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STAKEHOLDER INVOLVEMENT IN DECISION MAKING: THE DEVELOPMENT OF A MASS PARTICIPATION TOOL

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December 8, 2022

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by

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Acknowledgement

Time flies. when I was here the first time, in the VUB, was 4 years ago. In the previous office in the B building, my promoter, Prof. dr. Cathy Macharis showed me a piece of research paper that a chart with multiple colorful lines are illustrated. At that time, I was still a master student, and didn't know that this chart would accompany me for so many years. After the first meeting with Cathy, I was still busy with finishing my master program. Cathy kindly offered me a student job, so I could gradually get used to what I would working on, i.e., the multi-actor multi-criteria analysis, MAMCA. I stayed in the research group the entire summer to study MAMCA methodology and develop its software. And in September 2018, I opened the door to the decision-support world.

I learned too many things during my 4-year PhD student life. Cathy taught me that decision making is not a simple mathematical problem, and that the output of a decision is not just an aggregated number. It is people to perform the evaluation, not the computer. Therefore, it is necessary to consider people's feelings and ensure that they are treated equally. Furthermore, we should consider the opinions from all the stakeholder groups. This is what my PhD about, to express the opinions from more participants, to facilitate a more comprehensive decision-making analysis. In addition to inspiring me with different ideas and guiding me when I went in the wrong direction, Cathy introduced me to many influential researchers in the field of operational research to broaden my horizons. She introduced me to Prof. dr. Pierre Kunsch, who is a very kind professor who taught me his philosophy: the decision-making methods should be understandable to the participants. She introduced me to Prof. dr. Yves De Smet, who is a great researcher and mentor, guided me to implement the experiments patiently, helped me publish scientific papers successfully. I really appreciate their efforts in mentoring me.

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路漫漫其修远兮，吾将上下而求索。
Long, long had been my road and far, far was the journey;
I would go up and down to seek my heart’s desire.

He Huang

Abstract

In a decision-making problem, sometimes there is a need to involve multiple stakeholder groups because of different reasons. For example, a sustainability decision-making problem needs to account not only for economic development but also for environmental and social actions; it must involve the key stakeholder groups in decisions. Decision-making requires support from key stakeholder groups, and the stakeholder groups need to express their opinions because the decision outcome will have an impact on those groups in turn. Multi-criteria group decision-making (MCGDM) is a family of methods that takes into account conflicting criteria and simultaneously pursuing the interests of multiple stakeholder groups. However, when larger groups, such as citizens, are involved in the decision-making process, decision-making problems become more complicated. Thus, it may be insufficient to invite only representatives of stakeholder groups, as conventional MCGDM does. In these cases, it might be more appropriate to establish a channel to hear from more voices in order to foster legibility and transparency in decision-making. A possible solution is to involve more participants in the decision-making process. I call it mass-participation decision-making. However, involving more participants also further increases the cost and complexity of the decision process and increases the number of potential conflicts among the participants due to the larger number of participants. Furthermore, the assessments made by participants who do not receive guidance or lack expertise run a higher risk of inaccuracy.

Therefore, I propose a new mass-participation decision-making framework, with the intention to exploit the benefits of mass-participation decision-making and minimize the drawbacks because of higher participants. Among existing MCGDM frameworks, multi-actor multi-criteria analysis (MAMCA) is chosen as a foundation. It is an MCGDM framework that allows different stakeholder groups to use different criteria to assess the performance of alternatives. The assessment results can be visualized in a single view that reflects the interests of different stakeholder groups. MAMCA is a suitable framework to express the preferences of stakeholder groups. With MAMCA, stakeholder groups can be made aware of the interests of other groups, so as to have a better mutual understanding of their positions, thereby making them more prone to searching for compromised solutions and to possibly reach a consensus.

Thus far, MAMCA has not yet been applied in mass participation contexts. When citizens or other large groups are involved in MAMCA projects, the current practice is to invite their representatives to a workshop along with other stakeholder groups, where they elicit criteria weights and assess the performances of the alternatives. However, when a stakeholder group is strongly heterogeneous, i.e., when its members have different priorities regarding the criteria, it is questionable whether the chosen representatives can represent the groups' interests. In these cases, the representation of the group by a single appointed representative might lead to an unacceptable loss of information.

Thus, the proposed mass-participation framework aims to provide a more legible procedure to increasing the level of representation; this is done by including more participants at different stages of the decision-making process when necessary, while also minimizing the negative effects when the number of participants increases. The process of the framework is executed as follows: first, the conventional MAMCA steps are followed to structure the problems, define the alternatives, and identify key stakeholder groups. Then, the stakeholder groups that need mass participation are identified. Next, the criteria sets for stakeholder groups are then defined. Optionally, the facilitators can select criteria by soliciting the opinions from participants. Then, the participants in the mass participation groups respond to a survey to rank the criteria in order of importance, from highest to lowest. There is an extra step that needs to be taken if the participants hold diverse priorities, they are then clustered into subgroups according to their priorities, i.e., their ranking of the criteria. Then, using clustering analysis, representatives from the subgroups are chosen and invited to a workshop for further assessment. Following the instructions of the facilitators, the stakeholder group representatives will elicit the criteria weights and assess the alternatives during the workshop. Lastly, the assessment results of the group are displayed. The representatives of groups can discuss to seek the final consensus.

This PhD dissertation presents both a framework and a tool for mass-participation. A theoretical framework alone is insufficient to facilitate the use of a mass participation MAMCA framework in a real-world decision-making problem; therefore, I enrich it as a mass participation tool by developing a software that can perform mass-participation decision-making. I propose how the mass-participation decision-making is applied in the framework. The framework itself consists of several methodologies to facilitate the decision-making: First, I propose a criteria pre-processing framework, that helps facilitators to select criteria for stakeholder groups by taking into account participants' opinions. Then, a new clustering algorithm is developed that can cluster the participants into subgroups based on their priorities in the mass participation groups and identify the representatives of the subgroups; I also build a model to assist facilitators in reaching a possible consensus among stakeholder groups' preferences by providing numerical references for the performance of the alternatives. Finally, this dissertation also includes the development of a dedicated software and a survey tool which facilitates mass-participation.

List of abbreviations

Below, the list of abbreviations that has been used throughout this thesis, can be found. This list is made per chapter to show where each abbreviation appears first. No new entry will be made if a certain abbreviation returns in a later chapter.

Chapter 1	
MCDM	Multi-criteria decision making
GDM	Group decision making
MCGDM	Multi-criteria group-decision making
SMCE	Social multi-criteria evaluation
MCE	Multi-criteria evaluation
MAMCA	Multi-Actor multi-Criteria analysis
AHP	Analytic hierarchy process
SES	Socioeconomic status
CMALGDM	complex multi-attribute large-group decision-making
PROMETHEE	Preference ranking organization method for enrichment evaluation

Chapter 2

GDSM	Group decision support methods
MERN	MongoDB, Node.js, Express, React
DR	Direct Rating
SMART	Simple multiattribute rating technique
SOAP	Simple object access protocol
REST	Representational state transfer protocol
JSON	JavaScript object notation
MILP	Mixed integer linear programming

Chapter 3

MCA	Multi-criteria analysis
PROSE	Profile ranking with order statistics evaluations
NNW	Not-normalized weight
NW	Normalized weight

Chapter 4

CLS	Construction logistics scenarios
BCR	Brussels-capital region

Chapter 5

WCSS	Within-cluster sum of squres

Chapter 6

WSI	Weight stability intervals

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Chapter 1

Introduction

1.1 Background

For the first sentence of the first chapter, I ask one question: ‘Is there a policy where no one complains?’ Real life gives the answer already: Yellow vest protests [2], French pension reform strikes [3], protests against responses to the COVID-19 pandemic [4], Fridays For Future [5,6], etc.[7–10]. These mass demonstrations show that the decision of policymakers can easily lead to resistance from the public [11,12]. Social movements can emerge when the public wants to promote, implement, resist, prevent or undo a social policy [13]. In other words, when people are not satisfied with the current situation in terms of economic [14], political [15], climate [16] or any other context in which they are affected or have influence, they might try another approach to express their opinions [17]; because they care about these decisions, and they are aware that they will be influenced by them. When individuals and/or organizations influence or are influenced by the decision, they are perceived as stakeholders of the problem [18, 19].

There is an old saying in China, ‘When there is a flood, it is preferable to divert than to block the water.’ [20]. When the stakeholders want to express their opinions, it is better to create a channel to hear their voices instead of ignoring them. Therefore, instead of proposing policies that do not satisfy stakeholders, I suggest to already involve the stakeholder groups in the decision-making process, because the solutions need the support from them [21, 22]. I argue that in many cases, stakeholders should have the same influence as policymakers in a decision-making problem. A social problem should not be addressed by a single group of policymakers, e.g., the authority or the government, but rather by soliciting opinions from various stakeholder groups, particularly citizens. For this reason, so-called participatory decision-making was proposed [23–27], which refers to the involvement of stakeholders in the decision-making process. I argue that in many cases, it is insufficient to obtain support from stakeholders through the voices of appointed representatives. In these cases, I argue that as many different opinions as possible should be heard. Because, as evidenced by the various mass demonstrations, the public's voices can differ.

Whether seeking a solution based on the opinions of a small group of people or the general public, the debate began when Greek and Roman political thought about 'the many' and 'the few' [28]. I argue that it is necessary to increase the scale of participation, i.e., to involve a large number of people in the decision-making process, also known as mass-participation decision-making. Several researchers have already laid out the advantages of the mass-participation [29–31], and the detailed discussion will be presented in Section 1.2.2. Hereby, I argue why it is necessary to propose the mass-participation decision-making in light of the aforementioned social phenomena: to facilitate the sustainable development. As previously stated, citizens have different concerns in terms of environmental, social, and economic problems. It can be argue that hearing their opinions on these issues facilitates the sustainable development. Mass participation provides a bird's-eye view of public opinion, allowing for the consideration of both majority and minority opinions. It promotes people-centered, long-term development as well as social equality [32]. Mass-participation is a bidirectional need for policy-makers and the general public. On the one hand, the policymakers need their policies to get support from the public through mass-participation [33]; on the other hand, the public needs mass-participation to express their concern. The possible way of communication in mass-participation is shown in Figure 1.1, that mass-participation decision-making creates channels of communication between various stakeholder groups, as well as in public. It can help stakeholder groups understand the positions of other groups and share empathy, which promotes a compromise solution. In the following section, I discuss how to apply a mass-participation decision-making in a multi-criteria context.

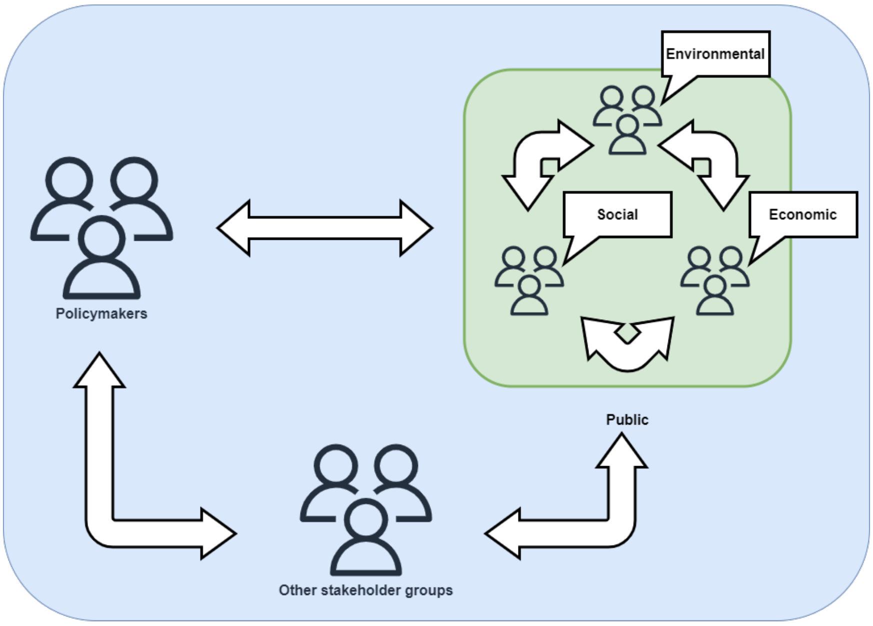

Figure 1.1: A possible way of communication in the mass-participation decision-making

1.2 Mass-participation in a multi-criteria context

1.2.1 From decision-making to group decision-making

Decision-making can be complicated. For example, a sustainability decision-making problem needs to account not only for economic development but also for environmental and social actions and must involve the key stakeholder groups in decisions [34–37]. It is unlikely that one alternative dominates the others, i.e., a choice that outperforms the other options on every criterion [38]. In these situations, decision-makers are faced with trade-offs between conflicting criteria. It is known as a multiple-criteria decision-making (MCDM) problem in the operational research literature [39]. MCDM methods are designed to structure and address such problems. The aim of MCDM methods is to help decision-makers address the choice among a set of alternatives based on a set of criteria. Thus, they support decision-makers in addressing complex-structure problems and seek optimal solutions by considering the trade-offs among the criteria [40]. Multi-criteria decision support has become popular for properly framing a problem and explicitly evaluating multiple criteria [41].

However, as mentioned before, sometimes there is a need to involve multiple stakeholder groups in decision-making problems for different reasons, for example, to get the support from the stakeholder groups [42], to seek the expertise of specific groups [43]. When more than one decision-maker is required, the problem transforms into a group decision-making (GDM) problem, i.e., a multi-criteria group-decision making (MCGDM) problem [44]. Two types of participants can be distinguished in MCGDM problems, namely experts and stakeholders. In expert-based MCGDM, several experts are invited to evaluate the problem with the aim to leverage collective intelligence; the stakeholder-based MCGDM can invite individuals from different interest groups that hold different priorities and objectives, i.e., stakeholder groups [45, 46], to consider diverse points of view [47]. Stakeholder-based MCGDM has become increasingly popular, for example, in the fields of transportation and mobility [48–50], energy [51–53], and other environmental issues [54, 55]. I can argue that since different solutions to problems have an impact on different stakeholders and generate conflicting points of view, the problem should no longer be resolved based solely on the preferences of the decision-maker and should instead be taken into account and supported by all stakeholder groups involved. [56].

There are two main approaches to structure the participation in MCGDM [57]. One option is for the stakeholders to first reach consensus on the alternatives, criteria, scores, weights, etc., and then provide a single ranking of the alternatives as in a regular MCDM. Another option is for the stakeholders to define their own criteria, evaluate the alternatives to obtain personal rankings, and aggregate the scores of the alternatives at the end of the process. Te Boveldt categorizes these two approaches as the input-level and output-level aggregation frameworks [58]. Table 1.1 shows the different techniques and methodologies that are used to solve MCGDM problems.

Table 1.1: Multi-criteria group decision-making literature

Framework	Technique/Methodology
Input-level aggregation framework	Multi-Criteria Mapping [59,60]
	Social multi-criteria evaluation (SMCE) [61]
	Multi-criteria evaluation (MCE) [62,63]
	Deliberative Multicriteria Evaluation [62]
Output-level aggregation framework	Decision analysis interview [64]
	Participatory Multicriteria Evaluation [63]
	Participatory MCDA [65]
	Multi-actor multi-criteria analysis (MAMCA) [66]

In MCGDM problems with stakeholder involvement, I can argue that there are three problems arise that relate to the representation of stakeholder groups. These problems are as follows:

1. How can all the relevant stakeholder groups be identified?
2. To what extent do the selected criteria represent the interests of the stakeholder groups?
3. To what extent do the individual that are selected as representatives actually represent the interest of their respective stakeholder groups?

Output-level aggregation frameworks are arguably more appropriate for solving the second representation problem because particular criteria can be defined for stakeholder groups. Therefore, the criteria of the groups can arguably better represent the interests of the groups. Among the output-level aggregation frameworks, I can argue that multi-actor multi-criteria analysis (MAMCA) is a suitable solution for the first representation problem.

Multi-actor multi-criteria analysis

MAMCA is an extension of MCDM that allows the involvement of multiple stakeholder groups [67]. In MAMCA, Macharis and Baudry recommend conducting a stakeholder analysis to obtain a comprehensive understanding of the stakeholders, with the aims to cover points of view from various key stakeholder groups [68]. The structure of MAMCA is shown in Figure 1.2, and the detailed description of each step is given in Chapter 2. MAMCA allows different stakeholder groups to use different criteria sets for the performance assessment of the alternatives. First, stakeholder groups can make a coherent alternative performance assessment based on their own criteria, which can better express the groups' preferences and reveal intergroup conflicts. Second, it arguably increases the awareness of the presence of other groups and can have a better understanding of their positions, which might make them more likely to search for common solutions to reach a consensus.

