x]) \tag{2.21}$$

$$R(a_N|[x]) = \lambda_{NP} Pr(X|[x]) + \lambda_{NN} Pr(\neg X|[x]) \tag{2.22}$$

where $Pr(X|[x])$ is the conditional probability of an object belonging to X.

The decision rules can be determined based on the Bayesian decision procedure using minimum-risk decision rules as follows [80]:

(P) If $R(a_P|[x]) \leqslant R(a_B|[x])$ and $R(a_P|[x]) \leqslant R(a_N|[x])$, then $x \in POS(X)$;

(B) If $R(a_B|[x]) \leqslant R(a_P|[x])$ and $R(a_B|[x]) \leqslant R(a_N|[x])$, then $x \in BND(X)$;

(N) If $R(a_N|[x]) \leqslant R(a_P|[x])$ and $R(a_N|[x]) \leqslant R(a_B|[x])$, then $x \in NEG(X)$;

The decision rules (P)-(N) can be simplified based on the assumption that $\lambda_{PP} \leqslant \lambda_{BP} \leqslant \lambda_{NP}$ and $\lambda_{NN} \leqslant \lambda_{BN} \leqslant \lambda_{PN}$, along with the fact that $Pr(X|[x]) + Pr(\neg X|[x]) = 1$, as follows [80]:

(P1) If $Pr(X|[x]) \geqslant \alpha$ and $Pr(X|[x]) \geqslant \gamma$, then $x \in POS(X)$;

(B1) If $Pr(X|[x]) \leqslant \alpha$ and $Pr(X|[x]) \geqslant \beta$, then $x \in BND(X)$;

(N1) If $Pr(X|[x]) \leqslant \beta$ and $Pr(X|[x]) \leqslant \gamma$, then $x \in NEG(X)$.

where α, β and γ are the decision thresholds, which can be calculated as follows:

$$\alpha = \frac{\lambda_{PN} - \lambda_{BN}}{(\lambda_{PN} - \lambda_{BN}) + (\lambda_{BP} - \lambda_{PP})} \tag{2.23}$$

$$\beta = \frac{\lambda_{BN} - \lambda_{NN}}{(\lambda_{BN} - \lambda_{NN}) + (\lambda_{NP} - \lambda_{BP})} \tag{2.24}$$

$$\gamma = \frac{\lambda_{PN} - \lambda_{NN}}{(\lambda_{PN} - \lambda_{NN}) + (\lambda_{NP} - \lambda_{PP})} \tag{2.25}$$

When $(\lambda_{PN} - \lambda_{BN})(\lambda_{NP} - \lambda_{BP}) > (\lambda_{BP} - \lambda_{PP})(\lambda_{BN} - \lambda_{NN})$ is satisfied, the thresholds satisfy $0 < \beta < \gamma < \alpha < 1$. Under these conditions, the simplified rules (P1)-(N1) can be further simplified [80]:

(P2) If $Pr(X|[x]) \geqslant \alpha$, then $x \in POS(X)$;

(B2) If $\beta < Pr(X|[x]) < \alpha$, then $x \in BND(X)$;

(N2) If $Pr(X|[x]) \leqslant \beta$, then $x \in NEG(X)$.

Chapter 3

Research Results

In this chapter, we will provide a succinct summary of the main proposals developed in this research, which align with the objectives of this doctoral thesis. We will discuss the research innovations and present the obtained results for each proposal, which are outlined below:

1. The consideration of bounded rational behavior of decision-makers in sustainability evaluation.
2. A novel CRP model developed based on 3WD in LSGDM.
3. Online reviews-driven decision process, which includes two proposals:
   - The consideration of incomplete online reviews in decision-making.
   - The utilization of hybrid online reviews in decision-making.

3.1. Decision-maker's bounded rational behavior in sustainability evaluation

Sustainability projects are long-term and comprehensive endeavors that aim to address environmental, social, and economic challenges while promoting sustainable development. Conducting sustainability evaluations is essential to maximize the benefits and select the most suitable projects. However, existing researches in sustainability evaluation primarily rely on utility theory and assume decision-makers to be completely rational [52, 89]. In reality, decision-makers are often constrained by bounded rationality, especially when they face risk and uncertain situations [31, 87]. This discrepancy challenges the traditional utility theory and the assumption of decision-makers as completely rational beings. Therefore, in the context of sustainability evaluation, it becomes necessary to address and account for these limitations in decision-making.

To consider the bounded rationality of decision-maker in sustainability evaluation, we propose an innovative decision-making framework for sustainability evaluation that combines Gaussian interval type-2 fuzzy sets (IT2FSs) and prospect theory. Gaussian IT2FSs are highly suitable for this framework as they can effectively model personalized individual semantics while offering advantages such as ease of representation, optimization, continuity, and fast operation for small rule bases [70]. Thus, Gaussian IT2FSs are employed to effectively capture and represent personalized individual semantics in our proposed framework. On the other hand, prospect theory, originally proposed by Kahneman and Tversky [31], operates on the premise of bounded rationality. It introduces a significant innovation by anchoring the value function to reference points instead of absolute values [31]. This method facilitates the division of the value function into gain and loss domains, enabling an investigation of individuals' psychological behavior in response to gains and losses, respectively [76]. Leveraging this advantage, prospect theory is selected to effectively capture the decision-makers's psychological characteristics in our framework.

The specific contributions of this proposal are summarized as follows:

1. Employ Gaussian IT2FSs to model linguistic terms, which can capture personalized individual semantics, providing a flexible representation that aligns with decision-makers' subjective interpretations.

2. Propose the Gaussian interval type-2 fuzzy entropy model. By utilizing the proposed entropy model, we can effectively calculate the weights of criteria, thereby aiding in the selection of the most suitable sustainability project.

3. Introduce a novel Gaussian interval type-2 fuzzy distance measure. Unlike existing distance measures, our proposed measure offers the advantage of simultaneously avoiding information loss while improving computational efficiency.

4. Define a Gaussian IT2FSs-based prospect theory method, which offers a more accurate and stable representation of decision-makers' strategies, facilitating a comprehensive description of their psychological behavior.

The paper related to this proposal is the following one:

He, S. F., Wang, Y. M., & Martínez, L. (2022). Gaussian IT2FSs-based prospect theory method with application to the evaluation of renewable energy sources. Computers & Industrial Engineering, 169, 108266.

