

Applied Large-Scale Group Decision Making Using Systemic Consensus and Fuzzy Method of Comparative Linguistic Expressions

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Abstract. The complexity of democratic public decision-making has augmented with the surge of volumes of information. One response is using digital tools in decision-making processes to enable more flexibility than the conventional yes or no responses. We proposed a solution for a large-scale democratic decision-making process using soft computing and fuzzy logic, based on systemic consensus and action design research. Our integrative fuzzy decision-making process was designed to allow the consideration of all the arguments, the deliberation of all the alternatives, and the assessment of each alternative using comparative linguistic expressions. The method was used to resolve a conflict-generating traffic problem in Geuensee, a municipality in the Swiss canton of Luzern. The citizens voted on two dimensions of resistance and support about each of the proposed alternatives. The results were computed using fuzzy membership functions and a fuzzy logic table, evaluated with different computational variants. The output was a ranking of the best options, as assessed by the decision-makers. We found that this method for smart participation of citizens was accepted and generated involvement, leading to an effective outcome for the decision-makers. In the last section, we discuss evaluation and ethical considerations.

Keywords: participative decision making, fuzzy voting, fuzzy logic, comparative linguistic expressions, smart governance, cognitive cities.

1 Introduction

Democracies rely on the majority rule, a system of decision-making where the largest group decides the outcome, while as the less numerous groups must succumb to the majority's decision. This generates the inevitable winners - losers paradigm, which impacts all levels of our democratic mentality. Thus, whenever a controversial matter arises, most effort is allocated to gathering the majority by convincing as many people as possible of one point of view or the other. The resulting power struggles utilize a lot of resources and often shift the conversation from the main concern. [10, 25] To prevent the manipulation of decision-makers with emotional or rhetorical methods, evidence-

based decision-making has been increasingly promoted in formal settings, in which a set of objective criteria is used and weighed, based on impact or relevance. In some decision-making methods, the focus is on maximizing consensus by discussing and voting in successive rounds. [1, 7]

Also, citizens want and are expected to participate more than ever in thinking, deciding, and implementing decisions in societies. Finger and Portmann [5] have argued that the smart city – performing city-relevant duties by using ICT – must not only focus on resource management and sustainability as it is often expected, but also on the needs of the individual, which are often overlooked [19, 20]. The same applies to regions, where value can be created by bringing citizens into the decision-making process. [14].

In the following, we will present our framework and case study of Unterdorf St. in the canton of Luzern, Switzerland, where a real-life community traffic problem was resolved, and subsequent conflict was mediated, by using systemic consensus principles. We developed and applied a transdisciplinary [22] framework for large scale group decision-making (LS-GDM) using fuzzy methods, to perform comparative linguistic expressions on two scales of resistance and support about the 13 alternatives, resulting into a ranking of to be pursued in descending order of priority.

Section 2 briefly reviews the concepts of decision-making, large scale group decision-making (LS-GDM), systemic consensus, fuzzy decision-making, and comparative linguistic expressions (CLEs). Section 3 presents our framework for LS-GDM, using systemic consensus, CLEs and fuzzy logic. Section 4 introduces the case study of Unterdorfstrasse, a real LS-GDM, to demonstrate the functionality of the proposed process. In section 5, conclusions, ethical considerations, and reflections are presented.

2 Preliminary definitions

2.1 Literature Review

Large-scale group decision-making [11] using fuzzy methods [26] has been researched extensively, [11] by using CLEs, trapezoidal membership functions, [7, 9] and computing with words. [13] Some of these studies also present consensus reaching processes, related to LS-GDM, often involving multi-criteria decision-making. [1, 7, 8] Public decisions are a special case of LS-GDM, for which Torres van Grinsven, Hudec, Portmann and D’Onofrio [21] proposed a paradigm of flexible voting using fuzzy sets to enable more participation [19, 20] and human-computer interaction. [2]

Most of the literature on decision-making processes using fuzzy sets [1] involves experts and focuses on arguments, criteria, weighting [7, 12] and the study of hesitance [27] while as in our case study we chose the approach of including all the affected individuals in the decision-making process and deciding only about the alternatives in a single round of voting, without any other formal criteria than the self-evaluated levels of resistance and support. [6, 22]

The main difference from other fuzzy models such as fuzzy TOPSIS or AHP is that the decision reflects the support and resistance of the citizens about the alternatives, and not their assessment of criteria, as no objective criteria are used. [7, 8, 12] The decision-makers learned all the information and the arguments collected in favor and

against, discussed about them, considered all the alternatives, and voted using fuzzy sliders over the course of one single in-person event. We chose to use ordinary fuzzy sets although recent extensions of them exist, in order to make the process of decision-making very simple, explainable, and understandable by all people, since the model was used for a public, democratic decision.