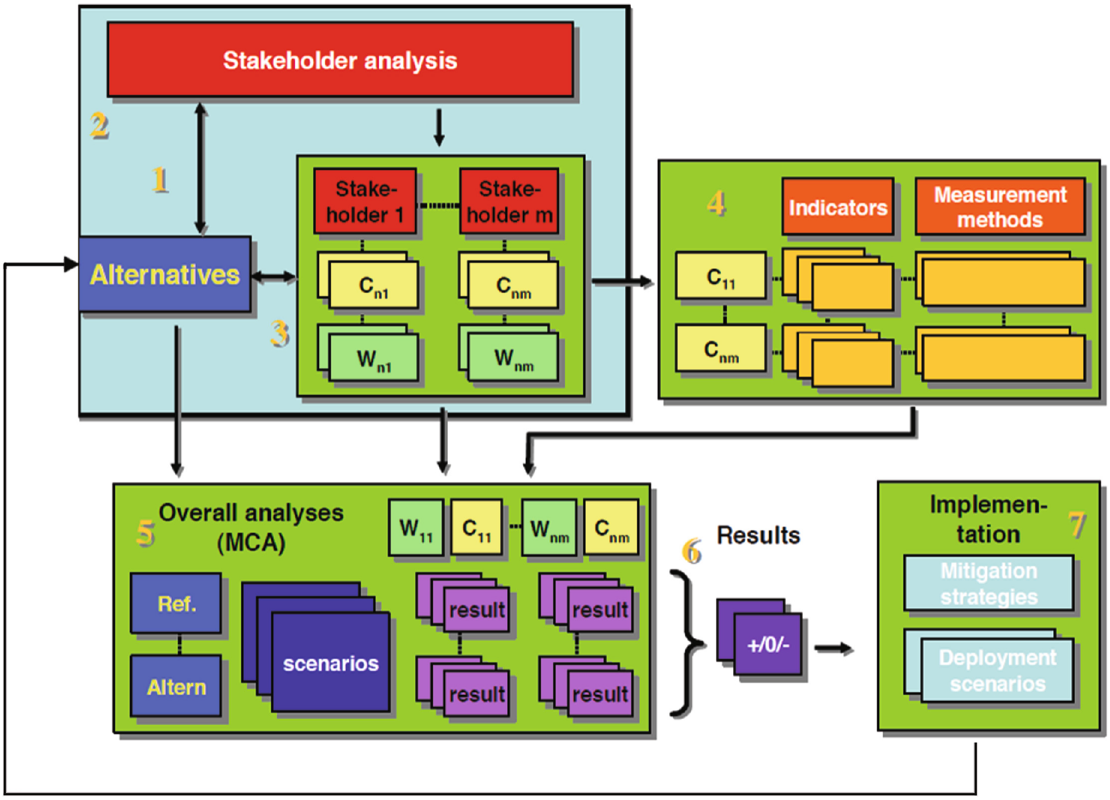

Figure 1.2: The methodology of MAMCA [1]

Although MAMCA can address the first and second representation problems, the third representation problem has not yet been addressed. In MAMCA, the representatives are selected to provide input on behalf of their respective stakeholder groups in workshops [69–72]. However, this raises the question whether the representatives aim to defend their self-interest or the interests of the whole group [73]. The problem becomes more crucial when a large group such as citizens is involved. A large stakeholder group is more complicated than a traditional stakeholder group because the interests, preferences, and socioeconomic status (SES) of individuals are more likely to be more diverse [74]. Glass argues that providing the participants in the group with a direct voice channel can ensure the democracy and equality of the decision-making process [75]. And this is the reason mass-participation is proposed [76, 77]. However, as the number of participants increases, the costs for various resources increase [47] and operational challenges also arise [78].

This leads to the research problem of this dissertation as follows: **How can mass participation be integrated in MCGDM?** In the following subsection, I first introduce previously presented approaches for solving the aforementioned problems. And based on lessons learned from them, I propose a novel mass-participation framework.

1.2.2 From group decision-making to mass-participation decision-making

Mass-participation refers to an event that involves a large group of participants, for example, a sport in which the public can participates [79, 80], a web community to which the public can contributes [81]. However, this terminology is rarely used in a context of decision-making. Rossi used mass-participation in his publication about legal decision-making [82]. The concept of mass-participation I use in this dissertation refers to involving a large number of participants in at least one large stakeholder group in the decision-making process. I call this kind of group the mass-participation stakeholder group. The number of participants should statistically represent mass-participation groups' entire population's interests, priorities, and preferences[1]. When one or several representatives cannot express the opinions and preferences from one stakeholder groups, when the number of stakeholders is too large to take them into consideration individually, the 'mass' is needed. The objective of mass-participation is to arguably ensure that the diverse views in large stakeholder groups are taken into account in the decision-making process.

The advantages and disadvantages of mass-participation decision-making

Mass-participation decision-making can produce many positive results. It has also been criticized in some aspects [87]. The advantages and disadvantages of mass participation are listed in Table 1.2.

Table 1.2: The advantages and disadvantages of mass-participation decision-making

	Advantages	Disadvantages
Decision process	Foster legibility and transparency in decision-making[88–90] Provides better-quality information for decision-makers [91, 92]	Greater risk of inaccurate decisions because of incorrect execution throughout the process [93, 94] Higher cost in resources [95–97] More difficult to manage [78] Participants lack expertise and knowledge [98, 99]
Outcomes	Increases trust in the decision-making process [100] Provides group members higher satisfaction and influence [93] Contributes to sustainable development [101, 102]	Increases heterogeneity in stakeholder groups, which leads to a higher number of potential decision-making conflicts [103, 104]

Mass-participation decision-making aims to promote decisions by soliciting the opinions from public [78]. As Callahan [105], Fischer [106], Fukuyama [107], and King et al. [108] argued, greater levels of participation can be conducive to the leg-

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[1] The necessary number of participants can be estimated by different approaches, more detail can be found in [83–86].

ible and transparent process of building trust and strengthening accountability. More participation provides better information for the decision-making process and encourages decision-makers listen to what participants consider important [91]. Cooper and Wood argued that participants can feel more satisfied and influenced when there is more comprehensive participation, i.e., when more participants are involved and they are involved in more stages of the decision-making process [93]. Mass-participation decision-making can also better support sustainable development as it can promote social justice and equality in the decision-making process [102, 109].

However, mass-participation decision-making has several disadvantages. The more participants there are, the greater the amount of information that needs to be processed [93], which leads to greater risk of wrong decisions being made because of incorrect execution [94]. There are also higher costs in terms of different resources, such as time [47, 95–97]. And managing the decision-making process is more difficult, as structures become more complex and 'face-to-face' relationships more difficult [78]. Mass-participation decision-making is also risky because the participants may lack expertise and knowledge in the area of the decision-making problem [98, 99]. Thus, it can be difficult for them to assess the alternatives and make correct decisions without guidance [110, 111]. Furthermore, mass-participation decision-making reveals the participants' diverse perspectives [81]. It is the objective to have mass-participation, but it might also lead to more conflicts in one large stakeholder group, thereby making it difficult to reach consensus [112, 113].

Existing mass-participation decision-making frameworks and lessons learned

To exploit the benefits of mass-participation decision-making and avoid its drawbacks, many frameworks have been proposed [114–118]; some authors have also provided comprehensive strategies for structuring mass-participation decision making problems [101, 119–123]. In this dissertation, I will only briefly introduce the existing mass-participation decision-making frameworks in the context of MCGDM problem.

Initially, mass-participation decision-making frameworks were proposed based on MCDM methods, for example, the analytic hierarchy process (AHP) [124]. Ignaccolo et al. investigated citizen preferences in designing new transport services from a multiple-criteria perspective by applying AHP [125]. They designed a survey with a structured questionnaire to collect data from 674 citizens throughout the study area; the final result was obtained by calculating the geometric mean of the individuals [126]. To investigate the preference heterogeneity of the individuals, the sample was clustered according to socioeconomic status (SES), e.g., the working area and transportation modes.

Another trend in solving mass-participation decision-making problems is to apply fuzzy linguistic methods [127, 128]. These frameworks have similar names, e.g., complex multi-attribute large-group decision-making (CMALGDM) [129], large-scale multi-attribute group decision-making [130], multi-attribute large-scale group decision-making [131], and multi-criteria large-group decision-making [132]. To address the heterogeneity caused by increasing the number of participants, clustering analysis is applied in these frameworks [133]. Cluster analysis helps to identify clusters with similar perspectives, thus effectively reducing the complexity of the structure.

The above frameworks attempt to address the drawbacks of mass participation in the context of MCGDM problem. Here is how they did it: when there was a large number of participants, the researchers distributed surveys to collect data from participants, which reduced costs [125, 129–132]. In addition, to correctly reflect the judgment of participants, improve the evaluation information, and investigate heterogeneity to reach a final consensus, various clustering methods have been proposed [134–136]. These frameworks provide insights for solving decision-making problems when a large number of participants are involved in the decision-making process. However, the literature also reveals unresolved limitations: participants may lack domain-specific expertise and knowledge, and incorrect assessments may occur because limited guidance participants receive. Therefore, the real preferences of the participants might not be expressed [137].

Meanwhile, the existing approaches commonly apply clustering analysis to partition the participants in a large group into subgroups in order to reveal the conflicting interests within the group and avoid ignoring different points of view [138]. As can be seen in the examples given above, currently, clustering analysis is applied based on participants' SESs [125], participants' preferences, i.e., the assessment scores of alternatives [135, 139–142]. If participants are clustered based on their SESs, it is questionable if participants in one clustered subgroup can have similar priorities and interests [143, 144]. For example, In the transport service study, Ignaccolo et al. clustered the participants into university students, daily visitors, walkers, bikers, etc. [125]. It is unlikely that the university students surveyed, that is, more than 400 participants, all held similar opinions. Furthermore, the participants can have overlapping SESs, making it difficult to cluster. Clustering based on participants' preferences appears to be a better solution to support mass-participation decision-making. However, as mentioned above, the lack of expertise and knowledge of the participants may lead to incorrect assessments. Applying clustering directly to the assessment results is risky. In addition, directly inviting participants to assess the performance of alternatives is risky because it is more objective [145]. It requires participants to have a comprehensive understanding of the alternatives and possibly expertise [130]. It is questionable whether the information in the survey can help participants to properly understand the alternatives.

I argue that the risks of mass-participation decision-making do not decrease in previous mass-participation framework. Therefore, in this dissertation, I propose a novel framework for mass-participation decision-making problems that is integrated into MAMCA in order to help address the aforementioned risks and address the previously stated research problems. As mentioned above, the conventional MAMCA setting can better solve the first two representation problems of MCGDM because the stakeholder groups are identified after the stakeholder analysis, and they are allowed to define criteria for their group. However, to better solve the third representation problem, that is, to find the representatives who can actually represent the interests of the groups when there are large groups involved, I suggest integrating the mass-participation concept into MAMCA. Therefore, it is necessary to review the conventional method of the MAMCA evaluation process and propose methods to integrate mass participation in different stages. Conventionally, after the facilitator builds the problem structure, stakeholder analysis is performed, and the criteria sets of the groups are defined [1]. The representatives of the stakeholder groups are then invited to a workshop to assess the alternatives. MAMCA software serves as an interaction tool to facilitate the assessment process [146]. After the assessment, the results are presented to the representatives. A possible consensual solution is then chosen after a discussion.

Based on the lessons learned in the preceding section, I can draw the following conclusion for constructing a novel mass-participation framework:

1. Involve participants in the different stages of the decision-making problem. For example, the participants can be invited to select the criteria for the stakeholder groups in MAMCA evaluation. This approach can significantly enhance the effectiveness of collaboration, facilitate a positive decision outcome [147], increase satisfaction, and gain trust from groups [93, 100], because the decision-making process is made more legible and transparent to the participants.

2. Distribute a survey to collect data. A survey is a good solution for collecting data; as the number of participants increases, the cost of the operations also increases [148, 149]. Additionally, members of mass participation groups, such as citizens and residents, are quite difficult to reach. In more extreme situations, for example, the global pandemic, offline workshops are challenging, and surveys are more suitable [150].

3. Invite participants to give criteria weights but not to assess alternative performances. Inviting participants to directly assess alternative performances through surveys is not recommended. First, doing so further increases the complexity of the structure. Second, if there is no guidance, the assessment results might not correctly express the participants' preferences. Lastly, the alternative performance assessment can be subjective and usually requires a more objective procedure, which usually relies on quantitative information [145]. However, participants usually do not have the kind of expertise required to gather such information.

4. Cluster participants based on their priorities instead of SES or alternative performance assessment. The criteria elicitation result can illustrate the priorities of the participants. Clustering the participants from one mass-participation group into subgroups can reveal their conflicting interests and priorities, which can avoid the ignoring of different points of view from participants in certain groups.

5. After clustering, it is also necessary to identify individuals in subgroups that can defend the interests of the subgroups. These individuals are selected as representatives of the mass-participation group, and will be invited to participate in work-

shops to conduct criteria weight elicitation and alternative performance assessment. This is an essential step, because it can help solve the third representation problem: the representatives can arguably defend the interests of the subgroups. Furthermore, this step decreases the risks in decision-making process. Representatives can perform the weight elicitation and alternative performance assessment steps under the guidance of facilitators, thereby reducing the possibility of incorrect execution leading to a wrong decision.

1.2.3 Mass participation framework for MAMCA

Finally, I propose a mass-participation framework for MAMCA. It is executed as follows:

1. The potential alternatives to solve the problems are defined. The decision-makers need to identify and classify the alternatives in terms of different scenarios, policy measures and so on. It is also possible to solicit the opinions from the participants, as a product of co-creation [151].
2. Stakeholder analysis is applied. Besides conventional stakeholder groups, mass-participation stakeholder groups are identified.
3. After the stakeholder groups are identified, facilitators need to define the criteria for different stakeholder groups. They can optionally solicit opinions from participants in stakeholder groups to help them select criteria.
4. A stakeholder clustering analysis is applied to investigate the heterogeneity within mass-participation stakeholder groups. If the opinions, priorities, interests, or preferences of participants are diverse, the participants needs to be clustered into subgroups. And the representatives of subgroups are selected
5. Representatives of stakeholder groups are invited to the decision-making workshop. In the workshop, the representatives of the stakeholder groups will elicit the weights of the criteria and assess the alternatives by following the guidance of facilitators.
6. The assessment results are presented, sensitivity analysis can be applied, and the representatives discuss to seek the final consensus.
7. The policymakers decide the alternative(s) to implement. During this step, as the advantages and disadvantages of an alternative for each stakeholder are better understood, it is possible to incorporate new alternatives or modify existing ones. This will create a feedback loop for the start of the process.

The framework procedure is illustrated in Figure 1.3. By following this procedure, it can benefit from mass-participation decision-making and minimize its shortcomings. This framework can involve more participants in MAMCA in criteria definition step.

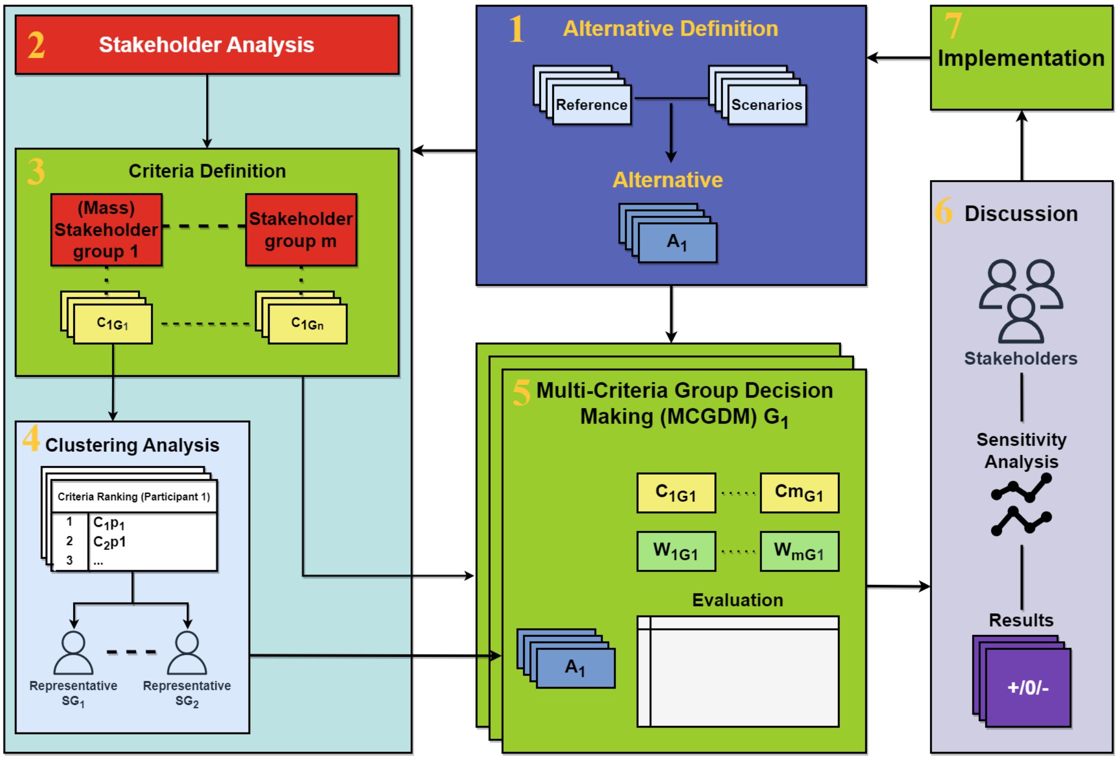

Figure 1.3: Mass-participation framework based on MAMCA

And the clustering analysis can investigate the priorities of groups and select representatives. These two steps help MAMCA to address two representation problems; the selected criteria can better represent the interests of the stakeholder groups, and the selected representatives can better represent the interests of the groups. This process establishes a formal way in which to select representatives from a large number of participants. Additionally, it reveals the heterogeneity of mass-participation groups without further increasing the complexity of the problem. Facilitators at the workshop can guide the representatives in the assessment process and assist them in properly expressing their preferences [47]. As a result, the assessment process is more manageable and the risk of incorrect decisions is reduced compared to other mass participation decision-making frameworks. [152, 153].

Mass-participation MAMCA framework addresses the aforementioned three representation problems and provides a more legible and transparent process when large groups are involved in decision-making problems. However, to implement it, there are several challenges that need to be addressed. These challenges are as follows:

1. A decision-making tool can support facilitators in constructing decision-making problems. It provides data visualization to participants to help them understand the problems and the related alternatives, criteria, and assessment results. Therefore,

to facilitate the MAMCA process, a MAMCA software has been developed [146]. However, the current MAMCA software has no feature for mass participation.