3.2. A novel CRP model based on three-way decision for LSGDM

In managing a sizable group of experts, conflicts or polarized opinions often arise owing to the array of interests, knowledge backgrounds, and thinking patterns among them [55].

Failing to resolve these conflicts prior to reaching a final decision can result in discontent among certain experts and diminish the decision's reliability. To overcome this limitation and ensure consensus on the chosen solution, a CRP is typically conducted in LSGDM problems [35]. Traditionally, the consensus degree of the group is assessed in each round of the CRP to determine if the current level of agreement meets a predefined threshold, and whether further discussion rounds are necessary [18]. However, most existing consensus measurement methods only categorize experts into two opposing groups: those who have achieved the desired consensus and those who have not [38]. This binary classification fails to account for the possibility that experts who did not meet the consensus threshold in one round may still reach consensus in subsequent rounds without adjusting their initial opinions. Consequently, these methods may result in over-adjustment and increase the cost of the decision-making process.

To address such over-adjustment situation, we will develop a new CRP model based on the concept of three-way decision [80]. Three-way decision models divide the decision space into three distinct regions: positive, negative, and boundary [11]. These regions correspond to acceptance, rejection, and non-commitment, respectively. Unlike traditional two-way decisions that only involve acceptance and rejection, three-way decisions introduce a non-commitment option [82], which helps minimize decision loss by allowing experts to refrain from making decisions when there is insufficient information available [41]. This characteristic makes three-way decision models well-suited for establishing a consensus measurement mechanism, as they can enhance the effectiveness of the CRP. From the perspective of three-way decision, only experts categorized to the negative region necessitate adjustments to their opinions, while experts located in the boundary region are not required to do so, as consensus can potentially be achieved through modifications implemented by experts in the negative region.

The specific contributions of this proposal are summarized as follows:

1. Utilize Extended Comparative Linguistic Expression with Symbolic Translation (ELICIT) information to capture and represent experts' preferences. ELICIT information follows a similar reasoning process as human beings and ensures accurate computations of linguistic terms while preserving interpretability. This interpretability plays a crucial role in generating meaningful feedback during the CRP.

2. Construct a social network that incorporates both preference similarity and trust relationships among experts. Both preference similarity and trust relationships are important indicators for social connections among experts. Incorporating them in social network construction can enhance the accuracy and effectiveness of capturing the relationships among experts.

3. Define a novel CRP model based on three-way decision theory. Unlike existing CRP methods that only classify experts into two opposing groups, our proposed model incor-

porates a non-commitment decision, reducing the risk of over-adjustment and increasing the decision utility.

The paper related to this proposal is the following one:

Wang, Y. M., He, S. F., Zamora, D. G., Pan, X. H., & Martínez, L. (2023). A large scale group three-way decision-based consensus model for site selection of new energy vehicle charging stations. Expert Systems with Applications, 214, 119107.

3.3. Online reviews-driven decision processes

In traditional sustainability evaluation, information is typically sourced directly from decision-makers. However, the emergence of Web 2.0 and the widespread use of portable terminal devices have opened up new avenues for information acquisition. Online reviews, which capture the genuine opinions of a vast number of users, contain valuable information. Therefore, this section will focus on the utilization of online reviews as a way to enhance decision-making processes.

3.3.1. The consideration of incomplete online reviews in decision-making

When utilizing online reviews to aid in decision-making, it is worth noting that these reviews may not always provide comprehensive information covering all the different criteria [28]. For instance, in a decision problem involving the evaluation of new energy vehicles based on criteria "appearance", "interior", "space", "power", "cost performance" and "comfortability", not all online reviews will evaluate each aspect. For example, a review may lack a comment on "power" due to the reviewer's personal preferences, time constraints, or other reasons. However, even in such cases, the evaluations of other aspects can still provide valuable insights for potential users and should not be disregarded when making a decision [26]. Therefore, effectively utilizing online reviews as an information source in MCDM requires the adoption of suitable methods for managing incomplete information and handling uncertainty. However, the existing methods [16, 42, 45, 85] in the literature often exhibit common limitations in addressing these challenges.

To address the challenge of incomplete online reviews, this research presents a novel MCDM framework that utilizes online reviews efficiently. The proposed framework incorporates an information processing mechanism that transforms online reviews into Probabilistic Linguistic Term Sets (PLTSs) with interval uncertainty [73]. This transformation allows for a more comprehensive representation of the uncertainty inherent in online reviews. Additionally, a weight-determination model is introduced to calculate the weights of the criteria, considering the interval values to better capture the uncertainty associated with the criteria. Furthermore, the ER algorithm is extended to accommodate PLTSs with interval uncertainty, enabling the fusion of evaluation information and the generation of interval-valued expected

utilities for the alternatives. This extension takes into account the incomplete information, thus providing a more robust decision-making process.

The specific contributions of this proposal are summarized as follows:

1. Propose a novel information transformation method that can effectively handle incomplete online reviews. As previously mentioned, online reviews may be incomplete sometimes and the existing researches often struggle to address this incompleteness. In this regard, PLTSs with interval uncertainty present a rational normalization technique by constructing interval values to represent the available information, which can be used to minimize information loss and maximize the utilization of the available data to the greatest extent possible.

2. Define an interval-valued weight determination model to address the uncertainty inherent in the evaluation information extracted from online reviews. Traditional weight determination methods often yield crisp weights, which limit their ability to capture and represent uncertainty. To overcome this limitation, this research proposes a new weight determination model that utilizes interval-valued weights.

3. Introduce an ER-based information fusion method to effectively aggregate PLTSs with interval uncertainty. By leveraging the ER algorithm, the proposed method enhances the fusion process of PLTSs with interval uncertainty and provides a robust and reliable framework for decision-making in the presence of interval uncertainty.

The paper related to this proposal is the following one:

He, S. F., Pan, X. H., Wang, Y. M., Zamora, D. G., & Martínez, L. (2024). A novel Multi-Criteria Decision Making framework based on Evidential Reasoning dealing with missing information from online reviews. Information Fusion, 106, 102264.