Thus, the framework proposed herein is built using a 7-step decision-making process (Table 4, Appendix), ethical system design [4, 16], and action design research (ADR) [18, 24]. The latter is a computer science research paradigm, known as “knowledge through making” [10, 19, 24] Despite being criticized on its rigor and relevance, we considered it most suitable for our participative fuzzy voting case, and we relied on continuous evaluation [3] and feedback collection to ensure its validity. [15] Lastly, in choosing to include transdisciplinarity, we strived for a “generative processes of harvesting, capitalizing, and leveraging multiple expertise” [6, p. 116] by including all the stakeholders and considering their life experience as “expertise”.

2.2 Group Decision-Making Methods

When a group of individuals are presented with a choice of one or more alternatives to a problem, or of means to reach a desired goal, there is a case of group decision-making (GDM). The main difference between GDM and LS-GDM, is the size of the group. [7, 11]

Consensus Reaching Process

In consensus reaching processes (CRP), the decision is the most optimal proposal that the participants support unanimously. CRP is usually characterized by the following steps: (1) gathering preferences, (2) computing agreement level, (3) consensus control, and (4) feedback generation [7], repeated as many times as necessary, until the maximum level of consensus is reached. Between repetitions, experts or representatives have guided discussions, with the goal of maximising consensus [1]. When consensus or the highest level of agreement is reached, the CRP ends.

Systemic Consensus

One alternative to classic consensus is the Systemic Consensus Principle (SCP). It does not require full consensus, but only to strive to obtain the minimum dissensus, by assessing resistance to all possible alternatives and prioritizing those with the lowest levels. The result indicates where the highest union of interests lies, in relation to each of the possibilities. [10, 25]

2.3 Fuzzy Decision-Making

In 1965 Lotfi Zadeh introduced a human computational decision-making approach that allows for more flexibility than crisp voting and enables consensus-driven processes. [26] In contrast with 1 and 0 crisp calculation, the assignment of intermediate

values represents human reasoning more precisely, because inherent hesitancy, uncertainty, and irrationality of human thinking processes can be integrated. [19]

Comparative Linguistic Expressions (CLEs) and Membership Functions

Comparative linguistic expressions (CLEs) are used in fuzzy systems to implement fuzzy membership functions along a rating scale. Any two consecutive CLEs may overlap in their membership level. They enable fuzzy decision-making by using words and statuses to express the opinion about an alternative.

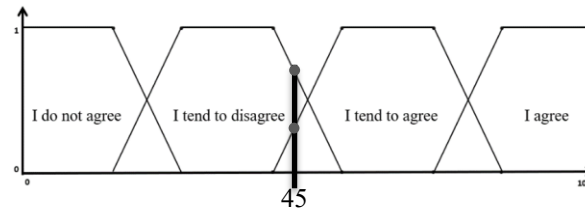


Fig. 1. Trapezoidal membership functions for agreement

Figure 1 shows all possible memberships by using four CLEs from “I do not agree” to “I agree”. At any point, a maximum of two of the CLE statuses will have a membership-value above 0.

On the x-axis of Fig. 1, the chosen rating scale value 0.45 leads to a membership of the CLE “I tend to disagree” with a value of 0.6 and a membership of the CLE “I tend to agree” with a value of 0.4. The other two CLEs have a membership-value of 0.

Fuzzy Logic

Fuzzy logic is a concept in fuzzy decision-making which refers to the fact that states are linked logically and not exclusively mathematically to each other [20]. This approach opens various possibilities for dynamic decision-making. All possible combinations are to be listed in a logic table and a final state for each combination is to be defined. The logical operators AND, OR, as well as others can be used. Fuzzy logic allows for making logical connections and enables statements and weightings.