2. In step 3, there is no guideline to define the criteria for collaboration with participants. When the number of participants increases, it becomes more difficult to identify the criteria that represent the priorities of one stakeholder group, particularly for a mass-participation stakeholder group. Thus, it becomes important to select criteria for stakeholder groups by soliciting opinions from participants. However, currently there is no formal guideline for the process of defining criteria with participants.
3. In a mass-participation stakeholder group, heterogeneity is more likely to occur. Thus, in step 4, a cluster analysis is needed to investigate heterogeneity and, if necessary, to perform clustering. As discussed previously, I argue that clustering based on the priority of participants is more appropriate for mass-participation decision-making. A new algorithm is sought that can cluster participants based on their criteria ranking and identify representatives in subgroups.
4. In step 6, reaching consensus among stakeholder groups is difficult. During the alternative performance assessment, the conflicts of interest of different groups of stakeholders usually lead to distinct preferred solutions. Therefore, a compromise solution that satisfies all stakeholder groups is difficult to find.

1.3 Research objectives

The mass-participation framework based on MAMCA addresses the aforementioned three representation problems and the research problem: ‘How can mass participation be integrated in MCGDM?’ To help apply mass-participation MAMCA in real-life problems, the main objective of this dissertation is to develop a mass-participation tool based on the MAMCA methodology. Accordingly, the main objective is divided into several subobjectives as follows:

1. To make the mass-participation MAMCA framework possible to be implemented in an interactive tool, it is necessary to develop a new MAMCA software user interface to help facilitators and participants support the mass-participation decision-making problem. The software must include the necessary MCDM methods and data visualization, as well as the ability to implement mass-participation MAMCA.
2. A survey tool should be developed for MAMCA software to implement mass-participation decision-making. It can reach either participants online or offline and collect information asynchronously. It can facilitate the step 4 in the framework.
3. In step 3 of the framework, a guideline should be proposed to support facilitators in selecting criteria for stakeholder groups by soliciting opinions from participants.

The guidelines should respect the priorities of participants and keep the number of criteria within a reasonable range.

4. In step 4 of the framework, a new algorithm should be developed for clustering analysis. The clustering algorithm should cluster the participants into subgroups based on their priorities in the mass participation groups. The algorithm should also serve to identify individuals who can represent the subgroups, i.e., representatives.
5. In step 6 of the framework, a model is needed to support facilitators in finding a compromise that suits the preferences among representatives. As in MAMCA, the final solution will be sought through discussion, and the model will provide mathematical references for the alternatives' performances that can support the stakeholders in reaching consensus.

1.4 Contributions and outline

This dissertation is built in specific chapters to address the subobjectives that relate to the main objectives. An outline is shown in Figure 1.4.

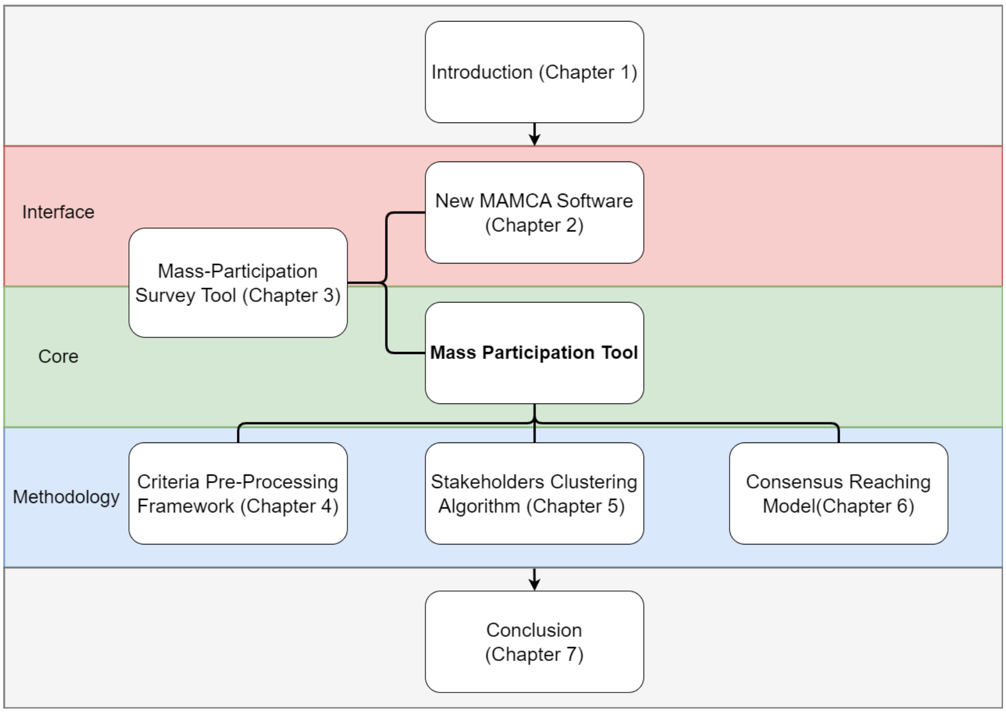

Figure 1.4: Dissertation outline

New Software and New Visualizations (Chapter 2 → Objective 1) - As mentioned above, the first challenge in applying mass-participation decision-making in MAMCA is the limitation of the current MAMCA software; new MAMCA software is therefore proposed. The development of this software makes it possible to extend it as a mass participation tool, hence maximizing participation involvement. This contribution highlights how the MAMCA methodology is integrated into the software and how the data are visualized. It focuses on enhancing the concept of 'stakeholder involvement' in development. A new data structure is developed, and the simpler user interface makes the tool more accessible. An easy-to-understand alternative performance assessment method is integrated into the software. Additionally, a participation system is proposed to guide stakeholders and facilitators in each step of MAMCA. The interaction experience between participants is improved.

Mass-Participation Survey Tool (Chapter 3 → Objective 2) - In this chapter, to fulfill the needs of collecting data from mass-participation stakeholder groups, a mass-participation survey tool is designed and developed for the new MAMCA software. This tool allows facilitators to design a dedicated survey for the mass-participation stakeholder group. The easy-to-understand evaluation process is designed to avoid time-consuming elicitation. This tool can visualize the score distribution based on the criteria priorities gathered from the participants. It is possible to assess the homogeneity and heterogeneity of the participants within the stakeholder group based on the SES profiles collected by the survey.

In this chapter, the mass-participation decision-making framework based on MAMCA is proposed for the first time. It introduces the situations in which mass participation is required in a MAMCA evaluation. However, the proposed evaluation procedure is not appropriate for all cases of mass participation. It does not take into account the situation in which one large group has a significant conflict in priorities. Throughout the study, I gain progressive insight and propose the formal mass-participation framework, which is illustrated in Chapter 5.

Criteria Pre-processing Framework (Chapter 4 → Objective 3) - In this chapter, a framework for the criteria pre-processing step in MAMCA is introduced to provide guidelines for the facilitators from the predefined criteria list and filter the criteria to determine the final criteria tree that can be used in subsequent MAMCA steps. It provides a procedure for deriving the criteria considering the objectives of the stakeholder groups. Furthermore, a mathematical model for filtering the criteria with the involvement of the stakeholders is developed. Based on the principles of Pareto analysis and the cognitive judgment theory 'magic number seven plus or minus two', a recommendation list of criteria is generated. Opinions are gathered from the participants and processed into a final criteria ranking. This prevents some key criteria from being omitted and limits the number of criteria. This framework is applied to a social decision-making case for construction logistics, and the result are compared with those of the conventional criteria definition method.

The proposed criteria pre-processing framework can serve for selecting criteria in different situations, and works better in the mass-participation decision-making framework. This is because it takes into account the different scores given by the participants to select highly relevant criteria for the group. Furthermore, the proposed criteria selection model can detect whether one stakeholder group's opinions are so diverse that clustering is required to partition the group into subgroups.

Stakeholder Clustering Algorithm (Chapter 5 → Objective 4) - As previously stated, heterogeneity is common in a large stakeholder group. When participants' opinions are too diverse, it is necessary to cluster the group into subgroups by identifying the group's different priorities. Then, several representatives can be invited to engage in the decision-making process that follows. In this chapter, I present a new clustering algorithm that aims to cluster the participants into different subgroups by identifying their priorities based on the weights they give to different criteria. The proposed approach follows the logic of the k-means clustering algorithm. It clusters the participants based on the criteria ranking distances, which are calculated through the weighted Kendall's τ coefficient. The algorithm is applied to a construction logistics project. It successfully clusters participants with different priorities and identifies corresponding representatives. The algorithm results are compared with the results of traditional k-means clustering.

This chapter proposes the formal procedure for mass-participation MAMCA, which was previously introduced in subsection 1.2.3. I explain how and why the proposed procedure differs from other existing procedures.

Consensus Reaching Model (Chapter 6 → Objective 5) - The purpose of this chapter is to propose a way to help the facilitator identify the compromise solutions so that the stakeholder groups can reach consensus. This is based on both the use of a weight sensitivity analysis model in the context of the preference ranking organization method for enrichment evaluation (PROMETHEE) and inverse mixed-integer linear optimization. This approach allows the minimum weight modification to be found for each stakeholder to improve the position of a given alternative in the individual rankings and, in an ideal case, to obtain the first position in all the rankings simultaneously. This approach is illustrated on two real MAMCA logistic project cases to find sustainable mobility solutions.

The consensus reaching model can support participants in reaching a consensus on the final solution. It provides options for facilitators and participants to consider. The model can be used for both mass participation MAMCA and traditional MAMCA.

Chapter 2

New MAMCA Software

2.1 Introduction

Several types of operations research methods have been developed to help decision-makers evaluate transport projects. A common method to do this is multiple-criteria decision-making (MCDM), ranking or sorting different alternatives based on at least two criteria [154]. MCDM has become more and more popular as it allows to evaluate different kinds of criteria (and not only economical ones). However, in practical transport cases, more than just one individual or group of individuals, called stakeholders, are involved, which can significantly influence or be influenced by the result of the decision [19]. Crucial is thus to incorporate different points of view from several stakeholders into such an analysis. As the result, it can reveal the preferences of different stakeholder groups, hence allowing easier and clearer decision-making.

MAMCA, an extension of traditional MCDM methods, was proposed for transport project evaluations [66]. During the decision-making process, different stakeholder groups are taken into account. The concept of stakeholder is involved at the early stage of the evaluation, which leads to a better understanding of the objectives for different stakeholders. MAMCA successfully reflects the preferences of every individual stakeholder and expresses their concerns. It has been applied in various domains, especially in the field of mobility and logistics [68]. MAMCA was used in different scenarios such as evaluating transport policy measures [155] and transport technologies [156]. It has also proven itself as a useful methodology in transport-related decision making [157].

To facilitate the application of the MAMCA methodology, a web tool was developed, called MAMCA software [146]. Since 2016, the MAMCA software has helped

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This chapter is based on Huang, H., Lebeau, P., & Macharis, C. (2020, May). The multi-actor multi-criteria analysis (MAMCA): new software and new visualizations. In International Conference on Decision Support System Technology (pp. 43-56). Springer, Cham.

decision-makers in different sectors to gain a better understanding of the MAMCA methodology and support them with decision-making. However, as time goes by, the limits of the original MAMCA software were exposed, mainly in the form of the difficulty of extending functions and outdated programming technology. Thus, new software is required to be developed to help MAMCA adapt to fast-paced technology changes, and capable of the situation that massive stakeholders can participate in the evaluation.

In this chapter, we will first introduce the MAMCA methodology in Sect.2.2. Sect.2.3 presents the new MAMCA software and its distinct features. Finally, we will discuss the future directions made possible by the new MAMCA software in Sect.2.4.

In order to present the features and illustrate visualizations of the software, a didactic last-mile case in the supply chain will be taken as an example.

2.1.1 Supply chain management case study

The case study entitled "The last-mile in the supply chain" is a fictive case study, but corresponds to real dilemma situations regarding home deliveries. It is aimed to gain insight into the extent to which different alternatives for the last mile of a supply chain for home deliveries contribute to the interests of the different stakeholder groups involved. As the stakeholder groups hold different priorities into different criteria, a multi-actor view is needed to show the different points of view of the stakeholder group. The list of alternatives and the criteria of the stakeholder groups are shown in Table 2.1 and Table 2.2.

Table 2.1: The alternatives in the supply chain management case

Alternative name	Alternative description
Electric Vehicles	Only Electric Vehicles are authorized to access the city center.
Mobile Depot & Cargo Bikes	Free parkings are foreseen for trucks that split their final deliveries with cargobikes.
Lockers delivered at night	Places are booked for companies in strategic areas in the city for lockers. They are delivered at night only.
Crowdsourced deliveries	Online customers can choose to be delivered from a crowdsourced service.
Business As Usual	-

2.2 MAMCA methodology

The steps of a classic MCDM process include the problem statement, alternatives and criteria definition, alternatives screening, scores determination, scores analysis, and drawing of conclusions [158]. Unlike classical MCDM methods, MAMCA takes stakeholder analysis to identify stakeholder groups after defining alternatives. Each stakeholder group can have different criteria tree.[67]. In Figure 1.2, the overall methodology of MAMCA is shown.

Table 2.2: The criteria of stakeholder groups in the supply chain management case

Stakeholder group	Citizens	Local Authorities	Logistics Service Providers	Receivers	Shippers
Criteria	Road Safety	Quality of life	Viability of investment	Low costs for receiving goods	Low cost deliveries
	Air Quality	Network optimization	Profitable operations	Convenient high quality deliveries	High level service
	Urban Accessibility	Social political acceptance	High level service	Attractive living environment	Positive impact on society
	Attractive Urban Environment	Positive business climate	Positive impact on society	Green concerns	Successful pick-ups
	Low Noise Nuisance		Employee satisfaction		

In the first step, the potential alternatives to solve the problems are defined. The decision-makers need to identify and classify the alternatives in terms of different scenarios, policy measures and so on. In the second step, stakeholder analysis is taken to identify the stakeholder groups. It is a crucial step in MAMCA as for each stakeholder group there is a different criteria tree. An in-depth understanding of each stakeholder group is needed. Next, criteria and the corresponding weights are chosen and defined for each stakeholder group. One or more indicators for each criterion need to be constructed in step four. The indicators can be used to measure each alternative, providing the scale for the judgment.

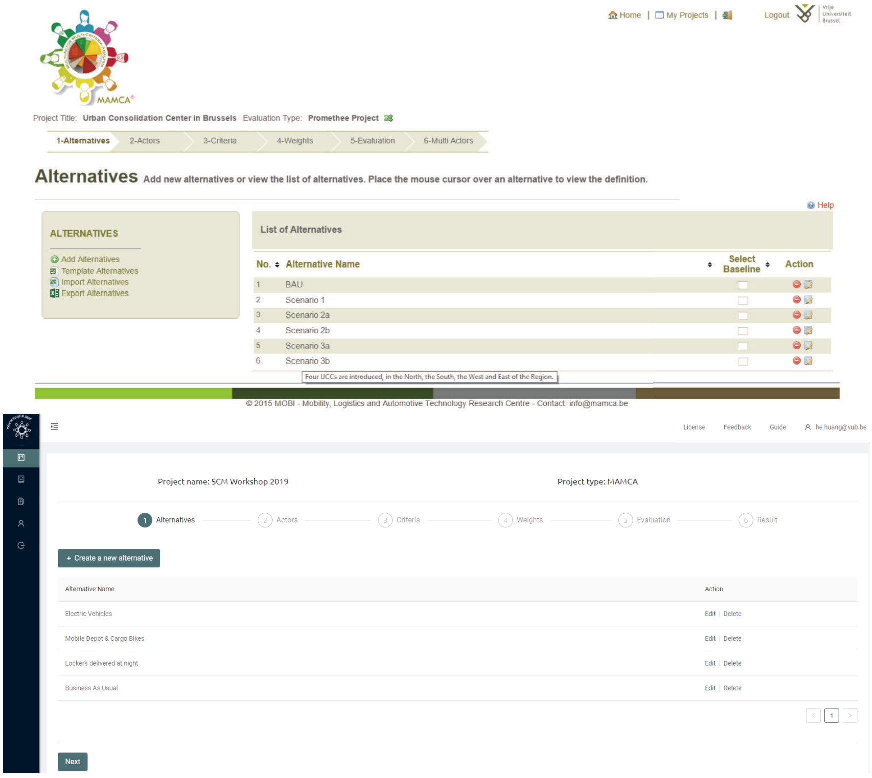
In step 5, the overall analysis is taken within stakeholder groups. Any MCDM methods can be used to assess the alternatives. The Group decision support methods (GDSM) are well suited in this step such as Preference ranking organization method for enrichment evaluation (PROMETHEE) [159], analytic hierarchy process (AHP) [160]. There is no conflict between stakeholder groups and groups. The final evaluations and results of every stakeholder group will only be confronted at the end of the analysis.

The results of the analysis are presented in step 6. Additionally, a sensitivity analysis can be performed to check the robustness of the results. For each stakeholder group, the multi-criteria analysis reveals their respective criteria and favored solutions, while the multi-actor multi-criteria analysis indicates the comparison of the different points of view of every stakeholder group, which supports the decision-maker in making the final decision. Eventually, the actual implementation of the decision chosen is taken. The information collected from the previous steps helps the decision-maker to define the implementation paths.

2.3 The New MAMCA software

To fulfill the need of MAMCA assessment with an interaction interface, MAMCA software was developed. However, the studies on MCDM increased every year, the innovated methodologies emerge and evolve fast [161]. The original version of MAMCA cannot integrate more MCDM methods because of the limitation of extensibility. In the workshop, it took time to introduce the MAMCA methodology and the MCDM method will be used in the evaluation. An efficient and simple MAMCA procedure is sought to speed up the workshop. Additionally, the higher capacity number of participants for analysis is asked, to maximize the participation involvement. In order to make the evaluation within a stakeholder group with a large number of participants feasible, extending the MAMCA software as a mass participation tool is needed. By doing this, it is possible to get more opinions from a large stakeholder group like citizens.

Thus, a new version of MAMCA software with high extensibility has been developed to integrate new information technologies and visualizations. Figure 2.1 illustrates the changes of user interfaces of the MAMCA software [1]. It is written in the software stack of MongoDB, Node.js, Express, React (MERN)[162].