3.3.2. Hybrid online reviews in decision-making

Until now, there has been extensive researches on utilizing online reviews for supporting MCDM. However, these researches have mainly focused on either online rating reviews [16, 85] or online textual reviews [12, 26]. As mentioned in subsection 2.3, online rating reviews typically employ a simple five-star rating system to evaluate products, services, or events, offering a straightforward and user-friendly approach. However, online rating reviews may limit users' freedom of expression and lack comment details. On the other hand, online textual reviews allow users to express their opinions in more detail through text. Nevertheless, users sometimes tend to overly emphasize specific aspects they like or dislike, resulting in a potential discrepancy between their expressed views and their true views.

To obtain opinions from online reviews that accurately reflect users' perspectives and effectively utilize all available information, this research proposes a novel decision framework based on hybrid online reviews. In this framework, online reviews are initially processed to

derive interval values, ensuring that both the text and rating information are considered in the decision-making process. Next, an automatic CRP is developed based on a novel MCC model for interval information. This CRP aims to achieve a collective opinion that represents the preferences of all users as comprehensively as possible. Subsequently, the TOPSIS method [29] is extended and enhanced to rank the interval information based on the performance of the alternatives with respect to the criteria.

The specific contributions of this proposal are summarized as follows:

1. Utilize hybrid online reviews. Previous studies have mainly focused on either rating reviews or textual reviews, which can result in information loss and may not accurately reflect the opinions of users. To overcome this limitation, this research proposes the utilization of hybrid online reviews, incorporating both types of reviews.

2. Propose an automatic CRP based on a novel interval MCC model. Most existing researches in the field often overlook how to obtain a collective preference that properly accounts for all the individual preferences. In contrast, this research proposes an automatic CRP based on a novel interval MCC model to efficiently and effectively achieve consensus among users. Different from the existing MCC models developed based on crisp numbers, the proposed interval MCC model can adequately handle the fuzziness and uncertainty inherent to hybrid online reviews.

3. Define interval TOPSIS method. TOPSIS as a classical decision-making method compares alternatives based on their distance to both the positive ideal solution and negative ideal solution. Since hybrid online reviews are modeled as interval information, the classical TOPSIS method is extended using interval arithmetic, distances, and order relations to ensure that the information from the online reviews is not lost during the process.

The paper related to this proposal is the following one:

He, S. F., Zamora, D. G., Pan, X. H., Wang, Y. M., & Martínez, L. (2023). A novel Online Reviews-based Decision-Making framework to manage rating and textual reviews. Experts system with Applications, 2nd round (Major revision)

Chapter 4

Conclusions and Future Works

In this section, we will conclude this memory by summarizing the various findings and conclusions drawn throughout this research, together with potential future researches directions that can be undertaken based on the results obtained.

4.1. Conclusions

Sustainable development is a crucial goal for all humanity. In this research, we focus on employing MCDM methodologies, particularly LSGDM, to assist in achieving sustainable development goals. The obtained results and conclusions are summarized as follows.

First, we have extended prospect theory into the Gaussian IT2FS environment, which enriches our understanding of decision-making processes in sustainability evaluation. By incorporating prospect theory, we gain a more comprehensive depiction of the psychological behavior exhibited by decision-makers. This extension enables us to capture the complexity of decision-making under uncertainty and complexity, considering cognitive limitations that can significantly impact decisions. Thus, this achievement marks a significant step forward in enhancing decision-making processes in sustainability evaluation, aligning with the first objective of this research.

Then, we have proposed a novel CRP within the LSGDM framework to solve sustainability decision problems. Such a CRP is grounded in three-way decision theory, aiming to mitigate the risk of over-adjustment and enhance the reliability and consensus of solutions in the decision-making process. This model strikes a balance between exploring new alternatives and maintaining consistency with existing preferences, ultimately leading to more reliable and unanimously agreed-upon solutions. This achieves the second objective of our research.

Additionally, we have presented two decision methodologies that consider online reviews in sustainability evaluation. When utilizing online reviews, it is essential to take two significant characteristics into account: incompleteness and heterogeneity. To tackle incompleteness, we have proposed a decision framework that includes a new information transformation method

designed to effectively manage incomplete online reviews. Additionally, a novel information fusion method based on ER is introduced to aggregate incomplete information. To address heterogeneity, we have defined another decision framework in which both rating and textual online reviews will be considered and processed into interval values. This completes the third objective of this research.

In summary, this research has successfully achieved all the objectives defined at the beginning of the study, providing valuable theories, tools, and models for addressing sustainability evaluation. The outcomes of this research have significantly improved the state of the art in the field before our investigation and have also opened up possibilities for further research, as discussed in the following section.

4.2. Future Works

Based on the results obtained, there are several potential researches directions that can build upon the findings of this doctoral thesis. Some of the possible future works include:

- Develop a sorting scheme for sustainability evaluation. While this research has focused on providing the ranking order of the alternatives, in some real-world decision problems it is more convenient to classify the alternatives into different groups according to their performance. Therefore, in the future, we will develop a classification framework to guide decision-makers on investing in multiple sustainable projects simultaneously to mitigate risks and maximize benefits.

- Integrate some interaction operators to consider the interrelationships among criteria to improve the reliability of decision results. It is important to acknowledge that criteria are not always independent of each other, they might exhibit certain links or dependencies. By studying and incorporating interaction operators into the decision-making process, the model can better capture and reflect these relationships among criteria, leading to more comprehensive and accurate evaluations in complex decision scenarios.

- Manage the uncooperative behavior of experts who refuse to follow the moderator's recommendations. While this research assumes all experts to be cooperative, it is essential to acknowledge that in real-life scenarios, some experts may not comply with the moderator's suggestions. Therefore, in future researches, developing strategies to manage and handle such uncooperative behavior is of paramount importance to ensure the robustness and effectiveness of the decision-making process.

- Propose other preference structures to effectively process the reviewers' information, such as their social connections or personalized individual semantics. Currently, when utilizing online reviews to aid decision-making, only the review contents are typically considered. However, individuals have different expression habits and tendencies, which

can impact the interpretation of their reviews. By considering additional information, such as their social connections or personalized individual semantics, it becomes possible to improve the accuracy of understanding and interpreting their reviews in a more nuanced manner.

- Develop a recommender system based on the proposed decision framework. By harnessing the valuable insights derived from online reviews and the decision-making framework, personalized recommendations can be generated for users. These recommendations will assist users in making well-informed choices that align with their unique preferences and specific requirements. Such a recommender system has the potential to significantly enhance user satisfaction and decision-making outcomes.

