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Consensus modeling with nonlinear utility and cost constraints: A case study

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ABSTRACT

In complex group decision making (GDM), reaching a consensus needs both the adequate communication and exchange between the individual decision makers (DMs) and the input of a moderator, who may take various effective actions, such as providing financial compensation (collectively referred to as "consensus cost"), to convince the DMs to gradually modify their opinions and to reach a final consensus. This study constructs new consensus models that aim to maximize the GDM utility under the premise of limited consensus cost and nonlinear utility/preference constraints for both the individual DMs and the moderator. The objective function (the utility level of the entire GDM) derived from the proposed models can be seen as a measurement of the group consensus degree. Moreover, using the pollutant reduction negotiations between the government and manufacturing enterprises as a case background, we construct a group reduction consensus model based on nonlinear preference constraints and limited consensus cost and economically interpret the model parameters. Results show that different preference combinations of the DM and moderator will affect the optimal consensus values. Additionally, the moderator's preference structure influences the final GDM results to some extent. The modeling mechanism used in this paper will be reference for solving real-life consensus GDM problems.

1. Introduction

In group decision making (GDM), different individual decision makers (DMs) will eventually form a consensus of either clear support or opposing opinion on a specific issue through full communication and multiple effective discussions [1–4]. However, most large complex GDM problems present two difficulties: (1) because of their different cultures and educational backgrounds, the DMs usually present their views in various ways [5–8]; and (2) the DMs usually represent different interest groups or they want their opinions to be taken seriously to fully reflect their own values [9], so it is difficult for them to spontaneously communicate with each other and to reach a compromise consensus. In such cases, GDM requires a moderator with strong leadership and communication skills [10–12], who exerts their authority and takes various effective actions, such as providing financial compensation (collectively referred to as "consensus cost"), to convince the DMs to gradually modify their opinions and to reach a final consensus. From the perspective of resource consumption, the moderator seeks to keep the total costs (e.g., time and fees) of the final consensus as low as possible [10,11,13], even in fuzzy GDM problems [14]. However, from the angle of each DM's utility (the numeric value that DMs allocate to a specific result based on their own preference [15]), a low cost is not conducive to obtaining a consensus. As a result, the moderator must allocate further resources to meet the majority of the DMs' utility preference needs.

The manufacturing industry provides an important source of local government revenue in China; however, local governments urgently need to control the pollution caused by these manufacturing enterprises. Hence as an example, this study examines the government/enterprise relationship on the issue of manufacturing pollutants (waste water, waste gas and waste) reduction (hereafter referred to simply as "reduction"). This case encompasses both GDM and consensus decision making aspects. On the one hand, through constant communication and consultation as well as the timely grasping of the actual enterprise development situation, the government helps the local enterprises to achieve energy conservation by means of policy formulation or financial support: in this instance the reduction negotiations between the government and enterprises is a GDM problem. On the other hand, the

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government needs to determine the specific amount of reduction for each enterprise after negotiations based on firm size: in this instance the specific reduction value is a consensus decision making problem. From the government perspective – without considering the actual reduction capability of enterprises – they will naturally want companies to reduce as much as possible while keeping the total cost of reaching a consensus on the reduction standards (consensus goal) as low as possible. From the enterprise perspective, they have different reduction abilities and often develop distinct attitudes (utility preferences) toward the reduction standards made by the government. The reduction consensus process of the example could be understood as: by arranging a reasonable consensus negotiation budget, the government not only persuades enterprises to accept the final standards, but it also realizes the optimal reduction utility for each enterprise to achieve a win–win outcome.