Project Title: **Urban Consolidation Center in Brussels** Evaluation Type: **Promethee Project**

Alternatives Add new alternatives or view the list of alternatives. Place the mouse cursor over an alternative to view the definition.

List of Alternatives

No.	Alternative Name	Select Baseline	Action
1	BAU	☐	
2	Scenario 1	☐	
3	Scenario 2a	☐	
4	Scenario 2b	☐	
5	Scenario 3a	☐	
6	Scenario 3b	☐	

Four UCCs are introduced, in the North, the South, the West and East of the Region.

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Project name: SCM Workshop 2019

Project type: MAMCA

Alternative Name	Action
Electric Vehicles	Edit | Delete
Mobile Depot & Cargo Bikes	Edit | Delete
Lockers delivered at night	Edit | Delete
Business As Usual	Edit | Delete

Figure 2.1: The user interface comparison of previous software (top) and current software (bottom)

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[1] For more information, please visit: `https://mamca.eu/`.

2.3.1 The evaluation steps and visualizations

The new MAMCA software follows the evaluation structures of MAMCA methodology. In a MAMCA project assessment, the software divides it into 6 steps, which include alternatives identification, stakeholder group identification, criteria definition, criteria weight allocation, alternative evaluation, discussion and results.

After creating a MAMCA project, the facilitator is able to define new alternatives, as well as modify and remove them. After defining alternatives, stakeholder groups are identified. Each stakeholder group is described according to the objectives they have regarding the alternatives. These objectives are the criteria used to evaluate the impact of scenarios on stakeholders' support. With these three first steps, the facilitator has designed the architecture of the MAMCA projects. Data are then collected in the next steps to run the analysis.

In the fourth step, each criterion is weighted. The participants can manually allocate weights. Still, other allocation methods are proposed in the software. The participants can choose the pairwise comparison, that they indicate their preference intensities for pairs of criteria.

Participants can also use Direct Rating (DR) [163]. All criteria will be rated on a 100-point scale. The most important criterion will be given by the highest number. All other criteria are then rated in comparison to the most important one. The rated scores will be normalized. Suppose there is a set of criteria in one stakeholder group, calling $F = \{f_1, f_2, \cdots, f_m\}$. $W = \{W_1, W_2, \cdots, W_m\}$ is the set of given priority scores for the criteria, and $w = \{w_1, w_2, w_m\}$ is the normalized criteria weights set. The final weight of criterion k will be:

$$w_k = \frac{W_k}{\sum_{j=1}^{m} W_j} \tag{2.1}$$

In the fifth step, in each stakeholder group, participants in the group should evaluate the alternatives based on their criteria. Currently, two additional methods are available: AHP developed by Saaty and Simple Multiattribute Rating Technique (SMART) [164]. If AHP is chosen, pairwise comparison is conducted between alternatives.

If SMART is chosen, the preferences of the alternatives can be rated on a 10-point scale. Suppose one participant has to evaluate a finite set of alternative $A = \{a_1, a_2, \cdots, a_n\}$ The performance score of P_i of alternative a_i will be calculated by means of weighted sums [165]:

$$P_i = \frac{\sum_{j=1}^{m} p_{ij} w_j}{10} \tag{2.2}$$

Where p_{ij} is the performance score of alternative a_i on the criterion f_j, w_j is the weight of criterion f_j. The final performance score is divided by 10 in order to keep the score ranges from 0 to 1.

Once all participants in one stakeholder group finished evaluating, the final performance score in the stakeholder group will be calculated in arithmetic mean. Say there are h stakeholders in a stakeholder group $X = \{X_1, X_2, X_3, \cdots, X_h\}$. The set of final scores F is thus:

$$F = \{F_i = \frac{\sum_{k=0}^{h} P_{ik}}{h}; i = 1, ..., n\} \tag{2.3}$$

Finally, after evaluation, the results are visualized. The new version distinct itself from the previous one, introducing lines with different marker symbols. This allows the lines to be more easily distinguished from one another, as well as to offer greater accessibility for black-and-white prints or color-blind readers. The Multi-Actor view as shown in Figure2.2 represents the final scores on different alternatives for each stakeholder group. The lines stand for the alternatives. It is easy to see that different stakeholder groups have different preferred alternatives. This chart represents the value of the MAMCA: it depicts clearly the support of each stakeholder for different solutions.

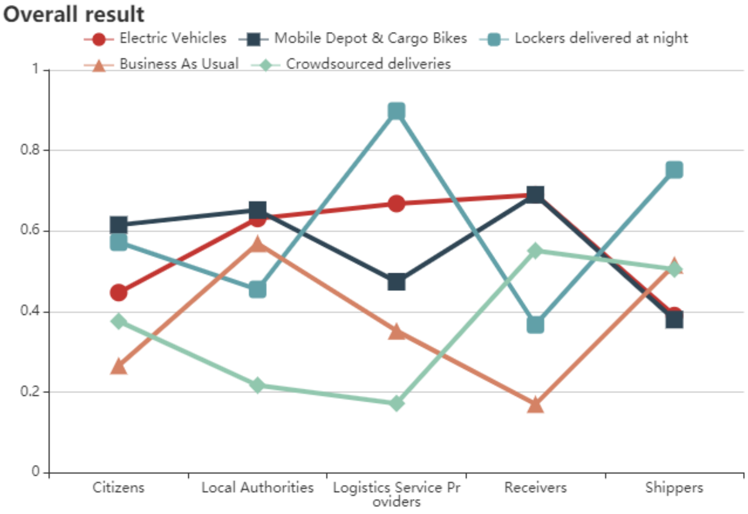
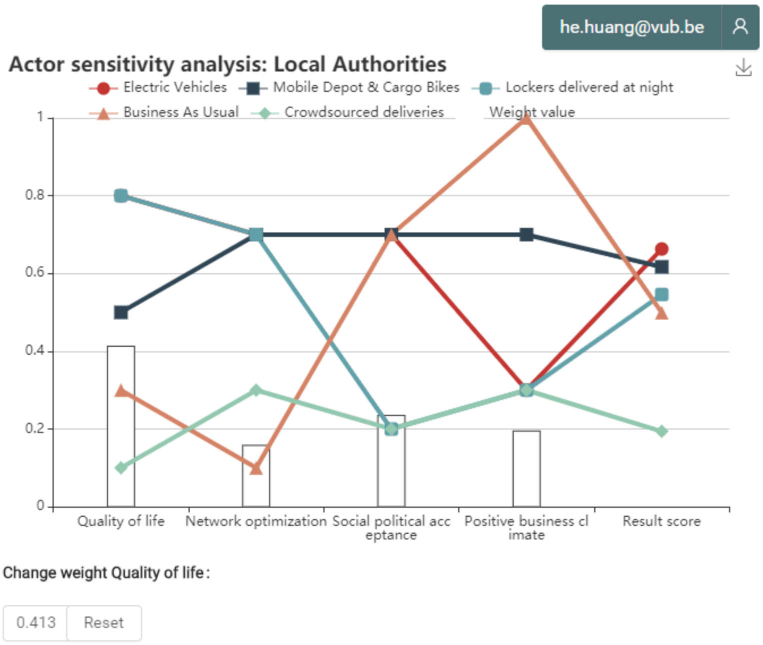


Figure 2.2: The Multi-Actor Analysis

The sensitivity analysis is integrated into the evaluation and weight chart. As shown in Figure2.3, The facilitator is able to change the weights of criteria in any stakeholder group, hence allowing to check the robustness of the results. As shown in the figure, by clicking the button top-right corner, the facilitator can check the weights allocation and evaluation results from different participants in the stakeholder group ‘Local Authorities’.

If there is more than one participant in the stakeholder group, the box plot of the weights’ difference can be shown when the facilitator wants to check the average result of one stakeholder group. As shown in Figure2.4, the box plot of each weight indicates the difference of the weights allocation from different stakeholders. This visualization is especially beneficial when there is a large number of participant in one stakeholder group. This allows the facilitator to know if stakeholders are more controversial about the importance of some criteria while having an agreement on other criteria. For example, in Figure2.4, it can be seen that there is bigger deviance in the weight allocation of criterion ‘Quality of life’, and a less deviance in the weight allocation of the criterion ‘Network optimization’.



Change weight Quality of life: 0.413

Figure 2.3: Actor sensitivity analysis

2.3.2 New features in the software

Besides the change of software stack, other major changes were made.

High effective technologies

The first major change of the software is the replacement of web services. Web services are means to exchange data and information over the network. By building the web services, the frontend of the software and backend can be separated. The web services will communicate from the frontend and the backend of the software. The web services can be built based on two styles, the previous version of MAMCA software relying on Simple Object Access Protocol (SOAP). However, the other style, Representational State Transfer Protocol (REST), which was defined later, has a better throughput and response time. It has the definite advantage over the SOAP style [166].

Another major change of technology is the programming language. Java and PHP are used in the previous version of MAMCA software, which is robust and secure. Op-

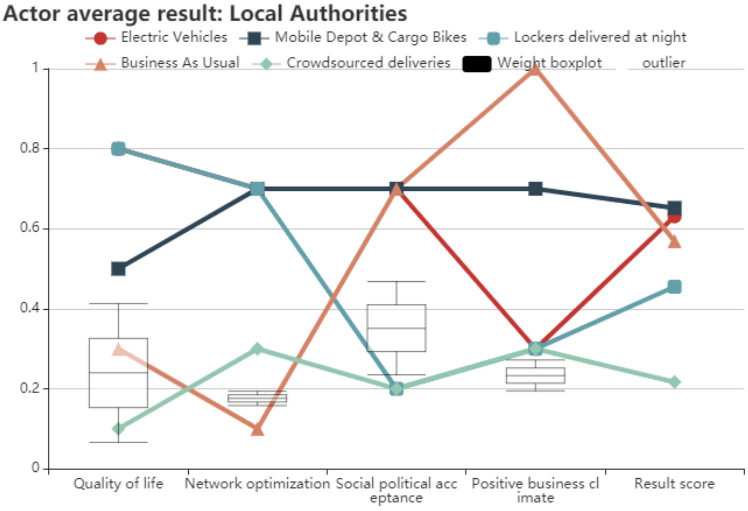


Figure 2.4: Average result of the stakeholder group 'Local Authorities'

Table 2.3: The performance of two versions of MAMCA software

	Previous MAMCA software	New MAMCA software
Request sent	49	2
Resources (kB)	1200	1.9
Response time (ms)	2816	42

positely, the new MAMCA software is written in JavaScript, both frontend and backend. With the help of JavaScript, it is possible to make MAMCA a single-page application, that is, a web interface composed of individual components which can be reloaded independently [167]. So there will be no need for reload of the entire page, which can save more resources for the software. The data transaction between the frontend and backend is through JavaScript Object Notation (JSON). As a lightweight data carrier, it is human-readable and efficient. [168] The final result is that the new software has less response time than the previous one. To test the performance of the new software, a controlled trial was taken between new MAMCA software and the previous version of MAMCA software. The same project was chosen, and pairwise comparison was taken in the same stakeholder group 'Local Authorities' to weigh the criteria. Network traffic was captured during the weighing, resources loaded and response time was recorded as shown in Table 2.3. The previous MAMCA software sent 49 requests to the server and loaded 1.2 MB resources in total. Oppositely, the new MAMCA software only sent 2 requests to the server and loaded 1.9 KB resources also with much faster response time.

New database structure

In the previous version of MAMCA software, the relational database is used. MySQL is used as the database management system. In the new MAMCA software, MongoDB is chosen, which is a NoSQL database. It is a document-oriented database, and the data is stored in JSON-like documents. It is more flexible than the SQL as it allows the different structure or fields. Talking about the performance of the database, MongoDB has higher reading and writing speed than the conventional SQL [169]. Furthermore, as a document-oriented database, the data of one project saved in MongoDB is not distributed in different database tables anymore, which is easier to collect and analyze for further data analysis.

2.3.3 Enhanced 'participation' concept

It is necessary to get an idea of the needs and objectives of the participants from different stakeholder group, that's the reason to develop the MAMCA software. The new MAMCA software is easier to involve more participants in the decision-making process. And in this software, it can have an easier, faster way to evaluate and better comprehension. We did this, by the integration of the SMART method which is a very straight forward way to evaluate alternatives. The new participation system also improves the interaction experience between participants.

The integration of SMART method

It was observed during MAMCA workshops that the evaluators most often spent a lot of time to understand the theory of the MCDM method. Also, it was time-consuming when they did the pairwise comparison if there are many criteria. Thirdly, for many it was still perceived as a black box. That's why SMART is integrated in the software. As the oldest, simplest and most used MCDM method, the reason to apply this method into software is that participants will be able to understand how their input is used to calculate preference scores, which is more unlikely in PROMETHEE and AHP. In contrast to AHP, there is no issue of participants having to perform lots of pairwise comparisons. Another advantage of SMART is that the overall performance scores can be meaningfully interpreted, instead of being a dimensionless index that is only meaningful in comparison to other scores.

Comparing to AHP, SMART sacrifices accuracy and sensitivity for its simplicity. Because of the subjective nature of technique, SMART is not consistent in contrast to the pairwise comparison. It is not suggested to use SMART method to make the final decision but a way to get insight into the objectives with different alternatives in a short time [170]. With SMART, the participants can save more time to comprehend the meaning of the performance score, and understand the importance of the presence of other participants in the group: as shown in (2.2), it is easy to know the different weight allocation on criteria and the different preference on alternatives from other participants will affect the final score of one alternative.

Easier interaction between participants

The facilitator and participants can have a better experience in communication and comparison in the new software thanks to the new participation system. It helps facilitate the MAMCA evaluation, especially in a workshop. The figure Figure2.5 shows how the new participation system works.

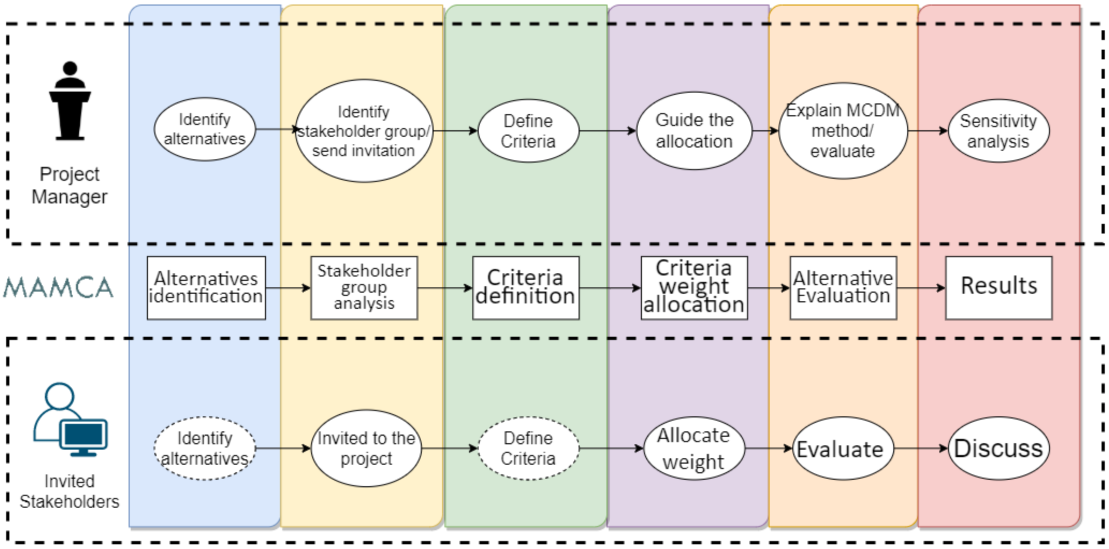


Figure 2.5: The new participation system in the MAMCA software

After identifying the stakeholder groups in a MAMCA project, the facilitator can invite participants to the project through the email invitation. As the dashed circles in the Figure2.5 indicates, it is optional that the facilitator and participants can identify alternatives together. The participants can also define the criteria of their groups with guidance from the facilitator.

The facilitator can coordinate the works of participants. For example, normally the weight allocation of criteria is more subjective than the evaluation of alternatives. The participants can allocate weights based on their priority. Though when they evaluate the alternatives, they may need help from the experts. They can discuss the consensual performance scores of alternatives in the stakeholder group. The facilitator can put the scores they discussed in the evaluation Table After that, the participants are able to use the same performance scores from the facilitator with one click of a button.

During the evaluation, the facilitator is free to check the weight allocations and alternative evaluations from participants. Also, as mentioned before, after the evaluation, the participants can check the average stakeholder group result. Stakeholders in the same stakeholder group are able to check the result of others. The participants can do the sensitivity analysis, in order to reach the consensus among all. The new software expresses the differences of MAMCA from the other MCDM methodology: it searches the win-win solutions by taking the different points of view from participants' accounts. The new software can help participants understand the impact on each other.

2.4 Discussion and future Work

The motivation for developing the new software is to make the MAMCA methodology more understandable and more accessible for the participants in the project. The software is refined for ease of use and reliability and is especially suitable for the evaluation in workshops. The integration of the SMART method allows participants to understand the evaluation steps, hence being more transparent.

Because of the characteristic of the development stack, the new MAMCA software is easy to extend functions, which means there can be more features to integrate into the future works.

Improvement on the concept of 'participation'

The first refinement for further work is to improve the concept of 'Participation'. In the MAMCA workshop, the participants can discuss the weight differences of the criteria, compare the performance scores they give to alternatives. Afterwards, the participants will discuss and find a compromised solution. The discussion among the participants to seek consensus is one of the most important part of participation in MAMCA workshop. A suitable method to help participants search consensus can facilitate the discussion and improve the participation quality. Doan and De Smet developed an alternative weight sensitivity analysis based on linear programming (MILP) [171]. It can be applied in the MAMCA methodology to offer a consensus between different participants by taking the inverse optimization point of view. This can help the participants better understand the positions of the others and improve the quality of discussion.