4.3. Additional Publications

During the development of this research, several other publications have been presented, which are not included in this memory. Below is a list of those publications:

† International journals:

- Shi-Fan He, Ying-Ming Wang, Xiao-Hong Pan, Kwai-Sang Chin. A novel behavioral three-way decision model with application to the treatment of mild symptoms of COVID-19, *Applied Soft Computing*, 124: 109055, 2022.
- Shi-Fan He, Ying-Ming Wang. Evaluating new energy vehicles by picture fuzzy sets based on sentiment analysis from online reviews, *Artificial Intelligence Review*, 56(3): 2171-2192, 2023.
- Shi-Fan He, Ying-Ming Wang, Xiao-Hong Pan, Kwai-Sang Chin. Decision analysis framework based on incomplete online textual reviews, *Information Sciences*, 584:701-718, 2022.

† Book chapters:

- Xiao-Hong Pan, Shi-Fan He, Diego García-Zamora, Luis Martínez. "Interval type-2 fuzzy decision analysis framework based on Online Textual Reviews". In: *Advances in Complex Decision Making: Using Machine Learning and Tools for Service-Oriented Computing.* Taylor & Francis Group, LLC CRC, Routledg; 2023

Appendix A

Resumen escrito en Español

A.1. Motivación

El desarrollo sostenible se refiere a un concepto y a un enfoque cuyo objetivo es satisfacer las necesidades de la generación actual garantizando al mismo tiempo que las generaciones futuras puedan satisfacer sus propias necesidades [63]. En él se reconoce la importancia de perseguir el desarrollo económico y social de una manera que minimice los impactos negativos sobre el medio ambiente, haciendo de la sostenibilidad una consideración fundamental en todos los países. Los Objetivos de Desarrollo Sostenible (ODSs) introducidos por la Agenda 2030 [1] son objetivos a nivel mundial para fomentar la paz, la justicia y la prosperidad en un planeta sano. Para impulsar el desarrollo sostenible, es esencial emprender diversos esfuerzos, como invertir en energías renovables y tecnologías verdes. Sin embargo, es necesario evaluar la eficacia de los proyectos de sostenibilidad debido a su complejidad, a sus implicaciones a largo plazo y sus incertidumbres inherentes. En este sentido, la Toma de Decisiones Multicriterio (MCDM) ofrece una herramienta práctica para llevar a cabo evaluaciones y decisiones sobre sostenibilidad, teniendo en cuenta distintos criterios y factores.

A medida que las situaciones de toma de decisiones se vuelven cada vez más complejas, la toma de decisiones individual en MCDM puede presentar dificultades para considerar toda la información relevante, lo que conduce a posibles sesgos y a la posibilidad de llegar a conclusiones poco razonables y fiables. Para hacer frente a este reto, los métodos de toma de decisiones en grupo (GDM) han sido ampliamente estudiados. Estos métodos refieren al proceso de tomar decisiones de forma colectiva, con la participación de múltiples individuos que se reúnen para analizar un problema, evaluar alternativas y tomar una decisión conjunta [33, 51, 66]. Sin embargo, la GDM tradicional se centra principalmente en pequeños grupos de expertos. Muchos problemas del mundo real, en particular los asociados a proyectos de sostenibilidad que tienen un impacto significativo en aspectos económicos, sociales y medioambientales, requieren la participación de múltiples expertos de diversos campos. Además, los

[1] https://sdgs.un.org/2030agenda

avances de la ciencia y la tecnología han facilitado la conectividad entre expertos. En consecuencia, la demanda de la toma de decisiones en grupos a gran escala (LSGDM) se ha hecho más pronunciada [19, 34, 44].

En LSGDM, los expertos suelen tener diferentes intereses, conocimientos y patrones de pensamiento, lo que puede dar lugar a la generación de opiniones diferentes, contradictorias o polarizadas [55]. Para garantizar la eficacia de LSGDM, es esencial emplear un Proceso de Alcance de Consenso (CRP) antes de evaluar y seleccionar la alternativa óptima para los problemas de LSGDM. Un CRP basado en redes sociales suele abarcar los siguientes tres pasos clave [6] (como se muestra en la Fig.A.1):

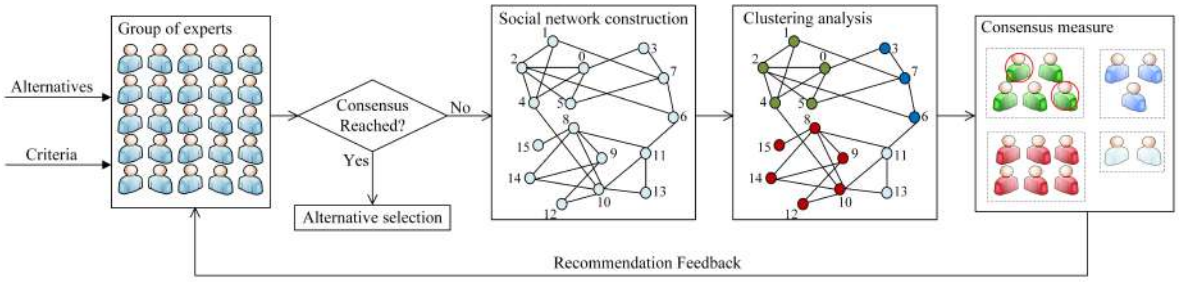

Figure A.1: Etapas del proceso de consenso basado en redes sociales

- *Construcción de redes sociales.* En la práctica, es habitual que los expertos implicados en problemas de LSGDM tengan relaciones existentes como partes interesadas o colaboradores. Esto implica la presencia de conexiones sociales entre ellos [44], y cabe señalar que las opiniones de los individuos pueden verse influidas por sus redes sociales o amigos [72]. En consecuencia, el LSGDM en el contexto de una red social ha adquirido una importancia significativa y ha sido objeto de una atención cada vez mayor. Las relaciones de similitud de preferencias y las relaciones de confianza son dos fundamentos comúnmente utilizados para construir una red social en LSGDM [6]. Sin embargo, las investigaciones existentes suelen construir redes sociales basándose únicamente en la similitud [27, 50, 64] o en la confianza [1, 39]. Para mejorar la calidad de la construcción de redes sociales en LSGDM, es crucial tener en cuenta tanto la similitud de preferencias como las relaciones de confianza.