In this chapter we briefly introduced the concepts of LS-GSM, CRP, SCP, fuzzy voting, CLEs, and fuzzy logic. In the next chapter, our framework for integrative fuzzy decision-making will be introduced.

3 Framework of an Integrative Fuzzy Decision-Making Process (I-FDM)

3.1 I-FDM Framework of the Decision-Making Process

Based on the concepts in the preliminary part, we developed a fuzzy decision-making process, which integrates all affected individuals as equal impact decision-makers

$D = \{d_1, \dots, d_n\}$, regardless of their specific expertise or lack thereof. The I-FDM process follows the following steps of decision-making:

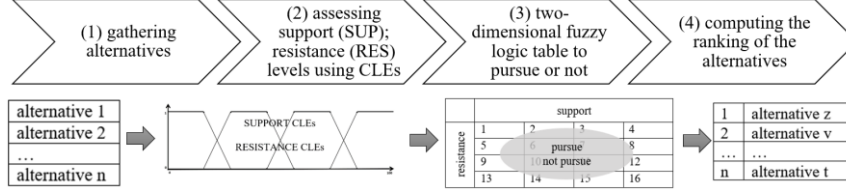


Fig. 2. The I-FDM process

After gathering the alternatives, we assess support and resistance levels by using CLE-sliders computed with membership functions. Then, we create a matrix of fuzzy logic rules, of how the CLE membership-values are computed to output statuses, indicating whether an alternative should be pursued or not. In the last step, through applying the fuzzy logic rules, a ranking of the alternatives by output statuses is generated.

3.2 Comparative Linguistic Expressions (CLEs)

In our framework, $S = \{s_1, s_2, s_3, s_4\}$ is the set of CLEs of support and $R = \{r_1, r_2, r_3, r_4\}$ is the set of CLEs for resistance. They are both represented through four statuses, as seen in Fig. 3. The following CLEs were considered the most suitable for the public decision-making process, and used for the two-slider assessment:

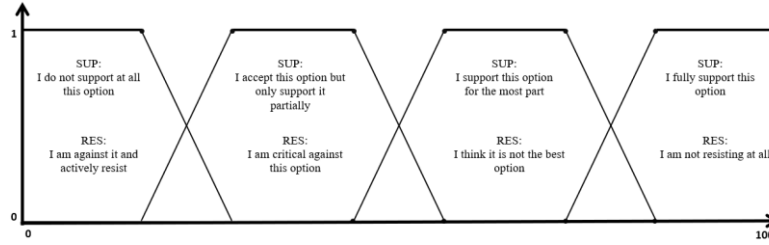


Fig. 3. Fuzzy membership function of S

The fuzzy envelopes, $envF(S)$ and $envF(R)$ are defined as a trapezoidal fuzzy membership function of support $S(a, b, c, d)$ and resistance $R(e, f, g, h)$ where $(a, b, \dots, h) \rightarrow [0, 1]$ and representing CLEs membership-degrees such that:

$$envF(S) = S(a, b, c, d) \quad (1)$$

$$envF(R) = R(e, f, g, h) \quad (2)$$

Since the single CLEs are not sharply divided, a trapezoidal membership-function of each CLE is used. Thus, we enabled a wide range on each CLE of a membership-degree of 1.00, as also shown in similar applications. [1]

Computing Fuzzy Envelopes

Every decision-maker d_i assesses all alternatives $ALT_j = \{a_1, a_2, \dots, a_n\}$, evaluating each of them by using the two sliders. These assessments $T_i = \{t_i^S, t_i^R\}$ per ALT_j are modelled by their fuzzy envelope (1) $t_i^S = \text{envF}(S)$ and (2) $t_i^R = \text{envF}(R)$; where i is the unique number of the decision-maker and j represents the unique number of each alternative to be assessed.

The arithmetic average of all ALT_j^R and ALT_j^S were computed. In the cases where A_j was very widely distributed, we considered the value to be not as significant as needed for a resilient result.