The new MAMCA software can help the facilitators design the MAMCA structure, for example help them define the alternatives and criteria. Meanwhile, the software can be further developed to make the MAMCA software as a co-creation and co-design platform [147]. The participants can be involved in the above mentioned steps, and this in-depth participation can facilitate alternatives and criteria meet the interests and preferences of the participants.

Integration of other MCDM methods

As any MCDM method can be used in the MAMCA methodology, especially the GDSM-method as they are able to cope with the stakeholder concept [67], other MCDM methods such as PROMETHEE can be integrated into the software thanks to easy extensibility of the software. By increasing the available methods the users have more freedom to choose suitable methods. For example, participants can use PROMETHEE as they provide different preference functions which suitable for different scenarios, or they can choose AHP because of its consistency.

Development for mass participation

Because of the flexibility and high performance of the new database in the software, it is prepared for mass participant involvement analysis. A stakeholder group such as citizens is able to include massive number of participants with different behaviors and preferences. Subgroups within one stakeholder group can be clustered based on their evaluation or preferences. A model will be designed to analyze and classify this large amount of data.

2.5 Conclusion

In this chapter, the new MAMCA software was introduced to better support the decision-making process of the stakeholders. As the new interaction tool for MAMCA methodology, it follows the evaluation structures of the methodology with a simple and clear user interface. It is aimed to have a better performance in workshop settings. The SMART method is integrated to make the participants focus on understanding the meaning of their scoring instead of spending time to comprehend the theory of the MCDM method. The software enhances the concept of participation during the evaluation. Besides the representative result visualizations, sensitivity analysis and box plots of weight allocations within stakeholder groups are developed. The participants can have a better understanding of the influence of their behaviors and preferences.

The MAMCA software is designed as a tool to understand and analyze the role and input of stakeholders in strategic processes. It can be seen as a transition tool as participants learn to look at the decision problem in a new and more empathetic way. The uniqueness of MAMCA lies in the multi-actor evaluation, as stakeholders learn to see how other stakeholders might have other goals and criteria. In the evaluation process, the participant is aware of the presence of the other stakeholders. There is a learning loop for the stakeholders. Participants can have a better understanding of each other's position, which makes a stakeholder group more prone to search common solutions, to reach the consensus. The idea is that the habits of one individual should be altered, however not in an imposed way, but rather in a voluntary way. In addition to this, we should be aware that individual behavior is not happening on an island. In the end, the MAMCA software is not a tool to make the decision for the participants, but a tool to help them to understand and analyze the role and input of themselves in strategic processes.

Chapter 3

Mass Participation Survey Tool

3.1 Introduction

In the decision-making process of public management, stakeholder involvement plays an important role. The stakeholders, as individuals, have influences on the decision-making [19]. Normally they have different backgrounds, representing different organizations/groups. They have interests in the objectives of the project and will be affected by the consequence of the decision taken [45]. By involving the participants from different stakeholder groups, the decision-maker can have a better understanding of the objectives of the different parties, which typically leads to higher implementation acceptance and lower chances of project failure [172]. In the meantime, the participants are able to voice their own interests or concerns. Furthermore, the participants can be aware of the presence of each other, and the process of the evaluation can reflect their mutual interests and conflicts explicitly [67].

Multi-Actor Multi-Criteria Analysis (MAMCA) is a methodology that extends the traditional Multi-Criteria Decision-Making (MCDM) methods by allowing the inclusion of multiple stakeholder groups (see Fig. 3.1). The involvement of stakeholder groups in MAMCA facilitates a more rational solution in the field of energy [173], transportation [156], logistic and mobility [68].

In the MAMCA evaluation process, it is found that some stakeholder groups are not suitable to be directly represented by one or a few participants. Because even when they have the same criteria, their priority to these criteria can be different [174]. Thus,

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This chapter is based on Huang, H., Mommens, K., Lebeau, P., & Macharis, C. (2021, May). The Multi-Actor Multi-Criteria Analysis (MAMCA) for Mass-Participation Decision Making. In International Conference on Decision Support System Technology (pp. 3-17). Springer, Cham.

a need for mass-participation comes to the table of discussion. An extended survey tool designed for mass-participation involvement in MAMCA software is developed.

In this chapter, we will first explain the further developed MAMCA methodology towards a mass-participation tool. Then, the MAMCA survey tool is introduced. Finally, a didactic case study of supply chain management is applied to demonstrate the mass-participation function.

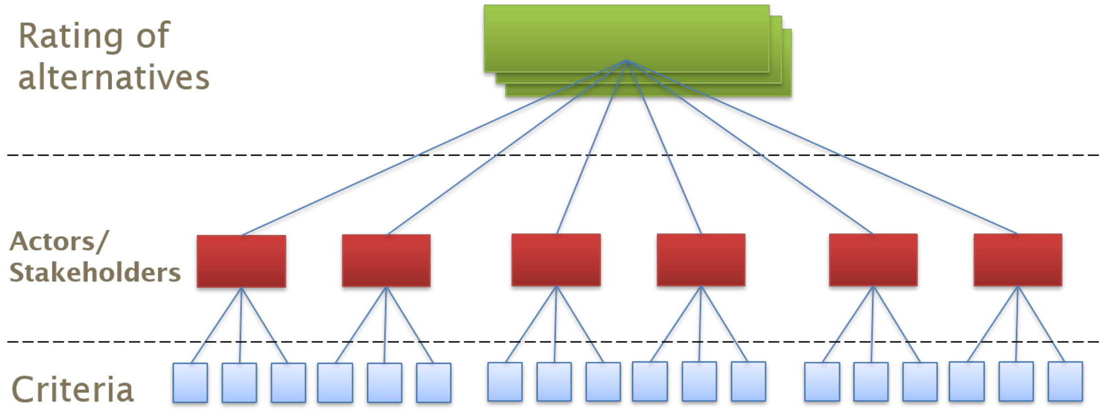


Figure 3.1: MAMCA structure

3.2 MAMCA methodology evolution

The introduction of MAMCA steps is given in Chapter 2. After the methodology was introduced for years [175], it was found that normally there is a need for more than one participant to represent their stakeholder group. More participants are invited in the workshop for the evaluation. Turcksin et al. invited 31 highly representative participants from 7 different groups to assess several biofuel options for Belgium that can contribute to the binding target of 10% renewable fuels in transport by 2020 [176]. Sun et al. surveyed 48 highly representative participants from 8 groups to evaluate the low-carbon transport policies in Tianjin, China [177]. Keseru et al. invited 40 participants into 7 different stakeholder groups to improve mobility in the city center of Leuven, Belgium [178]. It could be foreseen that the MAMCA evaluation is not satisfied with only one representative for each group, that is, the concept of the "stakeholder" gradually move to "stakeholder group", as it is hard for only one participant to represent the whole interest and preference of his/her group. Multiple participants can be invited for the evaluation of their stakeholder group. Participants within one group already negotiate, but there is still a bit of struggle with loud and quiet people. They may share the same criteria, yet they can hold different priorities to the criteria (see Fig. 3.2).

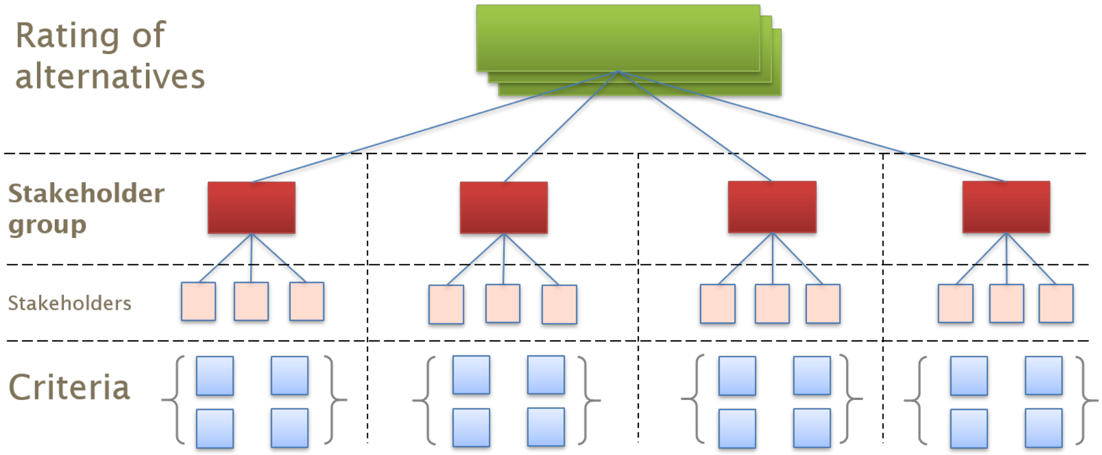


Figure 3.2: Evolved MAMCA structure

To better adapt the concept of stakeholder group involvement, and to better facilitate the workshop, a new MAMCA software was developed [179]. The new software enhances the participation experience, which can better include the evaluation of multiple participants in one stakeholder group. The standard MAMCA participation system was introduced in the software (see Fig. 2.5). The decision makers identify the alternatives and the facilitators define the criteria with stakeholders in the workshop. And the facilitators can coordinate the evaluation of the stakeholders. The weight allocation on criteria of the stakeholder group is the arithmetic mean of all the ranking scores of the participants in the group, and the box plot of the weights' differences will be shown. This participation system can help participants understand the impact on each other. They can check the points of view not only between the stakeholder groups but also within the group.

Still, for some stakeholder groups, this participation system is not well suited. Especially when there are stakeholder groups like citizens. This kind of group could have a large amount of stakeholders, it is important to collect more profiles from the group [180]. The opinions from the group need to be heard as much as possible, as it is considered a way to reduce uncertainty and to improve the democratic legitimacy of those processes. Because the participants in the group normally have different Socioeconomic status (SES), the different voices need to be heard, instead of only represented by one or limited amount during the evaluation. On the other hand, such participants are hard to reach. Seeing it is always time-consuming and costly to assemble a large number of participants at the same time, it is not feasible to invite all the participants in the workshop for the evaluation [100]. A new evaluation model for better assessment by such stakeholder groups is needed. Thus, mass-participation decision-making is proposed.

3.3 Mass-participation decision-making in MAMCA

Mass-participation is sought targeting to certain stakeholder group, which contains the following attributes:

1. A large number of participants within one stakeholder group;
2. The group that requires more than one representative to voice the preferences of the group;
3. The participants in the group have various relevant socio-economic status;
4. The participants are hard to reach and assemble;
5. The participants need an easy to understand and less time-consuming evaluation method.

Survey data collection is suitable for the evaluation of such a stakeholder group that fulfills the needs of the mentioned attributes [181]: Because it is not possible to gather all participants in a single MAMCA workshop, the survey offers them the possibility to do the weight allocation and evaluation individually, at a non-specified time. The survey consists of the following elements: Designing and answering survey questions, weight allocation, and alternative evaluation. In the survey, the facilitators can also ask questions on their socio-economic profiles for later research. The Profile Ranking with Order Statistics Evaluations (PROSE) is applied for the evaluation [182]. This approach combines MCDM, voting theory. After the evaluation, the facilitators can import the survey data to the MAMCA model of the main project. It is also possible to do a post-hoc analysis to find out the homogeneity and heterogeneity within the stakeholder group. As shown in Fig. 3.3, the MAMCA survey model aimed for mass-participation decision-making is proposed. In such a way, the participants and the facilitators can work independently. The participants can weigh the criteria and evaluate the alternatives under the assistance of the survey tool instruction, without guidance from the facilitators, unlike the standard MAMCA participation system where the participants have to participate in the physical or online workshop. In the following subsection, the necessary steps of the model are clarified.

3.3.1 Designing and answering survey Questions

When there is a large amount of participants in one stakeholder group, instead of treating the stakeholder group as a whole all the time, there is a need to look inside the characteristics of individuals. In a stakeholder group like citizens, the priorities and preferences of participants can vary according to gender, age, income, education, etc. By collecting socio-economic profiles of the stakeholders it can provide a “bird eye view” of the stakeholder group, which helps the decision-maker identify profiles, concerns, and opinions. It displays combined and comparable statistical snapshots of the stakeholder group.

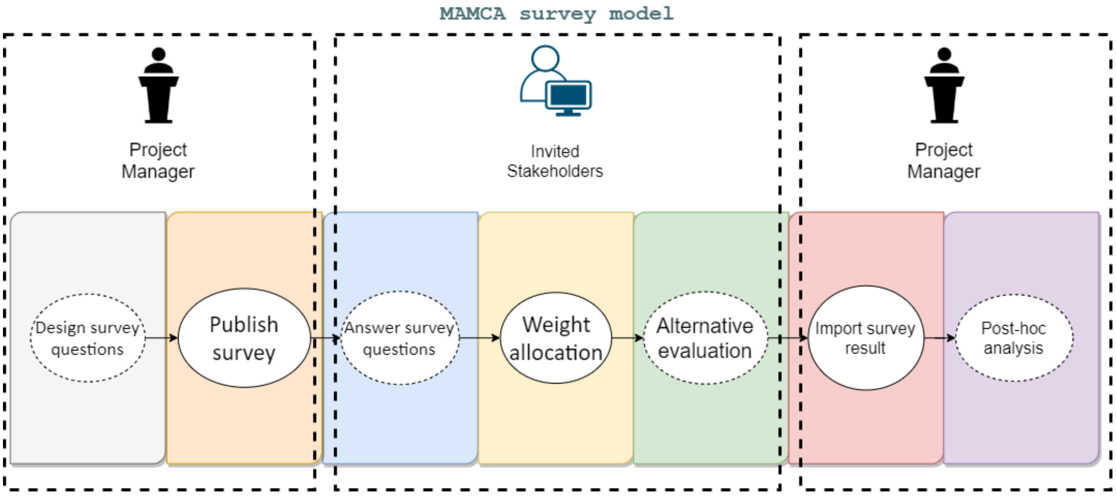


Figure 3.3: MAMCA survey model

The SES are important indicators in mass-participation decision-making, as the stakeholder group like “citizens”, ”residents” is in a more general term, that it is possible to find a significant difference statistically of the criteria priority ranking or alternative evaluation. In that case, the participants can be regrouped or divided into subgroups [183].

The analysis of the stakeholder group’s homogeneity and heterogeneity can be done by asking about some specific participants’ SES. The decision-maker can design survey questions for inquiring. After collecting the socioeconomic profiles of the participants, it is possible to do a post-hoc analysis by combining the criteria priority ranking and socio-economic profiles.

3.3.2 Weight allocation and alternative evaluation

The key point of the evaluation is to be fast, easy to understand but also mathematically sound. Because of the characteristics of the mass-participation stakeholder group, participants are often hard to reach, and they do not take the time to understand the methodology of the calculation, but focus on expressing their preference and priority. Also, non-technical participants are difficult to understand the mathematical meaning of the evaluation methods [184]. Thus, PROSE is chosen. This method applies a weighted sum approach based on order statistics to combine the individual profile distribution. It is well suitable for mass-participation evaluation, as it does not considers only the mean distribution values, but also standard deviations [182].

Weight allocation

An efficient and transparent weight elicitation technique proposed by Kunsch and Brans is applied in this model, which is based on semantic relative-importance classes; participants are required to weigh the criteria based on their priorities [24]. They need to represent relative importance's on an ordinal score level: 1 (Least important), 2 (Less important), 3 (Middle), 4 (More Important), 5 (Most important). The scale is chosen based on the magic number 7 plus or minus 2; by choosing the 5-point Likert scale (LS), the participants can have space of the mind to process the information [185]. In the meantime, the priority ranking has enough levels concerning the accuracy of the weighing. Plus, the "0" class (Not relative) is added for giving a vanishing weight in the judgment. participants are asked to define relative-importance classes in the above-mentioned scale. They need to rank at least one criterion as the "most important" as it is never empty. Then, participants weigh the other criteria by comparing the most important criterion.

Weight allocations from all participants in the group are collected. Suppose there are n criteria in the criteria set of the stakeholder group, the multiple-participant profiles of criterion k rank on the class weight score i_c is w_{ki_c}, which means the proportionality of the criterion percentage profile of the class weights. By taking the arithmetic mean of the importance's classes, the not-normalized weight (NNW) of the criterion k is gotten:

$$NNW_k = \sum_{i_c=0}^{5} i_c \times w_{ki_c}; i_c = 0,1,2,3,4,5 \tag{3.1}$$

Then the normalized weight (NW) of the criterion k is the NNW of criterion k proportional to the NNW set:

$$NW_k = \frac{NNW_k}{\sum_{j=1}^{n} NNW_j} \tag{3.2}$$

In this way, the global weight allocation of the participants from the stakeholder group is calculated.

Alternative evaluation

Suppose participants have to evaluate a finite set of alternative $A = \{a_1, a_2, ..., a_m\}$, participants are asked to give performance scores on the alternatives based on each criterion. A 5-point LS is used, and at least one alternative needs to be scored 5 as the "most preferred" for one criterion. The other alternatives are scored by comparing the most preferred alternative, which is treated as a benchmark. After collecting all the evaluation data, the performance percentage profile p_{tji} of alternative t on the class weight score i_a based on criterion j is gotten.

The calculation of the performance scores considers the profile distributions. to get the global performance indicator of an alternative a_t, say S_t, the global weight profile set $G_t = \{g_0, g_1, g_2, g_3, g_4, g_5\}$ needs to be calculated first:

$$G_t = \{g_{ti_a} = \sum_{j=1}^{n} NW_j \times p_{tji_a}\};\ i_a = 0, 1, 2, 3, 4, 5 \tag{3.3}$$

Where i_a is the alternative performance score class. After obtaining the global weight profile set of one alternative, its global mean score V_t can be calculated:

$$V_t = \sum_{i_a=0}^{5} i_a \times g_{ti_a} \tag{3.4}$$

Still, the sole global mean score loses the important information concerning the profile dispersion, as the high deviation on the alternative performance scores will result in a non-consensual solution among participants. To obtain a safer ranking, the standard deviation of the performance score is considered. The standard deviation σ_t of V_t is given in:

$$\sigma_t = \sqrt{\sum_{i_a=0}^{5} g_{ti_a} \times (i_a - V_t)^2} \tag{3.5}$$

The final global performance indicator combines mean value and spread measured by the standard deviation:

$$S_t = V_t - \sigma_t \tag{3.6}$$

Only the lower value from the interval of the standard deviation σ_t is kept for being on the safe performance side.

