

Fuzzy decision making and consensus: Challenges

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Abstract. Group decision making is part of every organizational life. It is a type of participatory process in which multiple decision makers acting collectively, analyze problems, consider and evaluate several alternatives, and select from among the alternatives a solution. In such a situation, an important issue is the level of agreement or consensus achieved among the group of decision makers before obtaining the solution. In the beginning, consensus was meant as a full and unanimous agreement. Regrettably, this stringent concept of consensus in many cases is a utopia. As a result, and from a pragmatic point of view, it makes more sense to speak about a degree of consensus and, here, the theory of fuzzy sets has delivered new tools for the analysis of such imprecise phenomena like consensus. Given the significance of reaching an accepted solution by all the decision makers, consensus is a major aim of group decision making problems and, in such a way, it has obtained a great attention in the literature. However, there still exist several dares which have to be tackled by the researchers. The purpose of this paper is to bring out several issues that represent challenges that have to be faced.

Keywords: Group decision making, consensus, fuzzy set theory, fuzzy logic

1. Introduction

Group decision making (GDM) is an important problem that is relevant to most crucial human activities. Essentially, in a GDM problem, individuals, namely decision makers, openly reveal their opinions, or preferences, as to the alternatives or options considered [32]. It is usually considered that decisions made by groups are often different from those made by individuals and research in social psychology on group performance suggests that group tends to be more effective than direct aggregation of individual group members' choices and makes better decisions than the most highly skilled individual in a group [64].

In a GDM situation, the group of decision makers interact to achieve a solution. To do so, the decision makers have to express their opinions by means of a set of assessments over a set of feasible alternatives. An important question here is the level of agreement or consensus reached among the group of decision makers before obtaining the solution. Many results of psychological investigations and also a real life experience clearly show that obtaining a solution without a sufficient agreement among the decision makers is not reasonable as it may be not accepted, and can lead to a solution with no chance for its practical implementation or even prevent the survival of the group in the long time period [23]. Therefore, it is desirable that the decision makers carry out a consensus process [5, 51], in which all of them discuss their opinions in order to arrive at consensus. Initially, the decision makers usually disagree in their opinions, that is, they are

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far from consensus. Normally, the communication process between the decision makers involves a designated person who coordinates all the decision makers of the group and tries to convince them to change their opinions for the benefit of the group. This role is directly attributed to a moderator who runs the consensus process until the group gets consensus [5, 30].

Traditionally, consensus was meant as a full and unanimous agreement. However, in practice, this definition is inconvenient because it only allows differentiating between two states, namely the absence and existence of consensus. In addition, it has been deemed questionable if such a state is possible in virtually all real world situations [33]. On the one hand, in nontrivial practical situations, groups rarely arrive at such a consensus because of some inherent differences in value systems, flexibility of members, etc. On the other hand, even if so, a consensus process may be too long [54]. Therefore, from a pragmatic point of view, consensus can be viewed not necessarily as a full and unanimous agreement, if not that it can be admitted that the decision makers are not willing to fully change their opinions so that consensus not be a unanimous agreement. According to it, consensus aims at attaining the consent, not necessarily the agreement, of the decision makers by accommodating views of all parties involved to accomplish a decision that will yield. This decision will be beneficial to the whole group, not necessarily to the particular decision makers who may give consent to what will not necessarily be their first choice but because, for instance, they wish to cooperate with the group. The full consent, however, does not mean that each decision maker is in full agreement [5]. In such a way, it makes more sense to speak about a distance from or a degree of consensus and, here, the fuzzy set theory introduced by Zadeh [66] has delivered new tools for the analysis of such imprecise phenomena like consensus.