- *Análisis de clústers.* Consiste en agrupar a los expertos en distintas clases. No sólo puede reducir la complejidad y el coste de las metodologías LSGDM, sino que también ayuda a identificar patrones comunes de opinión [59]. Hasta la fecha, se han propuesto numerosos métodos de agrupación desde diversas perspectivas, como el método de agrupación alternativo basado en la clasificación [46], el método de agrupación basado en la medida de similitud [24], el método de agrupación k-means [74], etcétera. Entre estos métodos, el método de Louvain [5] destaca como uno de los algoritmos de descubrimiento de comunidades [37] más eficaces. Demuestra la capacidad de agrupar con rapidez

y precisión redes a gran escala en varias comunidades distintas. Esta característica lo hace especialmente adecuado para LSGDM.

- *Construcción de modelos de consenso.* El consenso, definido como el acuerdo alcanzado por todos los expertos sobre alternativas viables [71], es esencial para garantizar que los resultados de la decisión sean reconocidos y aceptados por todos los participantes. Normalmente, los modelos de consenso constan de dos etapas: la medición del consenso y la recomendación de retroalimentación. La etapa de medición del consenso tiene por objeto determinar el nivel de consenso entre los expertos utilizando una medida de consenso [40, 84]. En esta etapa, se predefine un umbral de consenso para evaluar si se ha alcanzado el consenso [18]. Sin embargo, estos métodos suelen clasificar las preferencias de los expertos en dos categorías: alcanzar el consenso o no alcanzarlo. Cabe señalar que algunos expertos que no alcanzaron el consenso en una iteración pueden alcanzarlo en iteraciones posteriores, incluso sin ajustar sus opiniones.

En los últimos años, las tecnologías de la Web 2.0 han cambiado la forma en que las personas acceden a la información y la difunden. La Web 2.0 no sólo ofrece a los usuarios una plataforma para obtener información objetiva, sino que también les permite acceder a un amplio abanico de opiniones de otros usuarios. Estas reseñas en línea obtenidas de la web contienen información de usuarios/expertos del mundo real a gran escala, lo que puede ayudar significativamente en los procesos de toma de decisiones. Concretamente, en problemas de LSGDM, las preferencias de entrada no no están necesariamente limitadas a juicios subjetivos de expertos, sino que se pueden completar mediante reseñas en línea obtenidas de forma automática. En consecuencia, la toma de decisiones basada en opiniones en línea (ORDM, por sus siglas en inglés) ha recibido cada vez más atención [8, 15, 47]. En términos generales, hay tres fases implicadas en ORDM (como se muestra en la Fig. A.2):

- *Colección.*Las reseñas en línea abarcan información heterogénea, que puede incluir texto, imágenes, vídeos, valoraciones, etc. Entre estas formas, las reseñas de valoración en línea y las reseñas textuales en línea son los tipos más utilizados, y se han dedicado grandes esfuerzos a utilizarlos. Las valoraciones en línea suelen emplear un sencillo sistema de puntuación de cinco estrellas para evaluar productos, servicios o eventos, y ofrecen un enfoque sencillo y fácil de usar [85]. Por otro lado, las reseñas textuales en línea permiten a los usuarios expresar sus opiniones con mayor detalle a través de un texto escrito [26]. Los estudios anteriores se han centrado principalmente en la utilización de reseñas de valoración en línea [16] o reseñas textuales en línea [12]. Sin embargo, es importante tener en cuenta que las valoraciones en línea pueden limitar la libertad de expresión de los usuarios y carecer de detalles específicos sobre los artículos valorados, mientras que las valoraciones textuales en línea a veces pueden hacer excesivo hincapié en aspectos concretos que gustan o disgustan a los usuarios, lo que puede dar lugar a una desviación entre sus opiniones expresadas y sus verdaderas opiniones.

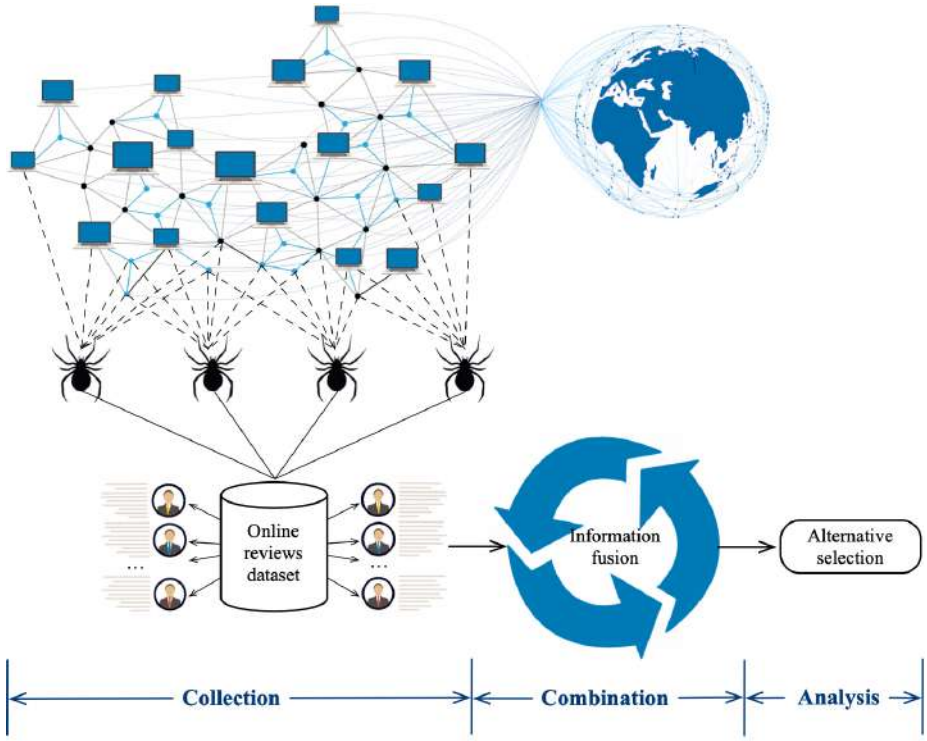

Figure A.2: Esquema general de la ORDM

- *Combinación.* La naturaleza cualitativa y masiva de las opiniones en línea plantea dificultades a la hora de utilizarlas directamente para la toma de decisiones. Por lo tanto, es necesario combinar las opiniones en línea en una única preferencia colectiva que resuma las opiniones de todos los usuarios individuales. La teoría de los conjuntos difusos [30] se emplea habitualmente para abordar esta necesidad, como la transformación de las reseñas en línea en conjuntos de términos lingüísticos probabilísticos [45], conjuntos difusos de imágenes [28], distribución porcentual discreta [16], evaluaciones lingüísticas [85], etcétera. Sin embargo, dos problemas clave siguen sin resolverse. En primer lugar, debido a las diferencias en la formación, las experiencias y los hábitos de los usuarios, no todos los comentarios proporcionados son completos. Por desgracia, los métodos existentes suelen pasar por alto el carácter incompleto de las reseñas recopiladas. En segundo lugar, los métodos existentes se basan principalmente en técnicas estadísticas, por lo que pueden pasar por alto las opiniones de los usuarios individuales.