3.3 Two-Dimensional Fuzzy Logic Table

When all decision-makers (D) have committed their opinion for each alternative through the two sliders, a two-dimensional assessment dataset $T = \{T_1, \dots, T_n\}$ results. This dataset is used for the defuzzification and fuzzy logic evaluation. [1]

Table 1 shows the fuzzy logic rules in a matrix of how the assessments of support and resistance (T) are calculated into output statuses (O) by a logical conjunction. The output statuses are the CLEs $O = (o_1, o_2, o_3) \rightarrow \{\text{rather not pursue; pursue critical; pursue clearly}\}$. All 16 rules are shown in the 4x4 matrix in Table 1.

Table 1. Two-dimensional fuzzy logic rule in a matrix

		Support CLEs S (s_1, s_2, s_3, s_4)			
		I do not support at all this alternative	I accept this alternative but only support it partially	I support this alternative for the most part	I fully support this alternative.
Resistance CLEs (r_1, r_2, r_3, r_4)	I am against it and resist active	rather not pursue	rather not pursue	rather not pursue	pursue, critical
	I am critical against this alternative	rather not pursue	rather not pursue	pursue, critical	pursue, critical
	I think it is not the best alternative	rather not pursue	rather not pursue	pursue, critical	pursue, critical
	I am not resisting at all	pursue, critical	pursue clearly	pursue clearly	pursue clearly

E.g., If t_j^S is s_1 AND t_j^R is r_1 , then result = o_1 (rather not pursue). (3)

Through this logic table, individually weighing the statuses is possible. The weighing rules were agreed upon at the beginning of the decision-making process.

The AND operation based on the rule table is computed as a MIN function ($O = (S \cap R)$). Each output status (o_1, o_2, o_3) is computed by a logical disjunction function ($o_1^{TOTAL} = o_1^A \cup o_1^B \cup \dots \cup o_1^N$), OR operator or MAX function.

3.4 The Ranking of the Alternatives

The output of the I-FDM is a list of alternatives, compiled by using the disjunction value per output status. These alternatives are to be examined in detail, and, if possible, implemented. If the implementation is not possible, the next highest-ranking alternative will be checked.

The comparative order of the CLE sets, the formation of the alternatives, and the highest output membership-values, define the subordination. For example, the alternative ALT_j with the highest value of $o_1 = \{\text{pursue clearly}\}$ will be at the top of the ranking.

In this chapter, the I-FDM framework was introduced, comprising of four steps: (1) gathering alternatives, (2) computing SUP and RES using CLEs and fuzzy envelopes, (4) using a fuzzy logic table to compute outputs based on SUP and RES, and (4) the final output, as a ranking of alternatives. In the following chapter, the case study of Unterdorf St. will be introduced.

4 Case Study

We applied the I-FDM framework to solve a long withstanding conflict around Unterdorf St. in Geuensee, Luzern, Switzerland, where between March 2022 and December 2022 we implemented a participative process combining crowdsourcing alternatives and arguments, voting workshops, and UX-designed digital tools for fuzzy voting, to decide which of the alternative solutions should be pursued further.

4.1 Methodology

Based on the action design research methodology, we have developed a process of fuzzy decision-making, striving for systemic consensus with the use of two dimensions of resistance and support, which were then computed using a two-dimensional matrix for obtaining a ranking of the top options favored by the decision-makers.

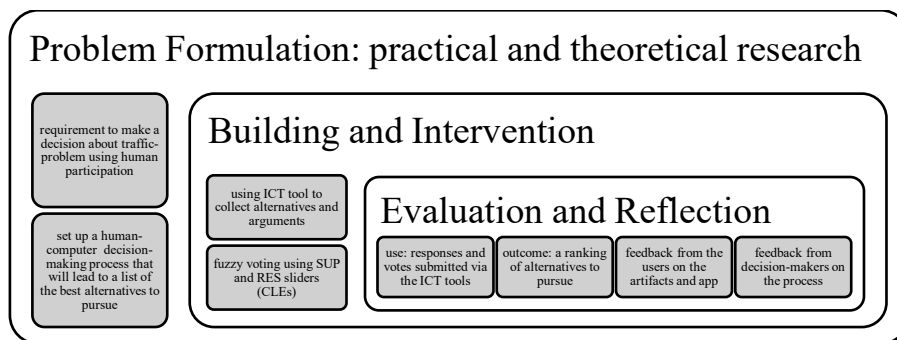


Fig. 4. Applied action design research in the process of decision-making

An important part of the methodology was the continuous evaluation, by means of collecting feedbacks in each production cycle: by assessing process steps, artifacts and

the app through the decision-makers and other people. The collection and processing of arguments and alternatives was also reflected upon, optimized, and jointly decided by those involved in the process.