Along with this line of reasoning, a concept of a fuzzy majority, which is represented by means of fuzzy linguistic quantifiers, was introduced by Kacprzyk [67]. This concept was used for deriving soft measures of consensus [33–35], which assess the degree of consensus in a more flexible way, reflecting the large spectrum of possible partial agreements and guiding the discussion process until widespread agreement, not always full, is achieved among the group of decision makers. Following this idea, numerous further extensions have been proposed. For a comprehensive review of group decision making and soft measures of consensus under a fuzzy majority, we may refer the reader to [7, 30, 37].

In a GDM problem, given the importance of obtaining an accepted solution by the whole group of decision makers, the consensus has attained a great attention and it is virtually a major goal of these problems. Especially, the interpretation of the consensus based on the concept of a fuzzy majority, which is more human-consistent and suitable for reflecting human perceptions of the meaning of consensus, has been the basis of most of the consensus approaches proposed by the researchers. However, there still exist several questions which have to be faced. The objective of this paper is to show the challenges that researchers in this topic still must face.

The rest of the paper is organized as follows. First, in Section 2, the typical fuzzy GDM framework is introduced along with a description of a usual consensus process. Next, the challenges which have to be faced by the new consensus approaches are presented in Section 3. Finally, in Section 4, we conclude this paper.

2. Fuzzy group decision making and consensus

This section is dedicated to introduce the typical fuzzy GDM framework to develop a consensus process. Particularly, we describe the fuzzy GDM problem, the usual consensus process, and the fuzzy linguistic quantifiers, which are utilized to represent the concept of a fuzzy majority.

2.1. Fuzzy GDM problem

A classical GDM situation [12, 19] is defined as a situation in which there is a problem to solve, a solution set of feasible alternatives, $X = \{x_1, x_2, \dots, x_n\}$ ($n \geq 2$), and a group of decision makers, $E = \{e_1, e_2, \dots, e_m\}$ ($m \geq 2$), which are characterized by their knowledge and background, who convey their preferences or opinions about the set of alternatives to achieve a common solution. Particularly, in a fuzzy context, the aim is to classify the alternatives from best to worst, associating with them some degrees of preference expressed in the $[0, 1]$ interval.

The opinions given by the decision makers have originally been equated with some utilities resulting from some courses of action, probabilities of them, and similarly. However, the process of GDM is focused on human beings, with their intrinsic subjectivity, imprecision and vagueness in the verbalization of opinions, and, therefore, the fuzzy set theory [66] has been utilized in this research area for a long time as it is a more general and richer representation of opinions than a subjective probability of the occurrence of an event in question,

which was the point of departure of many traditional GDM approaches [21, 24, 39].

The seminal works, in which fuzzy preference relations were used, were those ones by Spillman and Bezdek [52, 53]. A fuzzy preference relation PR on a set of alternatives X is a fuzzy set on the Cartesian product $X \times X$, i.e., it is characterized by a membership function $\mu_{PR} : X \times X \rightarrow [0, 1]$. Then, a fuzzy preference relation PR may be represented by the $n \times n$ matrix $PR = (pr_{ij})$, being $pr_{ij} = \mu_{PR}(x_i, x_j)$ ($\forall i, j \in \{1, \dots, n\}$) interpreted as the preference degree or intensity of the alternative x_i over x_j : $pr_{ij} = 0.5$ indicates indifference between x_i and x_j ($x_i \sim x_j$), $pr_{ij} = 1$ indicates that x_i is absolutely preferred to x_j , and $pr_{ij} > 0.5$ indicates that x_i is preferred to x_j ($x_i \succ x_j$). Based on this interpretation, we have that $pr_{ii} = 0.5 \forall i \in \{1, \dots, n\}$ ($x_i \sim x_i$). Since pr_{ii} 's (as well as the corresponding elements on the main diagonal in some other matrices) do not matter, they are usually written as ‘-’ instead of 0.5 [32].