- *Análisis.* A la hora de gestionar las opiniones en línea, los responsables de la toma de decisiones suelen prestar especial atención a determinados criterios. Por lo tanto, es crucial incorporar métodos MCDM en la fase de análisis de los procesos de ORDM. Estos métodos facilitan la evaluación de alternativas en función de varios criterios y ayudan a identificar la opción más adecuada [25]. En ORDM se emplean varios métodos de

análisis. Por ejemplo, Liang et al. [42] utilizaron un operador de síntesis difusa para la evaluación exhaustiva, mientras que Liu et al. [48] clasificaron las alternativas utilizando el operador de media ponderada difusa intuicionista. Liu y Teng [44] propusieron el método TODIM lingüístico probabilístico para comparar alternativas, y Fan et al. [16] emplearon el método PROMETHEE-II para determinar la clasificación de los productos candidatos. Sin embargo, los métodos MCDM basados en operadores difusos a menudo carecen de justificación teórica o práctica [54], mientras que otros métodos MCDM existentes utilizados en las investigaciones de ORDM enfrentan desafíos en el manejo efectivo de información incierta e incompleta.

En resumen,esta investigación pretende utilizar varios métodos de MCDM para impulsar el desarrollo sostenible , en particular mediante la aplicación del marco LSGDM. La creciente complejidad de los problemas de evaluación de la sostenibilidad y su impacto a largo plazo en la economía, la sociedad y el medio ambiente han provocado un aumento del número de expertos implicados en este tipo de procesos. Además, la llegada de las tecnologías Web 2.0 y el uso generalizado de dispositivos portátiles han facilitado la accesibilidad y la utilización de reseñas en línea, que podrían considerarse un problema especial de LSGDM con un enorme número de expertos implicados. Como se muestra en la Fig.A.3, aunque la inclusión de un mayor número de expertos tiene el potencial de mejorar la precisión de la evaluación de la sostenibilidad, también introduce nuevas características y retos que deben gestionarse cuidadosamente. Esta investigación pretende abordar estas características emergentes asociadas a los grupos de expertos a gran escala, desarrollar estrategias eficaces para gestionarlas adecuadamente y emplear los métodos propuestos para promover la sostenibilidad.

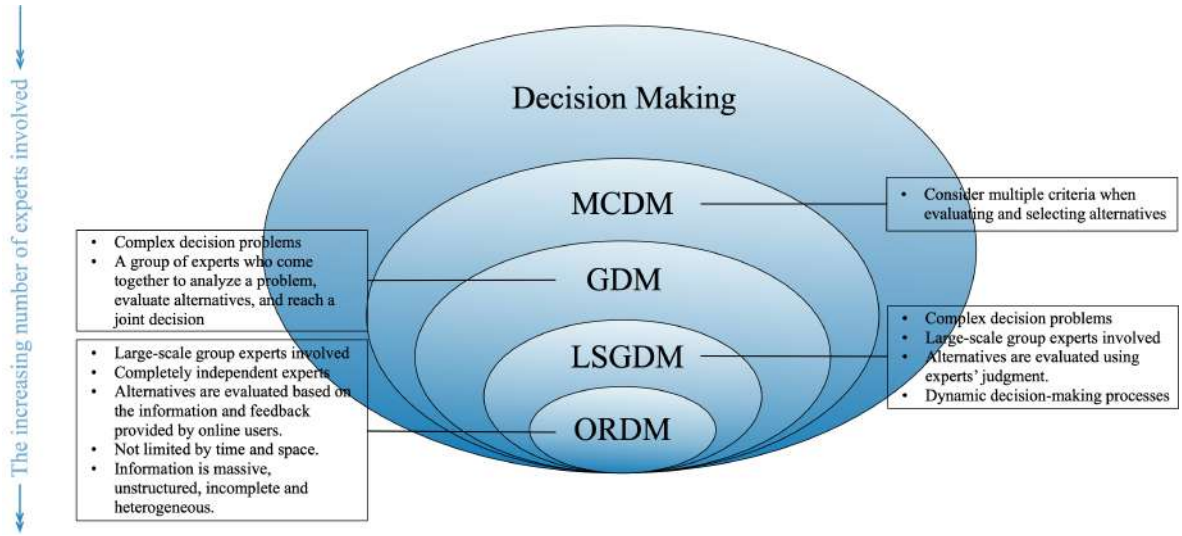

Figure A.3: Clasificación de la DMG según el número de expertos implicados

A.2. Objetivos

Teniendo en cuenta las limitaciones inherentes a las investigaciones actuales, tal y como se ha comentado en la sección anterior, y el objetivo de promover el desarrollo sostenible, el objetivo principal de esta tesis doctoral es utilizar metodologías MCDM para potenciar el desarrollo sostenible. En concreto, el objetivo principal se desarrolla mediante tres objetivos específicos:

1. **Considerar la racionalidad limitada de los responsables de la toma de decisiones en la evaluación de la sostenibilidad**: Este objetivo pretende considerar la limitación del comportamiento racional en los responsables de la toma de decisiones para la evaluación de la sostenibilidad. Es importante reconocer que los seres humanos muestran una racionalidad limitada, en particular cuando se enfrentan al riesgo y la incertidumbre. En el contexto de la evaluación de la sostenibilidad, los responsables de la toma de decisiones pueden no tener acceso a información completa, poseer una capacidad cognitiva limitada o enfrentarse a limitaciones de tiempo, todo lo cual puede afectar a su proceso de toma de decisiones. Al reconocer y tener en cuenta estas limitaciones, se puede desarrollar un enfoque más realista y eficaz de la evaluación de la sostenibilidad, que conduzca a decisiones fundamentadas y razonables en contextos de sostenibilidad complejos e inciertos.