The evaluation process of the MAMCA survey model is finished by now. The final weight allocation of the mass-participation stakeholder group can be used in the normal MAMCA evaluation process. However, it is advised not to include the alternative performance indicators as the final evaluation scores of the stakeholder group. Instead, the global performance indicators of alternatives should be treated as a reference to the participants' preferences. It is believed that the criteria priority ranking is much more objective than the alternative evaluation. The alternative evaluation requires more objective data and information to support, so the process of the alternative evaluation needs to be executed preferably by the experts. Still, the decision-maker can compare the result of the evaluation of experts and the participants' performance indicators for further investigating. E.g., they can have a discussion with the participants on it to see what their potential misconception is, use it to determine communication focus on specific alternatives.

3.4 Case study

In order to apply the MACMA survey model in practice, a survey tool is developed in the MACMA software. Dedicated pages for the survey tool are built, called “MAMCA survey tool” pages. Each MAMCA project has individual survey setting pages. And the decision-maker can publish the surveys dedicated to different stakeholder groups, in which different survey questions can be asked. Also, the decision-maker has an option to ask participants to evaluate alternatives or not, while the weight allocation of criteria is a must.

To demonstrate the MAMCA mass-participation function, a fictive case entitled “The last-mile in the supply chain” is used. The case aimed to gain insight into the extent to which different alternatives for the last mile of a supply chain for home deliveries contribute to the interests of the different stakeholder groups involved. In this case study, there is a stakeholder group “citizens”, that is suitable for validating the mass-participation function. In this study, only the stake-holder group “citizens” is focused upon. The data shown here are for demonstration reason only and are not the result of an actual survey that was performed among citizens. The criteria of the “citizens” group and the corresponding descriptions and directions of preference are shown in Table 3.1.

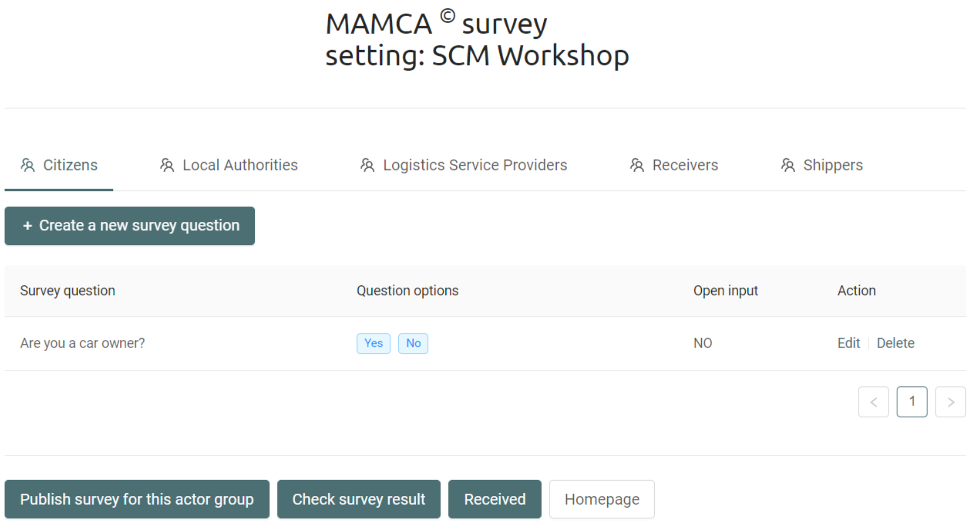
Table 3.1: Criteria of stakeholder group ‘citizens’

Criterion	Criterion description	Direction of preference
Road safety	The low risk that a person using the urban road network will be (fatally) injured	maximization
Air quality	Low concentration of particulate matter, NOx and SO2 in the air	maximization
Urban accessibility	Reduce freight transport, less congestion	maximization
Attractive urban environment	Attractive and livable urban environment for its citizens	maximization
Low noise nuisance	Reduce noise nuisance of road transportation	maximization

Before distributing the survey, a relevant question about the participants’ SES is raised: “Is there a significant difference on the criteria priority ranking between car owners and non-owners?”. The decision-maker can ask these types of questions through the survey (see Fig. 3.4). Then, a survey page dedicated to this stakeholder group can be generated. Participants need to rank the priority of the criteria. The decision-maker can choose if participants are also allowed to evaluate the alternatives.

3.4.1 Participants’ perspective

The participants receive the survey link that is sent by the decision-maker. The survey consists of 5 parts: Description of the project, overview of alternatives and criteria,

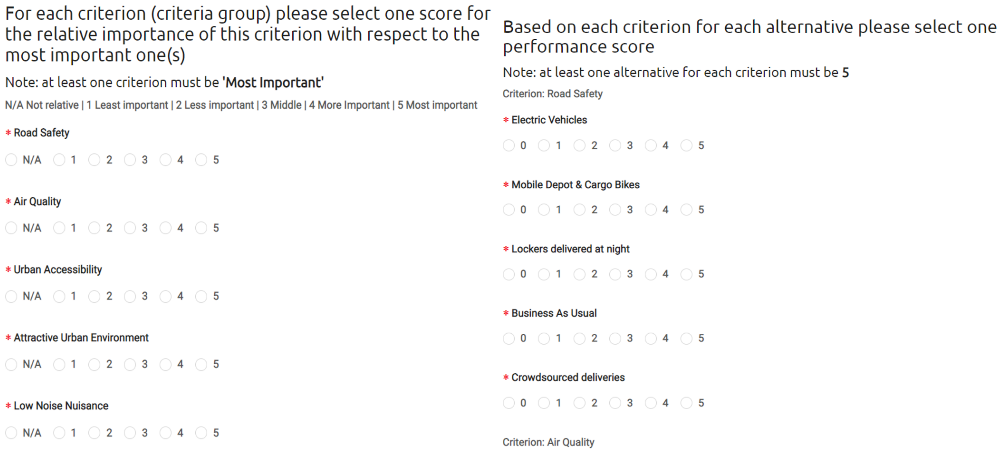


MAMCA © survey
setting: SCM Workshop

Survey question	Question options	Open input	Action
Are you a car owner?	Yes No	NO	Edit | Delete

Figure 3.4: The screenshot of MAMCA survey setting: design survey questions

answering survey questions (optional), weighing the criteria, evaluating the alternatives (optional). After going through the overview of the alternatives and criteria, they should answer the SES questions asked by the decision-maker. Next, the participants need to give the importance scores to the criteria, and optionally, they will give the performance scores to the alternatives based on their preferences (see Fig. 3.5).



For each criterion (criteria group) please select one score for the relative importance of this criterion with respect to the most important one(s)

Note: at least one criterion must be **'Most Important'**

N/A Not relative | 1 Least important | 2 Less important | 3 Middle | 4 More Important | 5 Most important

* Road Safety
○ N/A ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

* Air Quality
○ N/A ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

* Urban Accessibility
○ N/A ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

* Attractive Urban Environment
○ N/A ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

* Low Noise Nuisance
○ N/A ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

Based on each criterion for each alternative please select one performance score

Note: at least one alternative for each criterion must be **5**

Criterion: Road Safety

* Electric Vehicles
○ 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

* Mobile Depot & Cargo Bikes
○ 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

* Lockers delivered at night
○ 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

* Business As Usual
○ 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

* Crowdsourced deliveries
○ 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5

Criterion: Air Quality

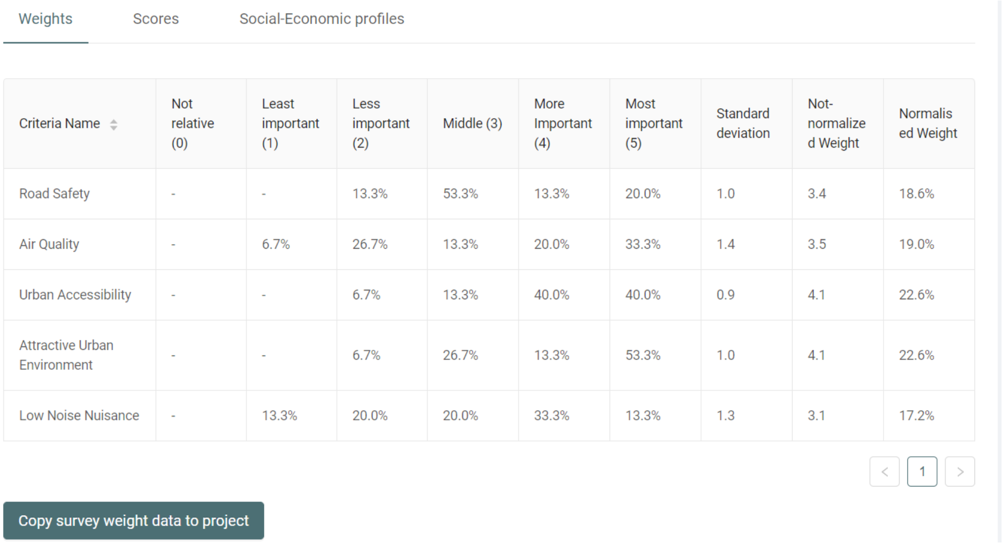
Figure 3.5: Screenshots of the weight allocation and alternatives evaluation pages

The participants do not need to log in to the software. By just answering the survey, the results will be registered.

3.4.2 Decision-maker's perspective

After invited participants have finished the evaluation, the decision-maker can check the final result of the survey in the MAMCA software. As shown in Fig. 3.6, the table of the weights' distribution allocated by the participants and calculated standard deviations are listed. In this example, it indicates that the criteria "Urban Accessibility" and "Attractive Urban Environment" have the highest NNWs; at the same time, these two criteria have the lowest standard deviations, which means they are the most important criteria in the points of view from the stakeholders. The NWs are the final weight allocation of the stakeholder group.

After all surveys are submitted and the quality of them are checked, the decision-maker can import the survey result to the MAMCA project by clicking one single button. The NWs of the survey will be treated as the weight allocation of the stakeholder group "citizens" and will be applied in the further evaluation of the MAMCA process.

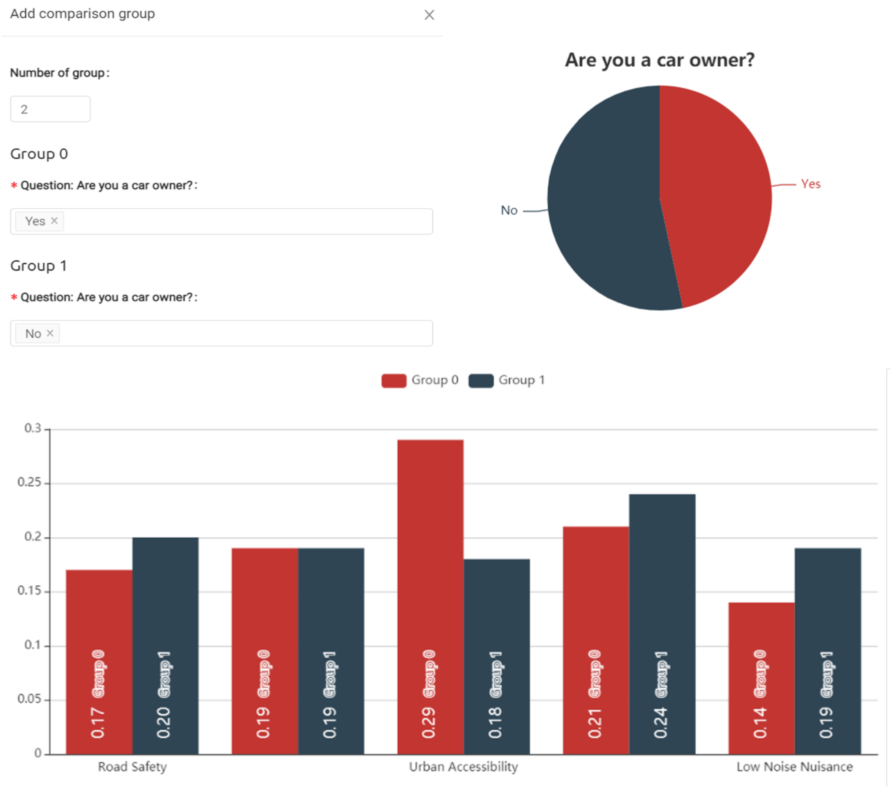


Criteria Name	Not relative (0)	Least important (1)	Less important (2)	Middle (3)	More Important (4)	Most important (5)	Standard deviation	Not-normalized Weight	Normalised Weight
Road Safety	-	-	13.3%	53.3%	13.3%	20.0%	1.0	3.4	18.6%
Air Quality	-	6.7%	26.7%	13.3%	20.0%	33.3%	1.4	3.5	19.0%
Urban Accessibility	-	-	6.7%	13.3%	40.0%	40.0%	0.9	4.1	22.6%
Attractive Urban Environment	-	-	6.7%	26.7%	13.3%	53.3%	1.0	4.1	22.6%
Low Noise Nuisance	-	13.3%	20.0%	20.0%	33.3%	13.3%	1.3	3.1	17.2%

Figure 3.6: Screenshot of the 'citizens' group's weight table

As mentioned before, in this case study, we would like to investigate if the car owners in the group "citizens" would have a different rank of criteria priority than those who do not own a car. In the MAMCA survey tool, the decision-maker can add comparison groups based on asked survey questions (see Fig. 3.7). Two groups are created based on if the participants own private cars. A pie chart showing the proportion of the answers indicates that the participants who own private cars are slightly fewer than those who do not. A bar chart is generated that shows the weight allocation of the criteria from the two comparison groups. It can be seen there is a large difference in the importance of the criterion "Urban Accessibility", that the car owners rank as the most important criterion among all, while the other participants rank it as the least important. Apart from that, the other importance of the criteria is similar. It makes sense that, the citizens overall find an attractive and livable urban environment important, but the car owners suffer from over-busy traffic, so they also think less congestion is really important.

The decision-maker can have a further discussion on it, as now the "citizens" group has two different criteria priorities because of urban accessibility. Two subgroups could be divided into the "citizens" group based on the SES "Private Car Ownership". The corresponding criteria weights are allocated regarding the SES. In the afterward MAMCA alternative evaluation, experts can give more rational evaluation scores for two subgroups concern about their interests.



Add comparison group

Number of group: 2

Group 0

* Question: Are you a car owner?: Yes

Group 1

* Question: Are you a car owner?: No

Figure 3.7: Screenshot of the comparison function

3.5 Limitations & directions for future fesearch

This study tries to demonstrate the new MAMCA mass-participation survey tool. A fictive case is used in this study; it is a didactic case that was applied in the university. The students are the actors for different stakeholder groups as role plays. In the end, 50 samples of the surveys are collected for the "citizens" stakeholder group. Still, there should be more responses of the voices as a mass-participation decision-making process. There are still a lot of potentials for this study. three directions for the future research are listed below:

1. This chapter mainly talks about the methodology of the mass-participation decision-making behind and focus on the presentation of the MAMCA survey tool. A real-world mass-participation case in the real world should be studied in the near future.
2. There is only a small discussion about the subgroup creation and evaluation after collecting the data. A dedicated work will be done to discuss when and how to regroup the stakeholder group or divided the group into subgroups based on the collected information, e.g., participants' criteria rankings, criteria weights, preferences, or SESs.
3. This survey tool can also serve as a validation tool for MAMCA evaluation. For example, after the MAMCA workshops, one or several alternatives are selected as solutions to be implement. A post-hoc survey could be distributed to verify that the solution meets the preferences of the participants. It is also possible to ask participants via the survey to incorporate new alternatives or modify existing ones.

3.6 Conclusion

MAMCA methodology now shifts the concept of the "stakeholder" to the "stakeholder group", trying to hear the points of view from more participants, instead of those of only one representative in each group. Elaborate types of groups like "citizens" have some characteristics that are inefficiently addressed by the current participation system. The participants within this group are normally hard-to-reach and have quite different SES. To involve more participants and hear the voices of them, a new MAMCA survey model for the mass-participation is designed. The survey model divides the tasks of the decision-maker and participants, such that they can work singly instead of being gathered in the workshop. PROSE method is used for the evaluation process. It is a transparent method that applies a weighted sum approach based on order statistics to combine the individual profile distribution. It is suitable for the mass-participation evaluation as it is easy to understand but also mathematically sound. Additionally, the decision-maker can inquire about the SES of participants for further investigation within the stakeholder group. Following this, a survey tool built in MAMCA software is developed. The survey tool can explore more detail within one single stakeholder group. As there is a large number of participants participating, their priorities might be different. The survey tool not only indicates the weight allocation of the criteria, but also the standard deviation of the importance scores given. The decision-maker is able to find the homogeneity and heterogeneity within the stakeholder group: By creating comparison groups, the weight allocation of the criteria from participants with different SES are displayed in a bar chart. If there is a significant difference in the ranking from the participants with different SES, the decision-maker should consider regrouping or identifying subgroups for the participants.

Chapter 4

Criteria Pre-processing Framework

4.1 Introduction

In operational research, when confronting two or more alternatives, multiple-criteria decision-making (MCDM) is a commonly used method for evaluation [186]. In the process of MCDM, stakeholder involvement is increasingly considered important [187]. An individual who is involved in the decision-making process that can influence or be influenced by the decision taken is called a stakeholder [19]. In particular applications, involving stakeholder groups is consider beneficial for the quality of the decisions can be improved [188]. Also, the influence of the different interest groups on decision-making is increased [189], and the decision-maker can better understand the points of view of the stakeholder groups [66]. Various multi-criteria group decision-making (MCGDM) frameworks with the involvement of stakeholder groups have been developed [58], such as Multi-Actor Multi-Criteria Analysis (MAMCA) [67]. It has been applied in various domains such as mobility and logistics to measure support from key stakeholder groups [68, 175]. MAMCA can be used for involving stakeholders at an early stage, which can help facilitators identify alternatives and define criteria in their stakeholder groups [179].