Fuzzy preference relations are one of the most used to represent the opinions given by the decision makers because of their effectiveness as a tool for modeling decision processes and their utility and easiness of use when we want to aggregate decision makers' preferences into group ones [32, 55]. Furthermore, other types of preference relations as, for instance, multiplicative preference relations [50], linguistic preference relations [2, 6], and intuitionistic fuzzy preference relations [40, 54, 62] are also used. However, the preference relations are not the only preference structures which are used to represent the opinions given by the decision makers. Other type of representation formats of preferences are:

- *Preference orderings*. The preferences of a decision maker $e_l \in E$ about a set of possible alternatives X are described as a preference ordering $O^l = \{o^l(1), \dots, o^l(n)\}$ where $o^l(\cdot)$ is a permutation function over the indexes set $\{1, \dots, n\}$ for this decision makers [55]. Therefore, a decision maker gives an ordered vector of alternatives from best to worst.
- *Utility values*. A decision maker $e_l \in E$ provides his/her preferences about a set of possible alternatives X by means of a set of n utility values $U^l = \{u^l_1, \dots, u^l_n\}$, $u^l_i \in [0, 1]$, the higher the value for an alternative, the better it satisfies decision maker' objective [28].

It is important to point out that among the different representation formats of preferences, preference

relations are the most used for solving GDM problems due to its effectiveness in modeling decision processes, because the effort to complete pairwise evaluations is far more manageable in comparison to any experimental overhead we need when assigning membership grades to all alternatives of the universe in a single step, which implies that the decision maker must be able to evaluate each alternative against all the others as a whole, which can be a difficult task. The pairwise comparison helps the decision maker focus only on two alternatives once at a time. It reduces uncertainty and hesitation while leading to the higher of consistency, that is, information which does not imply any kind of contradiction [15, 29, 58].

2.2. Consensus process

A way of solving a GDM problem is by carrying out a selection process. It consists in choosing a solution set of alternatives from the opinions expressed by the decision makers [19], without taking into account the level of agreement achieved among the decision makers. It involves two steps [8, 26]: (i) aggregation of individual preferences, where a collective opinion is obtained by means of the aggregation of all individual opinions, and (ii) exploitation of the collective preference, in which the global information about the alternatives is transformed into a global ranking of them, from which the set of solution alternatives is obtained. However, it can lead sometimes solutions which are not well accepted by some decision makers in the group [5, 51]. It is because the decision makers could think that their opinions have not been considered correctly to obtain the solution and, hence, they might reject it. To avoid it, it is recommendable that the decision makers conduct a consensus process in which they discuss and change their opinions gradually to achieve a sufficient level of agreement before applying the selection process. Consequently, GDM problems are usually faced by applying a consensus process and a selection process before a final solution is obtained [30, 36].

A consensus process proceeds in a multistage setting, in which the decision makers modify their initial opinions step by step until some consensus is achieved [5, 51]. In such a situation, it is presupposed that the decision makers are committed to those modifications. To model this process, two approaches have been used. On the one hand, the consensus process has been modeled by using matrix calculus or Markov chains to model the time evolution of changes of points of view toward consensus [14, 20, 25]. This approach has

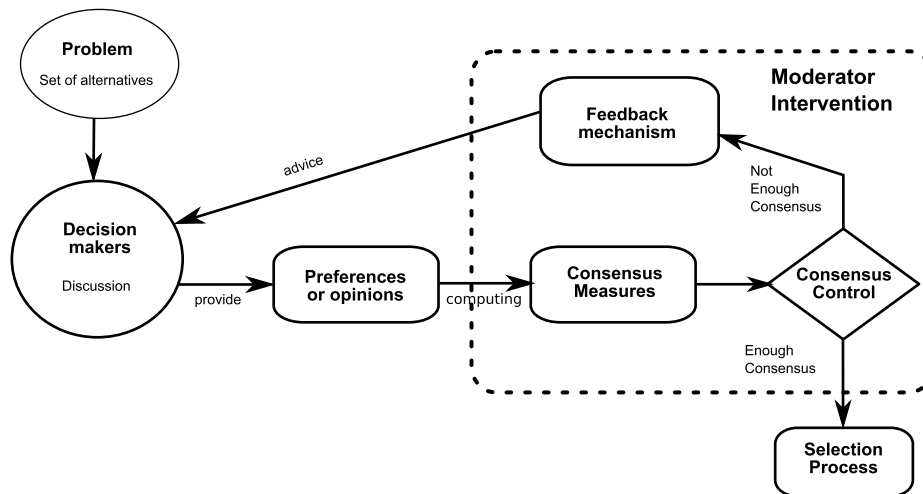


Fig. 1. Consensus process.