2. **Definir un CRP para LSGDM en la evaluación de la sostenibilidad**: Este objetivo pretende proponer un novedoso modelo CRP dentro del marco LSGDM para resolver problemas de decisión relacionados con sostenibilidad. Una limitación de la mayoría de los modelos CRP existentes es que sólo clasifican a los expertos en dos grupos opuestos, lo que puede dar lugar a un sobreajuste. Para superar esta limitación, propondremos un nuevo modelo CRP basado en la decisión tripartita. Este modelo incluye la decisión de aceptación (opiniones que no requieren ajuste), la decisión de rechazo (opiniones que necesitan ajuste) y la decisión de no compromiso (opiniones que no requieren ajuste en la ronda actual). Al incorporar la decisión de no compromiso, nuestro modelo CRP propuesto mejora la eficiencia de la decisión y proporciona una mayor flexibilidad en comparación con otros métodos existentes.

3. **Emplear reseñas online en la evaluación de la sostenibilidad**: Este objetivo pretende estudiar los procesos de decisión impulsados por las reseñas en línea para resolver problemas de decisión relacionados con la sostenibilidad. Como forma de comunicación electrónica "boca a boca", las reseñas en línea pueden proporcionar evaluaciones, experiencias y opiniones genuinas de un gran número de usuarios. Debido a sus características de independencia y credibilidad, las reseñas en línea suelen considerarse una fuente de información más fiable que las fuentes de información tradicionales. Sin embargo, la naturaleza masiva, incompleta y heterogénea de las reseñas en línea presenta desafíos

cuando se intenta utilizarlas directamente para la toma de decisiones. Para hacer frente a estos retos, esta investigación explora cómo incorporar eficazmente las reseñas en línea al proceso de toma de decisiones.

A.3. Estructura

En cumplimiento del artículo 25, punto 2, de la normativa vigente de los Estudios de Doctorado de la Universidad de Jaén (RD. 99/2011), esta tesis doctoral consistirá en una recopilación de artículos publicados o presentados por el doctorando. Con estos artículos se pretende dar cumplimiento a los objetivos expuestos en el apartado anterior. En concreto, esta investigación consta de cuatro artículos, tres de los cuales han sido publicados en revistas de reconocido prestigio internacional indexadas en la base de datos Journal Citation Reports (JCR), mientras que el restante está sometido en una revista del primer cuartil en la base de datos JCR.

La estructura de esta memoria de investigación consta de los siguientes capítulos:

- Capítulo 2: En este capítulo se presentan conceptos fundamentales relacionados con la investigación de la tesis doctoral, incluyendo la introducción de LSGDM y CRP, una discusión detallada sobre reseñas en línea, y la explicación de varios métodos y modelos que se utilizarán en la tesis doctoral.

- Capítulo 3: En este capítulo se realizará un resumen de las principales propuestas presentadas en esta memoria de investigación, haciendo hincapié en los resultados y conclusiones derivados de cada una de ellas.

- Capítulo 4: En este capítulo se incluyen los cuatro artículos mencionados anteriormente, junto con información detallada sobre las revistas en las que se han publicado o presentado.

- Capítulo 5: Se resumen las principales conclusiones de la tesis doctoral y se presentan varias investigaciones futuras posibles.

A.4. Resumen

El desarrollo sostenible es importante porque aborda los retos interconectados de la degradación medioambiental, la desigualdad social y la inestabilidad económica. De ahí que haya atraído cada vez más atención y que los ODS sean un objetivo compartido por todas las industrias. La evaluación de los proyectos de sostenibilidad desempeña un papel importante en la consecución de los ODS. Dada la compleja naturaleza, las consecuencias a largo plazo y las incertidumbres inherentes asociadas a la evaluación de la sostenibilidad, los responsables

de la toma de decisiones individuales o pequeños grupos de responsables pueden tener dificultades para considerar exhaustivamente toda la información relevante. Esto puede introducir sesgos y producir resultados poco razonables o fiables. Para hacer frente a este reto, LSGDM presenta un enfoque valioso, que implica a expertos que colaboran para analizar problemas y tomar decisiones. Con el fin de subsanar las deficiencias de la investigación existente a la hora de abordar la racionalidad limitada de los responsables de la toma de decisiones, optimizar los CRP con alta eficiencia y bajo coste, y emplear revisiones en línea para ayudar en las decisiones, esta investigación desarolla las siguientes propuestas:

1. Considerar el comportamiento racional limitado de los responsables de la toma de decisiones en la evaluación de la sostenibilidad mediante la teoría de las perspectivas. La teoría de prospectos ha sido considerada una herramienta eficaz para describir la racionalidad limitada. Por lo tanto, en esta investigación, extendemos la teoría de prospectos en el entorno IT2FS gaussiano, que puede modelar eficazmente la semántica individual personalizada al tiempo que ofrece ventajas como la facilidad de representación, la optimización, la continuidad y el funcionamiento rápido, proporcionando una descripción completa del comportamiento psicológico de los responsables de la toma de decisiones.

2. Proponer un modelo CRP novedoso en el marco de LSGDM para resolver problemas de sostenibilidad. El CRP es esencial para suavizar los conflictos o las opiniones polarizadas de los expertos en LSGDM y mejorar la fiabilidad de los resultados de la decisión. Por lo tanto, esta investigación propone un nuevo modelo CRP basado en la decisión de tres vías, que permite dividir el espacio de decisión en tres regiones distintas: positiva, negativa y límite. El modelo CRP propuesto puede reducir eficazmente el riesgo de sobreajuste y garantizar soluciones más fiables y consensuadas en el proceso de toma de decisiones.

3. Emplear reseñas en línea como soporte en la toma de decisiones para la evaluación de la sostenibilidad. La aparición de la Web 2.0 y el uso generalizado de dispositivos portátiles han aportado una nueva fuente de información para resolver problemas de sostenibilidad. Para utilizar eficazmente las reseñas en línea, hemos propuesto respectivamente un marco de decisión que tiene en cuenta el carácter incompleto y multiforme de las reseñas en línea, incorporando eficazmente las reseñas en línea para apoyar el proceso de toma de decisiones.