In MAMCA, stakeholder groups can have different criteria sets to reflect their respective preferences [1]. In the process, one stakeholder group can be represented by multiple participants. In large stakeholder groups such as citizens are involved, this type of participation can be referred to mass-participation[190]. In Figure 3.2, the MAMCA structure is illustrated. After defining the criteria, an MCDM process is applied for each

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This chapter is based on Huang, H., Cannoy, R., Brusselaers, N., & te Boveldt, G.. Criteria pre-processing in multi-actor multi-criteria analysis. Under review by the Journal of Multi-Criteria Decision Analysis.

participant, as the weight elicitation and alternative evaluation are executed individually [146]. Thus, MAMCA can retain the priorities and objectives of each stakeholder group, while in the meantime, the preference of each stakeholder will be reflected.

The determination of criteria is a fundamental step in the MAMCA process. The criteria for one stakeholder group reveal the group's priorities. It is advisable to keep the number of criteria as low as possible in order to avoid redundancy but retain homogeneity, and operationality [68]. However, facilitators might find it difficult to decide which criteria to select and which to discard. On the one hand, essential criteria must be retained, but on the other hand, too many criteria might lead to cognitive problems [191]. Especially for a larger group, the participants' priorities and preferences are likely to be diverse, which makes the determination of criteria more difficult [112]. Currently, there is no formal way to help facilitators define the criteria with stakeholder involvement. Hence, we argue that there is a need to develop a framework that can help facilitators select the criteria set that represents stakeholders' priorities but limits the overall number of criteria.

This chapter proposes a systematic criteria selection framework for MAMCA, which we call criteria pre-processing. In this framework, the potential criteria are first selected, then filtered. Finally, the individual criteria set for each stakeholder group is chosen by soliciting opinions from participants. This framework could serve as a mathematical reference for the facilitators in selecting the criteria. This procedure could be particularly useful in mass-participation applications, which are typically characterized by large numbers of divergent priorities [190].

In the following section, the MAMCA framework will be introduced. Next, the criteria pre-processing framework is introduced. The steps of pre-processing are defined, and the criteria selection model is explained. Finally, the framework is applied in a construction logistics case with the aim to demonstrate the plausibility of the model.

4.2 MAMCA Methodology

The MCDM process typically includes the following steps: problem statement, defining alternatives, defining criteria, eliciting criteria weights, appraising alternatives, analyzing scores, and drawing conclusions [158]. Because of the involvement of the stakeholders, extra steps are needed in MAMCA such as defining the stakeholders. Figure 6.2 illustrates the MAMCA framework and the steps of the analysis. There are seven steps in MAMCA: First, the potential alternatives need to be defined. In the consideration of different scenarios, policy measures, etc., decision makers identify alternatives. In the second step, the facilitators need to apply stakeholder analysis to identify stakeholder groups that need to be consulted and whose views to take into account. In the third step, the criteria are defined based on the objectives of the stakeholder groups. Different stakeholder groups may have different objectives, resulting in different criteria sets. This can help each stakeholder group express their priorities precisely.

In step 5, the participants from each stakeholder group need to allocate the weight for their criteria and assess the performance of alternatives based on their criteria. The form of criteria weight elicitation and alternative performance assessment can be different: a workshop can be held to invite representatives to evaluate for their stakeholder groups; it can also be realized in a mass-participation way by distributing a survey for the evaluation so that voices from more stakeholders can be heard [179]. MAMCA is allowed to use any MCDM method to evaluate alternatives, such as the Analytical Hierarchy Process (AHP) [160], ELECTRE [57], Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) [192], or Simple Multi-Attribute Rating Technique (SMART) [164].

At the end of the procedure, in step 6, the preference rankings of the different stakeholder groups are visualized in one chart, i.e., the multi-actor view chart. It shows the comparison of different alternatives and the alternative preference scores calculated for each of the stakeholder group. Then, the decision-maker can apply a mixed-integer linear programming model on the result to find a compromised solution for all stakeholder groups [193]. Finally, in step 7, the chosen alternative can be implemented after the decision is made.

4.2.1 Selection and definition of criteria in MAMCA

Criteria definition is important in MAMCA because the stakeholder groups are likely to have different criteria sets to reflect their priorities. A lack of a key criterion or the existence of a redundant criterion will highly influence the result of the analysis. Thus, a formal way to select the criteria set for each stakeholder group is essential.

We define the process of criteria definition as criteria pre-processing. Earlier applications of MAMCA followed different ways for pre-processing criteria. In their study of stakeholders' preferences for the future of transport in Europe, Keseru et al. [194] first applied content analysis of the mission statements of interest groups to identify their criteria [195]. Then an online survey was held among the participants of the stakeholder groups to validate the relevance of the pre-defined criteria. Afterwards, 5-8 criteria for each stakeholder group were selected for the later steps of the MAMCA. In their research on small-scale urban and regional mobility, Bulckaen et al. [196]. first reviewed existing evaluation approaches and best practices, before distributing a survey among stakeholders. After receiving feedback from stakeholders in workshops and the analysis of nine completed pilot projects, 16 criteria was divided according to the three pillars of sustainability. To assess stakeholder support for different biofuel options in Belgium, Turcksin et al. [176] first tracked a criteria list for each stakeholder group by literature review. Afterward, the pre-defined criteria are validated and evaluated by the representatives from each stakeholder group. By doing so, the final criteria set for each stakeholder group was rendered. In the study of social stakeholder support assessment of low-carbon transport policy in Tianjin, Sun et al. [177] collected and summarized the transport policy criteria by reviewing the relevant decision evaluation literature. Then, they conducted surveys with each stakeholder that could clearly express their objectives.

Subsequently, the decision set was drawn after a second summary.

It can be argued that the criteria pre-processing in previous studies are different but similar. Conventionally, facilitators always seek a pre-defined criteria list for stakeholder groups from previous similar cases, and consider the objectives of the stakeholders. Afterwards, the stakeholders are actively involved in the selection of the final criteria list for the following MAMCA analysis. Often, either a survey is distributed to collect the information from stakeholders or a workshop is held to validate the final list. Now that we have discussed the advantages and disadvantages of the conventional approach of selecting criteria based on the literature review, we introduce novel criteria pre-processing framework.

4.2.2 Principles applied in novel criteria pre-processing framework

Before introducing the framework, two important principles of the criteria pre-processing will be introduced. They are used in the framework to keep the number of criteria cognitively manageable while not missing important criteria.

Magic number seven plus or minus two

Seven plus or minus two is the human short-term memory span, which was proven by experiments and has been sorted out the law from Miller [185]. Based on his study, the memory span of young people is approximately 7 units, which are called chunks. And the chunk is the result of encoding. The encoding and subsequent decoding often lead to errors when there are more than 7 units to memorize. In MCDM, it is already stated in different literature that the number of criteria should be less than nine because it is the greatest amount of information an observer can 'give an object on the basis of an absolute judgment' [191, 197]. The accuracy of the weight allocation decreases when the number of criteria increases [198]. Thus, in MAMCA criteria pre-processing, we suggest limiting the number of criteria from 5 to 9.

Pareto analysis

The initial statement of Pareto analysis is that approximately 80 percent of wealth was concentrated in approximately 20 percent of a population [199]. According to Pareto's viewpoint, a small percentage of input can generate a large percentage of output [200]. Pareto analysis can be applied to any situation to discover the factors causing the result and arrange the factors in the order of their impact [201]. It is useful for identifying, prioritizing and addressing the factors that have the most impact [202]. 80% is a constant number but in this work, we only take the idea of the Pareto principle, that is the 'vital few' and 'trivial many' [203]. In the MCDA, there are 'vital few' criteria that will take up the majority of the weight [204]. By applying Pareto analysis in the MAMCA criteria pre-processing, it can illustrate which criteria have the greatest influence and which ones will have the least impact. Furthermore, a Pareto chart can provide a visualization of the impact of the criteria.

4.3 A novel criteria pre-processing Framework

The criteria pre-processing framework we propose is divided into three steps: initial criteria selection, criteria filtering and final criteria selection. Figure 4.1 illustrates how the framework works. Initial criteria selection and criteria filtering are the formal procedures for defining the criteria list for the final selection. These steps are summarized based on existing literature. In the final selection we will propose a new approach in selecting the criteria set with stakeholder involvement. In the following subsections, we introduce the framework step by step. To clarify, in this step, we chose the term 'relevance', as opposed to the commonly used word 'importance' in the literature, because the importance of criteria is typically used when determining their weights. However, this article does not concern the elicitation weights and only focuses on the selecting the criteria. As a result, the criteria are chosen for stakeholder groups based on their relevance levels to the problem.

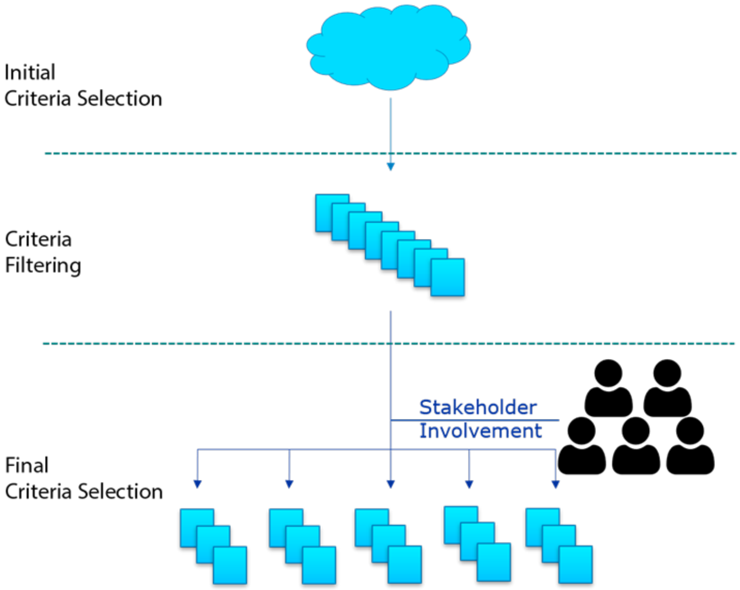

Figure 4.1: Criteria pre-processing framework

4.3.1 Initial criteria selection and criteria filtering

Initial criteria selection starts the process by brainstorming among the facilitators and experts by asking 'What can distinguish a good alternative from a bad alternative in the decision problem for stakeholder groups?' [205]. An extensive list of criteria can be defined to represent the priorities of various stakeholder groups regarding the decision-making problem. Referring to the previous related or similar cases and frameworks can aid in constructing the criteria list. For example, in the study of sustainable urban mobility in Leuven, the potential criteria list was set up based on previous frameworks [206]. To search for synergies in urban and regional mobility measures, Bulckaen et al. analyzed 16 case studies to define the criteria [207].

In many cases in can be useful to start the criteria selection process by deriving criteria from core themes. For example, in appraising sustainable development, facilitators can consider eliciting criteria under the three pillars of sustainability: economy, environment, and society [194, 207]. In this study, we say the groups we defined to derive the criteria in the initial selection only as ‘groups’, but not the ‘group criteria’ or ‘main criteria’. In the mentioned studies and the case study in the next section, the criteria lists were categorized under economy, environment, and society. These three groups are simple but vague, and it is difficult to ask stakeholders to distinguish the importance levels among these three groups. These groups work as ‘groups’ but not ‘criteria’, which are defined because it is easier to derive many criteria from them. Therefore, in the subsequent process, the criteria list is still in a flat structure, and the final criteria sets for stakeholder groups are not put in a hierarchy.

The first step’s criteria list cannot be used directly in the weight elicitation process as the large number of criteria might be difficult for stakeholders to process. Moreover, the criteria have not yet been evaluated against a range of qualities such as redundancy, independency etc. Therefore, in the criteria filtering step, the facilitators should first check the completeness of the criteria list and ensure that there are no redundant criteria. Then, for each criterion, it is necessary to check its independency, that is, the criterion in which the decision-maker can assess the alternatives based on it without knowing the preference of other criteria [208]. Also, double counting should be avoided because it will result in a higher weight of the criterion in the subsequent assessment [209]. Finally, the criteria must be measurable in order to reflect the stakeholders’ priorities [66]. A more detailed study on filtering criteria can be found in the literature [205, 210]. Roy and Mousseau also defined a consistent criteria family in terms of axioms. The criteria should meet the three axioms: exhaustivity, cohension, and non-redundancy [211]. After criteria filtering, the criteria list is ready for the final selection.

4.3.2 Final criteria selection

Following above two steps, facilitators need to select the criteria sets for different stakeholder groups. It is eventually possible to conduct a mass-participation survey to solicit opinions from a larger number of participants to select criteria for a large stakeholder group, such as citizens. We will first introduce the conventional approach of final criteria selection with stakeholder involvement, and then a new model is proposed to better support the facilitators to select final criteria for the groups.

Final criteria selection with stakeholder involvement in the conventional approach

In literature, no formal method has been formulated for selecting criteria in MAMCA. One approach is commonly used in recent MAMCA related publications [70,212,213], we call it in this study the conventional approach. In the conventional approach, the criteria dedicated to the stakeholder group can be selected by involving the stakeholders. The facilitators can distribute surveys or invite stakeholders to a workshop for selecting criteria. First, the criteria list is shown to the participants in each stakeholder group. Then they are asked to select the criteria they think are relevant for the decision-making problem. Then, the criteria that most participants select as relevant will be included in the final criteria set for the stakeholder groups. We define the criteria list as $C\colon =\{c_1, c_2, \ldots, c_n\}$, and there are m participants in one stakeholder group $A\colon =\{a_1, a_2, \ldots, a_m\}$. The criteria that one participant considers relevant are marked as 1, irrelevant as 0. Therefore, the participant scores can be represented by a $n \times m$ binary score matrix:

$$S_{n\times m}\colon = \begin{bmatrix} s_{1,1} & \cdots & s_{1,m} \\ \vdots & \ddots & \vdots \\ s_{n,1} & \cdots & s_{n,m} \end{bmatrix} \tag{4.1}$$

where $s_{i,j}$ represents the relevance of criterion i for participant j. We sum the each row of matrix 4.1 to obtain the score vector $Q := \{q_1, q_2, \cdots, q_n\}$, where q_i represents the sum of the binary relevance scores given by participants in one stakeholder group to criterion i.:

$$q_i = \sum_{j=1}^{m} s_{i,j}, i \in 1, \cdots, n. \tag{4.2}$$

The facilitators then choose the criteria that most participants select as relevant, that is, the facilitators choose a subset $Q\prime$ from vector Q that contains z criteria with the highest scores:

$$Q\prime \subset Q, |Q\prime| = z, \tag{4.3}$$

where $Q\prime$ contains the q_is with the highest scores, and the number of criteria z can be chosen by facilitators. In this way, criteria set for different stakeholder groups can be defined by asking the opinions from stakeholders. However, this conventional approach of criteria selection has several limitations:

1. The intensity of the relevance is not elicited. The participants are asked if the criteria are relevant or not. It is a simple definition as there are only two relevance levels, that is, 0 and 1.
2. The heterogeneity within groups is not shown. Variations in relevance levels of criteria for participants within a single stakeholder group are ignored. Large stake-

holder groups such as citizens, in particular, may have different priorities regarding criteria.

3. Implicit unfairness in certain cases. The number of selected criteria of participants is unlimited, which means that if they want, they can select all the criteria as relevant, or all of the criteria as irrelevant. This can result in implicit unfairness because participants who select more criteria as relevant can be regarded as have more votes/weights in the decision-making process.

New criteria selection model

To address the aforementioned limitations, we present a new criteria selection model to assist facilitators in selecting final criteria. The full process is illustrated in a flowchart (See Figure 4.2).