contributed much to the understanding of the consensus process and its dynamics, but it has been admitted much more promising to run the consensus process with the support of a special agent, called a moderator, who is responsible for running the consensus reaching session in question by persuading the decision makers to change their opinions by rational arguments, persuasion, etc., and keeping the process within a period of time considered [5]. In such a case, it is clear that the moderator should be supported by some information to be provided by consensus support tools, and here fuzzy logic can play an important role [18]. This second option of a moderator running the consensus process is more efficient and effective and, therefore, it has been predominant in the consensus approaches proposed in recent times.

In the following, we are going to describe the consensus approach based on a moderator as it is the most used in the literature. Here, the consensus process is defined as an iterative process composed by several consensus rounds in which the decision makers accept to modify their testimonies according to the advice given by the moderator, which knows the level of agreement or consensus among the decision makers in each moment of the consensus process by means of the computation of some consensus measures. Therefore, the consensus process is composed of the following steps (see Fig. 1):

1. The problem which has to be solved is shown to the decision makers, along with several alternatives among they have to choose the best one.

2. Decision makers discuss and share their knowledge about the problem and the alternatives with the aim of facilitating the process of latterly providing their preferences.
3. Decision makers express their opinions about the alternatives in some preference representation format.
4. The moderator receives all the preferences given by the decision makers and computes some consensus measures that will allow him to identify if an enough level of agreement or consensus has been reached or not.
5. If an enough level of agreement or consensus has been reached, the consensus process stops and the selection process begins. Otherwise, a feedback mechanism can be applied in which the moderator, with all the information that he/she has (all opinions given by the decision, consensus measures and so on) can prepare some guidance and advice for decision makers to more easily reach consensus. This step is optional and it is not present in all the consensus models.
6. Finally, the advice is provided to the decision makers and the first round of consensus finishes. Then, the decision makers must discuss their testimonies in order to approach their points of view (Step 2).

Finally, it is important to point out that the moderator can introduce some subjectivity in the consensus process. New consensus models have been proposed with the aim of making more effective and efficient the decision making process by substituting the moderator

figure or by providing to the moderator with better analysis tools [9, 11, 28, 38, 46]

2.3. Fuzzy linguistic quantifiers

To represent the amount of items, which satisfies a given predicate, quantifiers can be used. Classic logic is restricted to the use of two quantifiers: (i) “there exists”, and (ii) “for all”, which are closely related to the “or” and “and” connectives, respectively. However, human discourse is much richer and more diverse in its quantifiers, for example, “about 5”, “most”, “at least half”, “all”, “as many as possible”. For this reason, Zadeh introduced the concept of fuzzy linguistic quantifier [67] in an attempt to bridge the gap between formal systems and natural discourse and, in turn, provide a more flexible knowledge representation tool.

Zadeh proposed that the semantics of a fuzzy linguistic quantifier can be captured by using fuzzy subsets for its representation. In such a way, he differentiated between the following two types of fuzzy linguistic quantifiers:

- *Absolute quantifiers*, which are used to represent amounts that are absolute in nature as, for instance, “about 2” or “more than 5”, and are closely related to the concepts of the count or number of elements. These quantifiers were defined by Zadeh as fuzzy subsets of the non-negative real numbers R . In this approach, an absolute quantifier can be represented by a fuzzy subset Q , such that for any $r \in R^+$, the membership degree of r in Q , $Q(r)$, indicates the degree in which the amount r is compatible with the quantifier represented by Q .
- *Relative quantifiers*, which represent proportion type statements as, for example, “most” or “at least half”, and can be represented by fuzzy subsets of the unit interval. For each $r \in [0, 1]$, $Q(r)$ indicates the degree in which the proportion r is compatible with the meaning of the quantifier it represents.