Problem Formulation

The community of around 2000 people living in Geuensee, in the canton of Luzern, Switzerland, was dissatisfied with the traffic to and from an industrial area, passing through the residential street Unterdorf St., causing noise and safety risks. Previously proposed solutions have further escalated the conflict. The decision-making process started with 9 alternatives, to which 4 others were added during the process. [17]

Building and intervention

UX experts were involved for developing a dedicated, digital web-based platform, complying with all the values and requirements of the I-FDM process. In November 2022, two voting workshops have been organized, at which the decision-makers were informed about the problem, presented with the final 13 proposed alternatives as well as with the arguments collected in earlier stages. Finally, the decision-makers $D = \{d_1, \dots, d_{88}\}$ voted on the alternatives $ALT_j = \{a_1, a_2, \dots, a_{13}\}$ using two CLE sliders of resistance and support.

CLE Sliders

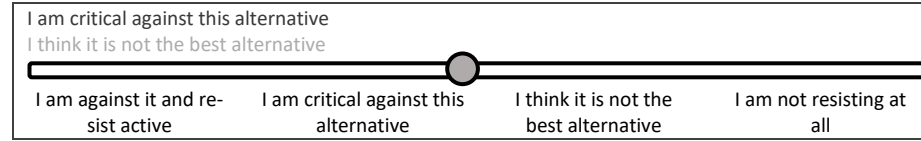


Fig. 5. Fuzzy sliders with membership functions, using transparency feedback of CLEs

Fig. 5 shows the display screen for one of the alternatives to be assessed. There is a slider, where the CLEs describe resistance-levels. They use text-feedback only, with different transparency levels, highlighted with a blue line on the upper slider, representing the membership level to the CLEs. In Fig. 5 the CLE “I am critical against this alternative” is chosen by a membership-degree of 80%, whereas the CLE “I think it is not the best alternative” is chosen by 20%. No numerical values of the assessment were shown on the screen.

4.2 Data Processing of CLE Membership-Values

A number of 2288 data entries were submitted on the 13 alternatives (ALT) by 88 decision-makers (D), during the two voting workshops. For each alternative, the average value per slider and the membership-degree to the CLEs s_1 to s_4 and r_1 to r_4 were calculated (Table 5, Appendix). Since the average values were the input variable in the fuzzy logic calculation, wherever the single assessments were very widely distributed, the values were classified as not sufficiently significant. Thus, we used the histograms to analyze the resilience of each of membership-degrees. (Fig. 6 and Fig. 7, Appendix)

4.3 Application of the Two-Dimensional Fuzzy Logic Table

The output statuses per alternative were calculated by the fuzzy logic rules from Table 1 using conjunction and disjunction. In Table 2 the computed membership-values of the output statuses are shown (Table 6, Appendix).

Table 2. Membership-degrees of output statuses of first 7 alternatives (only values > 0)

Alternative	Output statuses as CLEs			Rank
	Pursue clearly	Pursue critical	Rather not pursue	
3 Towards Sursee	0.167	0.833		1
8 Relocation		1.000		2
13 Repurposing		0.833	0.167	3
10 Combination time		0.750	0.250	4
7 Slow traffic		0.500	0.500	5
1 Schäracher St.		0.500	0.500	6
9 No action		0.167	0.750	7

Only one alternative “3 Towards Sursee” reaches the output status “pursue clearly”, with a membership-degree of 0.167. This option will therefore be the top priority on the ranking, followed by a descending list of the membership-degrees in the second CLE output status “pursue critical”. The second priority will be “8 Relocation”, followed by “13 Repurposing”, and so on, and so forth. Only the alternatives that are above option 9 “No action”, are to be checked in detail (Table 2).