A.5. Conclusiones y Trabajos Futuros

En esta sección, concluiremos esta memoria resumiendo los diversos resultados y conclusiones extraídos a lo largo de esta investigación, junto con las posibles direcciones futuras de investigación que pueden emprenderse basándose en los resultados obtenidos.

A.5.1. Conclusiones

El desarrollo sostenible es un objetivo crucial para toda la humanidad. En esta investigación, nos centramos en el empleo de metodologías MCDM, en particular LSGDM, para ayudar a alcanzar los objetivos de desarrollo sostenible. Los resultados y conclusiones obtenidos se resumen a continuación.

En primer lugar, hemos extendido la teoría de las perspectivas al entorno IT2FS gaussiano, lo que enriquece nuestra comprensión de los procesos de toma de decisiones en la evaluación de la sostenibilidad. Al incorporar la teoría de las perspectivas, obtenemos una descripción más completa del comportamiento psicológico que muestran los responsables de la toma de decisiones. Esta ampliación nos permite captar la complejidad de la toma de decisiones en condiciones de incertidumbre, teniendo en cuenta las limitaciones cognitivas que pueden afectar significativamente a las decisiones. Así pues, este logro supone un importante paso adelante en la mejora de los procesos de toma de decisiones en la evaluación de la sostenibilidad, alineándose con el primer objetivo de esta investigación.

A continuación, hemos propuesto un CRP dentro del marco LSGDM para resolver problemas de decisión sobre sostenibilidad. Dicho CRP se basa en la teoría de la decisión a tres bandas, con el objetivo de mitigar el riesgo de sobreajuste y mejorar la fiabilidad y el consenso de las soluciones en el proceso de toma de decisiones. Este modelo logra un equilibrio entre la exploración de nuevas alternativas y el mantenimiento de la coherencia con las preferencias existentes, lo que en última instancia conduce a soluciones más fiables y consensuadas. Con ello alcanzamos el segundo objetivo de nuestra investigación.

Además, hemos presentado dos metodologías de decisión que tienen en cuenta las reseñas en línea en la evaluación de la sostenibilidad. A la hora de utilizar las reseñas en línea, es esencial tener en cuenta dos características significativas: el carácter incompleto y la heterogeneidad. Para hacer frente al carácter incompleto, hemos propuesto un marco de decisión que incluye un nuevo método de transformación de la información diseñado para gestionar eficazmente las reseñas en línea incompletas. Además, se introduce un nuevo método de fusión de información basado en ER para agregar información incompleta. Para abordar la heterogeneidad, hemos definido otro marco de decisión en el que tanto las valoraciones como las reseñas textuales online serán consideradas y procesadas en valores intervalares. Esto completa el tercer objetivo de esta investigación.

En resumen, esta investigación ha alcanzado con éxito todos los objetivos definidos al inicio del estudio, aportando teorías, herramientas y modelos para abordar la evaluación de la sostenibilidad. Los resultados de esta investigación han mejorado significativamente el estado del arte en el campo anterior a nuestra investigación y también han abierto posibilidades para futuras investigaciones, como se discute en la siguiente sección.

A.5.2. Trabajos Futuros

A partir de los resultados obtenidos, existen varias direcciones potenciales de investigación que pueden basarse en las conclusiones de esta tesis doctoral. Algunos de los posibles trabajos futuros incluyen:

- Desarrollar un esquema de clasificación para la evaluación de la sostenibilidad. Aunque esta investigación se ha centrado en proporcionar el orden de clasificación de las alternativas, en algunos problemas de decisión del mundo real es más conveniente clasificar las alternativas en diferentes grupos según su rendimiento. Por lo tanto, en el futuro desarrollaremos un marco de clasificación para orientar a los responsables de la toma de decisiones sobre la inversión en múltiples proyectos sostenibles simultáneamente para mitigar los riesgos y maximizar los beneficios.

- Integrar algunos operadores de interacción para considerar las interrelaciones entre criterios y mejorar la fiabilidad de los resultados de las decisiones. Es importante reconocer que los criterios no siempre son independientes entre sí, sino que pueden presentar ciertos vínculos o dependencias. Al estudiar e incorporar operadores de interacción en el proceso de toma de decisiones, el modelo puede captar y reflejar mejor estas relaciones entre criterios, lo que conduce a evaluaciones más completas y precisas en escenarios de decisión complejos.

- Gestionar el comportamiento poco cooperativo de los expertos que se niegan a seguir las recomendaciones del moderador. Aunque esta investigación parte de la base de que todos los expertos cooperan, es esencial reconocer que, en la vida real, es posible que algunos expertos no sigan las sugerencias del moderador. Por lo tanto, en futuras investigaciones, el desarrollo de estrategias para gestionar y manejar este comportamiento no cooperativo es de suma importancia para garantizar la solidez y la eficacia del proceso de toma de decisiones.

- Proponer otras estructuras de preferencias para procesar eficazmente la información de los revisores, como sus conexiones sociales o la semántica individual personalizada. En la actualidad, cuando se utilizan las reseñas en línea como ayuda para la toma de decisiones, normalmente sólo se tiene en cuenta el contenido de la reseña. Sin embargo, los individuos tienen diferentes hábitos y tendencias de expresión, lo que puede influir en la interpretación de sus reseñas. Si se tiene en cuenta información adicional, como sus conexiones sociales o la semántica individual personalizada, es posible mejorar la precisión de la comprensión e interpretación de sus opiniones de una forma más matizada.

- Desarrollar un sistema de recomendación basado en el marco de decisión propuesto. Aprovechando la valiosa información derivada de los comentarios en línea y el marco de toma de decisiones, se pueden generar recomendaciones personalizadas para los usuarios.

Estas recomendaciones ayudarán a los usuarios a tomar decisiones bien informadas que se ajusten a sus preferencias y requisitos específicos. Un sistema de recomendación de este tipo puede mejorar significativamente la satisfacción del usuario y los resultados de la toma de decisiones.

Publicaciones adicionales

Durante el desarrollo de esta investigación se han presentado otras publicaciones, que no se incluyen en esta memoria. A continuación se presenta una lista de dichas publicaciones:

† Revistas Internationales:

- Shi-Fan He, Ying-Ming Wang, Xiao-Hong Pan, Kwai-Sang Chin. A novel behavioral three-way decision model with application to the treatment of mild symptoms of COVID-19, *Applied Soft Computing*, 124: 109055, 2022.
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