An absolute quantifier, $Q : R^+ \rightarrow [0, 1]$, satisfies $Q(0) = 0$ and $\exists k$ such that $Q(k) = 1$, whereas a relative quantifier, $Q : [0, 1] \rightarrow [0, 1]$, satisfies $Q(0) = 0$ and $\exists r \in [0, 1]$ such that $Q(r) = 1$.

The above concept of a fuzzy linguistic quantifier was essential to represent the concept of fuzzy majority for measuring consensus and deriving new solution concepts in GDM problems [33–35]. One the one hand, majority has been defined as a threshold number of individuals. On the other hand, fuzzy majority is a soft majority concept expressed by a fuzzy linguistic

quantifier exemplified by “much more than a half”, “almost all”, “most”, and so on, which can be formally handled by a calculus of linguistically quantified propositions [67] and also by using Yager’s Ordered Weighted Average (OWA) operators [65] or other aggregation operators that offers a much needed flexibility and generality [17, 68]. The fuzzy majority has then been the key point for the new definitions of soft consensus.

3. Challenges

Once the most important aspects of a fuzzy GDM problem have been described along with the main characteristics of a consensus process, both some challenges which have still to be solved and some new ones that have arisen as a consequence of the new features of the modern real-world applications are presented in this section. In particular, the following challenges have been identified: (i) consensus in social networks, (ii) consensus under new preference structures, (iii) consensus in heterogeneous contexts, (iv) consensus and new measures, (v) consensus and visualizations tools, and (vi) consensus and software. In the following subsections, we introduce all of them.

3.1. Consensus in social networks

Social networks [60] presents some characteristics that differentiate them to the situations in which the consensus approaches existing in the literature have usually been applied. For instance, on the one hand, social networks present thousands of users, but it is possible that many of them do not directly participate in the decision process. On the other hand, it is a common issue that some of the users might not be able to collaborate during a whole decision process, but only in a part. In addition, there is a real time communication among its members and it is typical that users exchange opinions through their interaction with other users. This interaction is habitually local in the sense that only neighboring agents in the network exchange information, establishing trust relationships among them [61]. Anyway, social networks have become a dominant force in society and the collective opinions given in a social network can determine the path society takes.

Therefore, it would be interesting to study some of the following challenges:

- Development of new consensus approaches adapted to the features of the social networks,

for example, to recommend tags, opinions, new friends, new items, etc.

- To introduce trust management models [59] in the consensus process. In such a way, trust degrees could be considered when we compute similarity among decision makers.

3.2. Consensus under new preference structures

Recently, new preference structures for representing the decision makers' opinions have been proposed. On the one hand, in [57], Torra presented the hesitant fuzzy sets, a new extension of fuzzy sets, motivated by the common difficulty that often appears when the membership degree of an element must be established and there are some possible values that make to hesitate about which one would be the right one. Since then, a quick growth and applicability of the hesitant fuzzy sets can be found in the specialized literature [31, 49]. On the other hand, when linguistic information is used to represent the preferences given by the decision makers, different linguistic computational models can be used [27], which rely on the special semantics of the linguistic terms, usually fuzzy numbers in the unit interval, and the linguistic aggregation operators are based on aggregation operators in $[0, 1]$. However, in [41], a new linguistic computational model based on discrete fuzzy numbers whose support is a subset of consecutive natural numbers was presented ensuring the accuracy and consistency of the model, and in which no underlying membership functions are needed.