In the first part of the section, we have presented the case study of Unterdorf St., a real-world application of the framework presented in section 2. The output was a ranking of 6 alternatives to be analysed for implementation by the decision-makers. Next, we will present the evaluation of our ADR method, conclusions, and reflections.

4.4 Evaluation

Dujmovic [3] defines evaluation as a process of assessing whether an object meets the requirements of the users and/or stakeholders. Considering this perspective, we have used the following evaluation guidelines.

Table 3. Outcome of the evaluation of the I-FDM

Use of Tools and Artifacts	We received a total of around 500 arguments on the 13 alternatives. Also, a total of 2288 CLE assessments were submitted by the 88 participants.
Outcome: The Ranking	Through the I-FDM process, we have generated and delivered a 6-item ranking of the most favored alternatives to be pursued by the decision-makers.
Feedback from Users on the Tools: Surveying the Decision-makers	A quantitative survey was applied to the voters about the digital platform built for the occasion. The feedback was positive: 97% answered that the decision-making tool was helpful for the assessment.
User Experience	An interesting UX observation potentially indicating that decision-making participants liked and deliberately made use of the possibility to choose in-between membership-degrees (Fig. 5), was that almost all of decision-makers (93%) chose one or more answers where two CLEs were shown at the same time, adding up to 32% of the 2288 assessments.

Feedback on the Process	The result was accepted by the representatives of the decision-makers and used for further verification. We employed qualitative methods of directly speaking with them, as well as the quantitative method of the survey. The result was that 88% of the participants said that they would use this method again.
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4.5 Conclusion

In this paper an integrative fuzzy decision-making framework has been presented, as it was applied with good results in the real-life case study of Unterdorf St. Being integrative and transdisciplinary, the model included all concerned parties as decision-makers, rather than only experts. The method combined measuring support, which is conventionally assessed in consensus-reaching processes (CRPs), with measuring resistance, thus striving for systemic consensus. The voting cycles were not repeated.

The results were computed with trapezoidal functions into fuzzy envelopes. A ranking was generated by applying fuzzy logic rules, allowing to weight the resistance as considered in the SCP. The 6-item list was handed to the decision-makers, for further verification and implementation, in descending order of priority.

In the evaluation section, we showed that the voting platform used the UX element of transparency-opacity of the status description, i.e., the transition from one CLE status to the other, to communicate to the user the ability to choose concomitant status memberships on each one of the CLE sliders. This feature was used by most of the users, for around a third of the assessments.

The feedback collected through surveys and qualitative assessments was overall positive, in terms of using the digital tools and other artifacts, of the result relative to the initial goal, and of using this decision-making method again.

Ethical System and Process Design

Our application of the I-FDM framework and consequent tools and artifacts produced, follows the paradigm of value-based IT design and ethical system design [16] by actively involving the stakeholders in all the phases of the system design. We wanted to make sure that the values of confidentiality, integrity, availability of data, authenticity, accuracy, are embedded into our integrative FDM framework.

Some examples are that the decision makers had access to the entire process and to intermediary results and were informed about how the data will be handled. Also, the problem statement was made clear, known to all, as well as the decisions that were taken and assumptions that were made in the beginning. The stage of gathering the alternatives was handled with particular care and transparency.

Our transdisciplinary integrative approach allowed all the stakeholders to participate, according to their own knowledge and competencies, and obtained a democratically legitimate result. Sufficient time was given for each step, allowing participants to understand and to find time to attend. Lastly, we tried to set the right expectations for the result. We also recommended that in deciding about the implementation, short-term as well as long-term perspectives would be carefully considered.

Reflection

The results of this process can be extrapolated in two main directions. Firstly, the I-FDM is suitable and effective in real-life case studies of urban planning, community conflict resolution, and others. The people that contributed throughout and participated in the voting, validated this method by giving their attendance and positive feedback. For the design science method, a key future takeaway is continuing the evaluation from multiple perspectives, as well as maintaining constant contact with real-world cases. The lack of excessive theorization of the research method helped to design a lean process, that put the users at its core. More analysis can be done of the data, by using different computational methods.

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Appendix: accessible on www.emmenegger.human-ist.ch

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