A common indicator to measure whether a consensus GDM process is effective or not, is calculating the degree of unanimity for or against the decision. Moreover, giving full consideration to the utility preference of each DM is extremely important to improve the consensus degree and the consensus range. Facing different problems and backgrounds, DMs in GDM tend to exhibit different preference attitudes and satisfaction levels. The monotonicity and concavity concepts indicate that the utility function plays a fundamental role in reflecting the DM's preference structure [16]. In 1968, Borch [17] first proposed the concept of target-oriented utility: this was subsequently promoted by, among others, Castagnoli and LiCalzi [18], Bordley and Kirkwood [19], Tsetlin and Winkler [20] and Durbach [21]. The target-oriented utility function generally specifies the utility to zero (if the target is not achieved) or to one (if the target is achieved) at a given probability information [22]. As the utility function can express the DM's preference structure (meaning that it can denote the DMs' subjective utility values) then apparently, only introducing two real numbers – zero and one – cannot fully express the DMs' subjective psychology. According to the fuzzy theory proposed by Zadeh [23], the membership degree of $[0, 1]$ can denote the DMs' utility level that will more accurately reflect the DMs' subjective judgments. For example, Refs. [24–26] measure the DMs' preference/utility by constructing linear utility functions based on membership degree. The most widely used linear utility function forms include the simple type [27,28], the piecewise type [24,29], the S-shaped type [25,26], the U-shaped type [30], the triangle type [31] and the trapezoidal type [14,32]. It is relatively simple to solve optimization models by linear forms, so they have been successfully applied in multi-objective GDM research [33,34]. However, in real-life decision making scenarios, DM's preferences generally follow nonlinear trends rather than a simple linear increment or decrement as their opinions change. That is, the traditional linear utility function cannot accurately describe the DMs' subjective utility changes in a GDM problem. For instance, the utility increment of improving wages from \$300 to \$800 for the low-income earners will be far more than that of improving wages from \$11,300 to \$11,800 for the high-income earners. Similarly, an increase in the utility amount from 70 to 80 points (out of 100) for a student will be far less than that from 90 to 100 points, meaning that they have to work harder. Therefore, the nonlinear utility function forms are very significant when exploring the group consensus problems.

Nonlinear utility functions have been successfully applied to solve a variety of decision making problems related to behavior or psychology, such as strategic choice [22], bilateral auctions [35] and the interpretation of agriculture economic phenomena [36]. Specifically, Feng and Lai [22] research the strategic freight forwarder selection of China Southern Airlines: they choose different utility functions with corresponding cost, benefit or interval forms for specific attributes. Their research helps managers to make reliable decisions and provides them with a coefficient to check the degree of group consensus. Jin et al. [35] propose a multi-round double auction mechanism based on dynamic utility function and genetic algorithms that considers the diverse utility forms of both buyers and sellers. They design auction protocol and system architecture and verify the practical value of the proposed mechanism. Further, Refs. [36,37] respectively explore agriculture economic phenomena and the bilateral single-issue negotiation problem with nonlinear utility function. Notably, the S-shaped value function first presented in 1979 [38], is a widely used nonlinear utility function form that is successfully applied in many areas. For example, Pandian [39] applies an S-shaped membership function into industrial engineering's fuzzy mix product selection problem and obtains an optimal solution with a high degree of satisfaction through a combination of neural networks and genetic algorithms. Using modified S-curve membership functions, David and Pandian [40] solve a transportation planning problem with given supply/demand and a multi-objective fuzzy. They compare S-type and linear membership function performances through a case study. Moreover, Raymond [41] applies S-shaped utility function and game theory to analyze the relationship between the psychology and the behavior of individual DMs, and concludes that there is a gap between the normative theory of ideal behavior and the descriptive theory of observed behavior. Moreover, a new S-type utility function is proposed by Kuznar [42] to measure the risk-sensitive behavior of organisms, which overcomes the previous concave or step utility function limitations relating to not modeling the attraction to risk, or an overly simple or discontinuous description of some complex behaviors. However, the minimum variance method and the branch and bound method [43,44], both prove that the DMs' preferences (except for the utility function) can also be expressed in terms of a pairwise comparison matrix in consensus decision making research.

Consensus decision making needs to fully consider the DMs' attitudes towards some specific problems, while nonlinear utility functions – particularly the S-shaped ones – can simulate the DMs' psychological preferences. Therefore, this study investigates how to introduce the nonlinear utility function into the consensus decision making research, while accounting for the consensus cost to realize the optimal group utility of the entire GDM. Using the pollutant reduction negotiations between government and manufacturing enterprises as a case background, this study constructs a group reduction consensus model based on diverse nonlinear preference constraints to further explain the rationality and economic significance of the proposed models. The main contributions of this paper are as follows: (1) compared with the linear form, the nonlinear utility function as introduced can effectively reflect individual preferences to more realistically obtain the optimal consensus opinion for the entire group; (2) the new optimization consensus models are based on the incentive compatibility principle [45,46]: through using incentives (measures), such as providing compensation or meeting individual utility requirements, the moderator ensures that each individual opinion is predisposed toward favoring the moderator's own interest, thereby obtaining their desired consensus opinion; and (3) the variable λ (see Section 3), as the objective function in the proposed models, can not only measure the entire group's utility level, but can also be considered as a new way to measure the consensus degree.

The reminder of this paper is constructed as follows: In Section 2 we introduce the utility functions on the basis of the DMs' opinions. We propose the maximum utility consensus optimization models based on parabolic or S-type utility curves in Section 3. Those consensus models view the limited negotiation cost as constraints, and also consider the risk preference of each individual DM. Taking the reduction GDM problem in the manufacturing industry as an example, Section 4 builds a group reduction