There are still some open questions about the use of new preference structures in consensus approaches:

- To extend the existing consensus models to work with hesitant fuzzy sets and their extensions.
- To study all elements of a consensus model which have to be adapted to operate with the linguistic computational model presented in [41] and, according to it, to propose new consensus models when fuzzy linguistic information is used to represent the preferences expressed by the decision makers.
- Development of new preference structures demonstrating its application in consensus models.

3.3. Consensus in heterogeneous contexts

In some GDM situations, it is considered that to each decision maker is assigned an importance degree

reflecting his/her importance level or knowledge degree about the problem, and, then, it is defined as a heterogeneous GDM framework [10, 42]. For instance, when several medical experts give their testimonies on the possible illness that a patient presents, there will be medical experts with more experience or with more study years than others and, as a consequence, their opinions must not be considered with equal relevance. This heterogeneity has been tackled by assigning a weight value to each decision maker that is used in the aggregation step to model their different importance levels or knowledge degrees. However, it would be desirable to develop consensus approaches which consider the decision makers' importance weights not only in the aggregation step but also in other steps of the consensus round. A first work following this idea was presented in [48], where fuzzy preference relations were assumed to represent the opinions given by the decision makers. This consensus model was proposed following the idea that the decision makers with lower importance or knowledge level will need more advice than those decision makers that previously have at their disposal a better knowledge about the problem to be solved and, therefore, can make better decisions. As a result, it incorporates a feedback mechanism computing different amount of advice according to the decision makers' importance level. However, it has some drawbacks: (i) the solution obtained tries to obey the fuzzy majority principle but there could exist a limit scenario in which the tyranny of the minority is accomplished if the excellence group is very small inside the group of decision makers, and (ii) it is not able to detect when a high importance decision maker is wrong or inconsistent.

Therefore, with respect to consensus approaches in heterogeneous contexts, some challenges still have to be faced:

- To improve the feedback mechanism proposed in [48] in order to overcome its drawbacks.
- To extend the idea of adjusting the amount of advice required by each decision maker depending on his/her own relevance or importance level to other consensus approaches in which other preference representation formats different to the fuzzy preference relations are used.
- To study other different applications within the consensus process in such a way that the heterogeneity existing among the decision makers may be used to guide the decision process.

3.4. Consensus and new measures

Soft consensus measures represent the level of agreement among the decision makers and, in consequence, they have usually been modeled mathematically via a similarity function measuring how close decision makers' opinions or preferences are. Similarity functions are defined based on the use of a metric describing the distance between decision makers' opinions or preferences. Different metrics or distance functions have been proposed to implement in consensus models as, for instance: the Manhattan distance, the Euclidean distance, the Dice distance, the Cosine distance, or the Jaccard distance [16]. The distance function used to calculate the similarity among the opinions given by the decision makers affects the convergence of the decision process towards a consensus solution. Therefore, it is very important how to select the distance function according to the characteristics of a particular GDM problem because different distance functions can produce significantly different results. In [13], using fuzzy preference relation to represent the opinions provided by the decision makers, it was proved that the Manhattan and the Euclidean distances increase the global consensus level as the number of decision makers increases. On the other hand, the Cosine and the Dice distances result in a fairly similar consensus levels regardless of the number of decision makers, whereas the Jaccard distance function produces the lowest global consensus levels, being fairly stable in value regardless of the number of decision makers.

Concerning the use of distance functions to create new soft consensus measures would be interesting to study some of the following challenges:

- To analyze the performance of the about distance functions when other type of preference relations are used, such as multiplicative, linguistic or intuitionistic preference relations.
- To study the intrinsic features of the above distance functions that can be responsible for the significant differences in their application.
- To develop new soft consensus measures using other different distance functions and to analyze their behavior.

3.5. Consensus and visualization tools

The advent of the new information and communication technologies have allowed the development of new collaboration and information tools for the decision

makers being able to find solutions to GDM problems in which they cannot meet together with the others [4, 56]. However, in GDM situations where the decision makers do not have the possibility of discussing together it is possible that they may not have a clear idea about the current level of consensus achieved among all of them. In typical GDM situations, the decision makers gather together to discuss their preferences about the different alternatives and, therefore, it is to some extent easy to decide which decision makers have related preferences just by attending to the discussions among the decision makers. On the one hand, the decision makers may join or form distinct groups to better debate and reason out about the pros and cons of all the alternatives. On the other hand, it is more easy for the decision makers to influence the others and to detect if some of them are trying to bias the consensus process if they know the consensus state. However, it is very probably that decision makers need some guidance to establish connections among them and to obtain a clear view of the consensus state when direct communication is not possible. In order to help the decision makers in such situations, visual elements could be used as they may allow to the decision makers to have a more profound and clear view about the current consensus process and about which decision makers have alike or different preferences about the alternatives. Furthermore, visual elements can help the decision makers to detect if others are trying to bias the consensus process.

Some initial efforts have been done in this direction [1, 43, 45, 46, 63], but it still is an early stage of development and several future challenges have to be faced:

- New techniques and tools to automatically generate high level information and consensus diagrams about the consensus process need to be developed. These visual elements should display both the evolution of the decision process among the various consensus rounds and the information related to a single round.
- Other instruments as, for example, verbalization, which is a powerful means of communication that may take full advantage of the used of natural language, may also be employed to complement the visualization tools.

3.6. Consensus and software

A wide range of different methodologies have been proposed in the literature to support the consensus

in fuzzy GDM situations [30, 43]. However, the new paradigms and ways of making decisions as, for instance, web 2.0 frameworks and e-democracy, have nowadays made the intricacy of GDM situations to increase, involving in many cases a huge number of decision makers [4]. In this new scenario, it is needed automatic software tools not only to combine the information in the best possible way but also to better analyze the whole context, providing a rapid and complete understanding about the current state of the decision process. Some initial works have been proposed [3, 44, 45, 47], but they present some weak points: (i) they are developed as closed systems and, hence, they are not aimed to be upgraded or extended by other researchers since in most of the cases they do not provide the source code or they are based in proprietary software, (ii) they are extremely dependent of the user interface and, therefore, they cannot be adapted to work in other environments such as smart phones, (iii) not all of them make available graphical visualizations or output measures displaying the evolution of the process, and (iv) they do not offer the possibility of creating a data set to test and compare the performance of different approaches.

Therefore, there are still challenges and open questions about the software tools developed to carry out the consensus in a fuzzy GDM problem:

- It would be desirable that the software tools could be easily extended and customized by other researcher.
- They should be developed following a Model-View-Controller software architecture [22] in such a way that the logic of the application is totally independent from the graphical user interface. It allows that the software tool can be easily adapted to work in other environments as, for instance, tablets, smart phones and web.
- To compare the performance of different consensus approaches, these software tools have to offer a test mode enabling to set a trial scenario.
- They have to use visualization tools providing a rapid insight of the consensus state.

4. Conclusions

Since Kacprzyk proposed the concept of soft consensus measures, many consensus approaches based on them have been proposed, being it a very productive topic in the last years. In this paper, we have first

introduced some basic concepts to understand the topic and, then, we have comprehensively analyzed and presented some challenges to draw the attention of the researchers because they are unsolved or have still not been addressed. Concretely, the researchers have to pay attention in the proposal of consensus approaches in social networks and in the definition of new consensus measures, the use of new preference structures to represent the opinions expressed by the decision makers, the development of software systems to carry out decision processes in the current complex scenarios and visualization tools supporting a better understanding of the consensus state, and the improvement of the consensus approaches in heterogeneous contexts. We think these challenges will contribute this research topic continue being a hot topic in the future.

Acknowledgments

This Project was funded by King Abdulaziz University (KAU), under grant no. (27-135-35/HiCi). The authors, therefore, acknowledge technical and financial support of KAU.

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