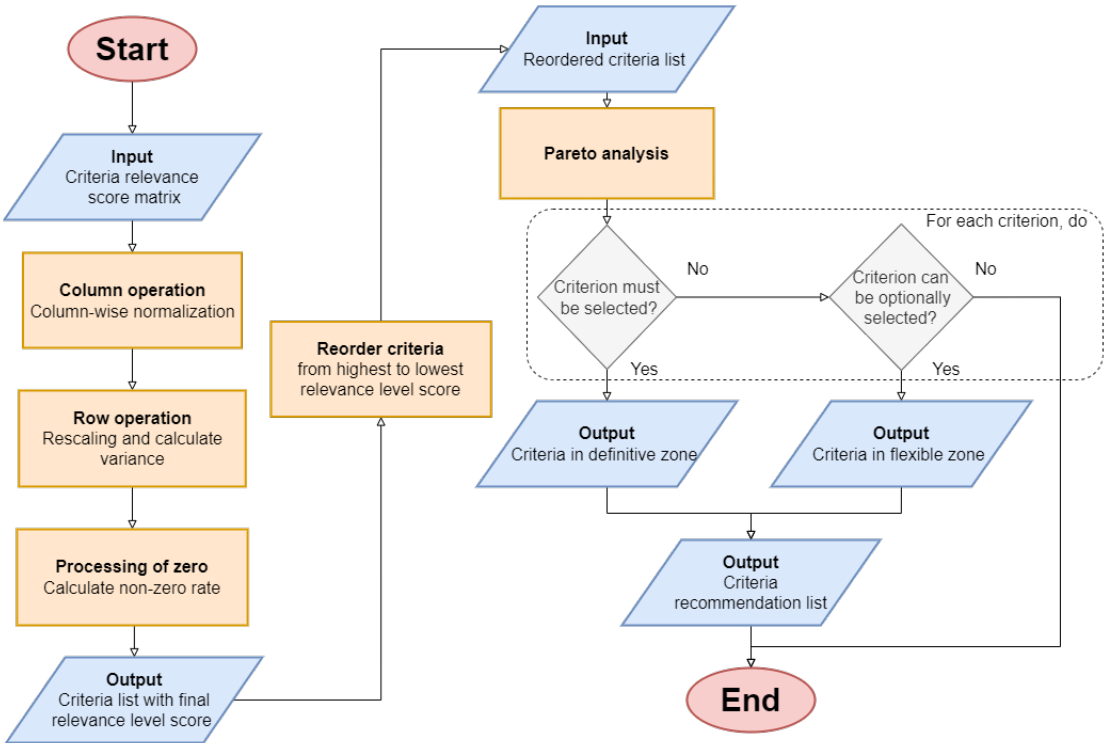

Figure 4.2: Flowchart of the new criteria selection model

The new criteria selection model starts with a new raw data collection. Participants are asked to select β criteria they think are relevant, where $\beta \in \{5,6,\cdots,9\}$ to meet the Miler's magic number [197]. Then, for criteria they consider relevant, they need to give scores to the criteria based on the relevance level on a $1-x$ ratio scale, for one stakeholder, at least one criterion must be given x. Thus, we obtained a new score matrix:

$$S\prime_{n\times m} \colon = \begin{bmatrix} s\prime_{1,1} & \cdots & s\prime_{1,m} \\ \vdots & \ddots & \vdots \\ s\prime_{n,1} & \cdots & s\prime_{n,m} \end{bmatrix}, s_{i,j} \in \{1,2,\cdots,x\},\ \left|s\prime_{*,j} \neq 0\right| = \beta, \exists s\prime_{*,j} = x, \tag{4.4}$$

where each matrix column represents the criteria scores given by one stakeholder, and each row records stakeholder scores for one criterion. To address the aforementioned limitations, the new criteria selection model consists of several operations that process raw data.: (a) column operation, (b) row operation, (c) processing of 0, and (d) Pareto analysis. To illustrate the operations, let us define a simple didactic 3×3 matrix as an example:

$$\begin{array}{cc} & \begin{array}{ccc} a_1 & a_2 & a_3 \end{array} \\ \begin{array}{c} c_1 \\ c_2 \\ c_3 \end{array} & \begin{bmatrix} 5 & 3 & 3 \\ 5 & 4 & 2 \\ 5 & 5 & 5 \end{bmatrix} \end{array}, \tag{4.5}$$

where the scores are on a $1-5$ ratio scale. As we mentioned before, the participants are asked to give the score on a ratio scale based on the relative relevance level regarding criteria. We are aware that different participants must have at least one most relevant criterion to them, i.e., criteria with x, so that all other criteria are given scores based on a relative ratio comparing to the most relevant one. However, the scores given by different participants are not comparable. In the example 4.5, even though c_3 is given 5, i.e., the most relevant by all participants, it is unknown if their '5's mean the same level of relevance. Therefore, we make the scores given by different participants comparable by apply a column-wise normalization:

$$s\prime^{col}_{i,j} = \frac{s_{i,j}}{\sum_{z=1}^{m} s_{z,j}}, \tag{4.6}$$

s.t.

$$\begin{bmatrix} 5 & 3 & 3 \\ 5 & 4 & 2 \\ 5 & 5 & 5 \end{bmatrix} \overset{\frac{s_{i,j}}{\sum_{z=1}^{m} s_{z,j}}}{\Longrightarrow} \begin{bmatrix} 0.33 & 0.25 & 0.3 \\ 0.33 & 0.33 & 0.2 \\ 0.33 & 0.42 & 0.5 \end{bmatrix}, \tag{4.7}$$

where the column-wise normalized matrix can be seen as each participant distributes 1 to all criteria. Scores given by different participants are comparable now.

The second step is row operation. Let us take a look at (4.5) again row-wisely, if we take the arithmetic mean scores of c_1, c_2, the same average scores are obtained. However, c_1 has a lower variance than c_2, indicating a higher level of mutual consent. To take it into account, we define a profile distribution table [182]:

Table 4.1: Profile distribution table

ID	1	2	3	4	5
c_1	0	0	66.7%	0	33.3%
c_2	0	33.3%	0	33.3%	33.3%
c_3	0	0	0	0	100%

where each row of data in Table 4.1 represents the percentage of the score distribution of one criterion on the scale. It is a transposition of one vector that can be concatenated as a profile distribution matrix:

$$D\colon = \begin{bmatrix} 0 & 0 & 66.7\% & 0 & 33.3\% \\ 0 & 33.3\% & 0 & 33.3\% & 33.3\% \\ 0 & 0 & 0 & 0 & 100\% \end{bmatrix}. \tag{4.8}$$

It records the score distribution on the scale. The mean score $\bar{v}_i$ and variance σ_i^2 on one criterion c_i are given in:

$$\bar{v}_i = \sum_{k=1}^{5} k \times d_{k,i}, \tag{4.9}$$

$$\sigma_i^2 = \sum_{k=1}^{5} d_{k,i} \cdot (\bar{v}_i - k)^2. \tag{4.10}$$

The relevance level score of one criterion c_i considering the variance is obtained as follows:

$$p = \bar{v}_i - \sigma_i, \tag{4.11}$$

s.t.

$$\begin{bmatrix} 5 & 3 & 3 \\ 5 & 4 & 2 \\ 5 & 5 & 5 \end{bmatrix} \xRightarrow{\text{row operation}} \begin{bmatrix} 2.78 \\ 2.55 \\ 5 \end{bmatrix}. \tag{4.12}$$

However, after the column operation, the scale represents the relevance level becomes different. There is a process of rescaling. Without losing any information, the suitable intervals for the new scale should distinguish the differences of the scores after the column operation. Therefore, we need to treat the scores given by participants as a new data set. We pick up non-zero scores in the column-wise normalized matrix after column operation $S\prime^{col}$ and sort it from lowest to highest ('0's will be processed in the next step):

$$O_{\beta \times m} = \{o_1, o_2, \cdots, o_{\beta \times m}\} = \{\underset{S\prime^{col} \backslash 0}{min}\, s\prime^{col}, \ldots, \underset{S\prime^{col} \backslash 0}{max}\, s\prime^{col}\}, \tag{4.13}$$

where $\beta \times m$ is the number of non-zero scores of the $n \times m$ matrix. Then a finite difference set can be defined as:

$$F = \{f_1, f_2, \cdots, f_{\beta \times m-1}\} = \{o_2 - o_1, o_3 - o_2, \cdots, o_{\beta \times m} - o_{\beta \times m-1}\} \tag{4.14}$$

The interval t that will not lose any information should satisfy:

$$t < \underset{F \backslash 0}{min}\, F. \tag{4.15}$$

So for the matrix of the example (4.7), the interval of the scale can be 0.03. However, this will result in a large scale. Sometimes, the profile distribution can be illustrated to the participants and facilitators to have a basic understanding on the score distribution of the criteria. When the scale is too large it will increase the difficulty for them to understand. Therefore, if the facilitators is tolerable to lose partial information of the normalized matrix, i.e., some different scores can be put in the same level, a smaller interval can be found. This interval can be as large as we do not lose the information from each individual, i.e., different scores given by one participant will not put in the same level after rescaling. This value can be found by first calculating the finite difference sets based each column of the column-wise normalized matrix:

$$F'_j = \{f'_{j,1}, \cdots, f'_{j,\beta-1}\} = \{\bar{s}'^{col}_{j,2} - \bar{s}'^{col}_{j,1}, \cdots, \bar{s}'^{col}_{j,\beta} - \bar{s}'^{col}_{j,\beta-1}\}, j = 1, \cdots, m, \tag{4.16}$$

where, $\bar{s}'^{col}_{j,i} (i = 1, 2, \cdots, \beta)$ is the non-zero normalized score from participant j, reordered from the lowest to highest. So the interval should satisfy:

$$t < \underset{j}{min}\, \underset{F'_j \backslash 0}{min}\, F'{}_j, j = 1, 2, \cdots, m \tag{4.17}$$

The facilitators should choose a suitable interval to put the scores on the same scale, the intervals should respect the condition of (4.15) or (4.17), depending on if the facilitators are willing to lose partial information. Then, a new profile distribution matrix $D\prime$ can be generated based on the new scale. It is also possible to rescale it using a definition similar in spirit to that of a histogram, because we look for a suitable equal interval to place the scores to better represent the distribution of data, as is done in most applications of histogram [214]. There are several guidelines and rules of thumb for determining the appropriate interval, i.e., the number of bins for a given data set for the histogram [215], for example, Freedman Diaconis rule [216], Sturges' rule [217], Scott's normal reference rule [218], etc. Now, instead of (4.11), the relevance level score of each criterion c_i can be computed as:

$$p\prime = \sum_{k=1}^{x} k \times d\prime_k - \sqrt{\sum_{k=1}^{x} d\prime_k \cdot \left(\sum_{k=1}^{x} k \times d\prime_k - k \right)^2} = \bar{v}\prime - \sigma\prime. \tag{4.18}$$

The third step is processing of 0. The previous procedure only considers non-zero scores, while 0 is ignored. We will process 0 exclusively in the following step. We decide to separate the processing of 0 and other non-zero values because:

- 0 means not relevant, which is chosen first along with the criteria that participants believe are relevant. Then, they assign relevance level scores to the relevant criteria on a $1-x$ scale. 0 and $1-x$ are chosen in different steps. Thus, 0 should not be treated together with $1-x$;
- For a given $n \times m$ matrix. There are fixed numbers of 0, i.e., $(n-\beta)\cdot m$, but they are distributed on different criteria. Meanwhile, the scores in $1-x$ may differ, which is why it is important to find a suitable new scale by considering the distribution of scores in $1-x$ in previous steps. However, there is a better way to process 0.

Therefore, we define a new indicator to process 0, the so called non-zero rate γ. For a criterion c_i:

$$r = \gamma \cdot (\bar{v}\prime - \sigma\prime) = \gamma \cdot p\prime, \tag{4.19}$$

By calculating the final relevance level score, a vector of the criteria's relevance level scores is obtained, i.e., $Rcolon = r_1, r_2, \ldots, r_n$.

Finally, the following Pareto analysis determines the final criteria for one stakeholder group. We reorder the criteria set $\bar{C} := \{c_{\bar{1}}, \ldots, c_{\bar{n}}\}$, where $r_{\bar{1}} > \ldots > r_{\bar{n}}$. Then we solve the following optimization to find the minimal number ($\bar{y}$) of criteria so that their summed aggregate scores will be at least α of the total score:

$$min\ \bar{y} \tag{4.20}$$

s.t.

$$\sum_{i=\bar{1}}^{\bar{y}} r_{\bar{i}} \geq \alpha \cdot \sum_{i=\bar{1}}^{\bar{n}} r_{\bar{i}}, \tag{4.21}$$

where we set $\alpha = 50\%$ to satisfy majority rules [219]. This should result in $5 \leq \bar{y} \leq 9$. Otherwise, increase the value of α until $\bar{y} = 5$ is obtained. We say that the criteria in the resulting set $\{c_{\bar{1}}, c_{\bar{2}\ldots}, c_{\bar{y}}\}$ belong to the **definitive zone**. If $\bar{y}$ obtained in Step 1 is equal to 9, stop. Otherwise, further increase α until $\bar{y} = 9$. We say that these additional criteria, i.e., those that are not already in the definitive zone, belong to the **flexible zone**. There is a possibility that when $\bar{y} > 9$ but $\alpha < 50\%$. This means that the participants in the stakeholder group have widely disparate priorities in terms of criteria; it is then suggested that the participants be divided into subgroups.

The output of the new criteria selection model is the classification of criteria in either of the two zones. All the criteria in the definitive zone are recommended to be chosen. The user is then free to add additional criteria from the Flexible Zone to the final criteria set, as long as the set size remains within the magic number.

4.4 Case Study

The criteria pre-processing framework has been implemented on a use in the evaluation of sustainable Construction Logistics Scenarios (CLS) evaluation in the dense urban Brussels-Capital Region (BCR), Belgium. The BCR encompasses the inner Brussels City Centre as well as its 19 surrounding municipalities within the large Pentagon (outer Ring). The pilot site is located in Anderlecht, one of the municipalities. The construction project is organized as a public-private partnership between the owner and city development agency and the main building contractor. The pilot site offers high relevancy for urban construction logistics because of its density, location, construction type, intermodal transport possibilities and the rich number of stakeholders involved [220]. With numerous stakeholders involved and vast potential conflicts, this testbed thus provides grounds for a MAMCA-based stakeholder framework for urban construction logistics, presented by Brusselaers et al. [220].Although the researchers included a broad spectrum of stakeholders in the BCR use case, Citizens were unable to be included in the evaluation due to technical and practical constraints linked to the SARS-CoV-2 pandemic. Concurrently, this leaves room for improvement in the context of mass participation of multi-actor multi-criteria analyses [190]. In light of this study, we analyze data linked to the actor group of Citizens to test the criteria pre-processing framework.

4.4.1 Criteria pre-processing

After defining the CLSs and identifying the stakeholder groups, the criteria pre-processing framework was applied to identify the criteria set for the stakeholder group of citizens. First, potential criteria were listed based on the findings of the CIVIC project under the three pillars of sustainability [221, 222]. These criteria were filtered in consideration of independence, double counting, and operationality. For example, there are three criteria in the initial list that might lead to double counting: “impact of construction works on transport infrastructure use”, “accessibility”, and “diverted traffic due to construction site”. “Impact of construction works on transport infrastructure use” refers to the impact of infrastructure works on the efficiency of a transport system. While “accessibility” means the accessibility of region in vicinity of construction site by road, public transport etc. Finally, “diverted traffic due to construction site” refers to the impact of diverted traffic. These three criteria are correlated with each other, which also leads to an independence issue. In this sense, these three criteria are redefined into one criterion: Impact on the traffic and accessibility. After applying criteria filtering, 21 criteria were selected in the list for the criteria final selection (see Table 4.2).

To select the final criteria set for the ‘citizens’ stakeholder group in the MAMCA, a survey was distributed in the construction site neighborhood to collect the opinions of the local residents. The interviewees were asked to first select minimum 9 criteria out of 23 they think are relevant, i.e., $\beta = 9$. Then, they were asked to give scores to the criteria they selected based on the extent of relevance on a 5-point Likert scale: 1 (Least relevant), 2 (Less relevant), 3 (Middle relevant), 4 (More relevant), 5 (Most relevant). We contacted 200 neighborhood households and asked them to complete the criteria ranking survey. At the end, 40 responses were received, thus a 21×40 matrix was obtained, i.e., $S\prime_{21\times40}, s_{i,j} \in [0..5]$.

Table 4.2: Potential criteria list

Group	ID	Criterion	Definition
Economic	CECO_1	Enforcement costs	Costs to ensure other parties comply with rules in the transport system and/or legislation during the construction works
	CECO_2	Viability of investment	Positive ROI (e.g. the investment in mobility or safety measures should result in more (efficient) work in the long term)
	CECO_3	Profitable operations	Objective to generate a profit by providing logistic or transport services during the construction works
	CECO_4	Transportation costs	The costs of transporting construction materials and/or personnel during the project
	CECO_5	Adaptation costs	Financial costs due to mobility impacts caused by the construction site (for example, detours, parking)
	CECO_6	Quality and reliability of deliveries of construction materials	The punctuality and the percentage of damage-free delivery of goods (from shipper and recipient perspective)
Environmental	CENV_1	Air pollution	Impact of construction works on local air quality (the main air pollutants considered are SO2, NO2, PM2.5 and PM10
	CENV_2	Climate change	Impact of construction works on greenhouse gas emissions CO2 (global impact)
	CENV_3	Noise pollution	Sound level caused by human activities, including transport, during construction projects
	CENV_4	Vibration	Impact of vibrations during construction works on the surrounding built-up environment (damage)

	CENV_5	Water pollution	Impact of construction projects on water quality (such as polluted water flows and affected volume and velocity)
	CENV_6	Biodiversity	Impact of construction works on an area of nature in the vicinity
	CENV_7	Landscape quality	Visual nuisance on surrounding environment
Societal	CSOC_1	Labour conditions	Labour conditions for employees during construction works
	CSOC_2	Social and political acceptance by citizens of impacts generated	Level of ease for stakeholders to comply with the authorities’ rules and regulations during construction works
	CSOC_3	Business climate during construction works	Attractiveness of the area in terms of business opportunities
	CSOC_4	Attractiveness (societal)	Impact of construction works on the attractiveness of the urban environment, defined as the recreational facilities in and around the construction zone
	CSOC_5	Social and economic revitalization	Impact after finishing the construction site
	CSOC_6	Security of construction material goods during construction works	Probability of construction materials being lost or stolen while being transported to, or stored on, the construction site
	CSOC_7	Traffic safety impacts	Traffic accidents during transport of goods and people to, from and within the site, as well as accidents caused by the changes in transport infrastructure at the site
	CSOC_8	Impact on the traffic and accessibility	Impact of infrastructure works on the efficiency of a transport system and accessibility of region in vicinity of construction site by road, public transport etc.

Final criteria selection based on the new selection model

First, the raw score matrix is normalized column-wise, thus $S'^{col}{}_{21\times 40}$ is obtained. The non-zero normalized values in the matrix, totaling 9×40, are placed in the vector $o_{360} = \left[\min_{S'^{col}\setminus 0} s'^{col}, \ldots, \max_{S'^{col}\setminus 0} s'^{col}\right]$ to obtain a new scale. In this case, we use Freedman–Diaconis rule to obtain a suitable scale [216]. It is a robust estimator that takes data variability and data size into account, which works well when the data size is under 200 [223]. The interval/bin width of the given vector $o_{\beta\times m}$ is:

$$Interval = 2\cdot\frac{IQR(o)}{\sqrt[3]{\beta\cdot m}} \tag{4.22}$$

where IQR is the interquartile range of the data. In this case, the interval is 0.0146, resulting a profile distribution scale D' with a $[1..11]$ scale. The histogram via the Freedman–Diaconis rule is illustrated in Figure 4.3.

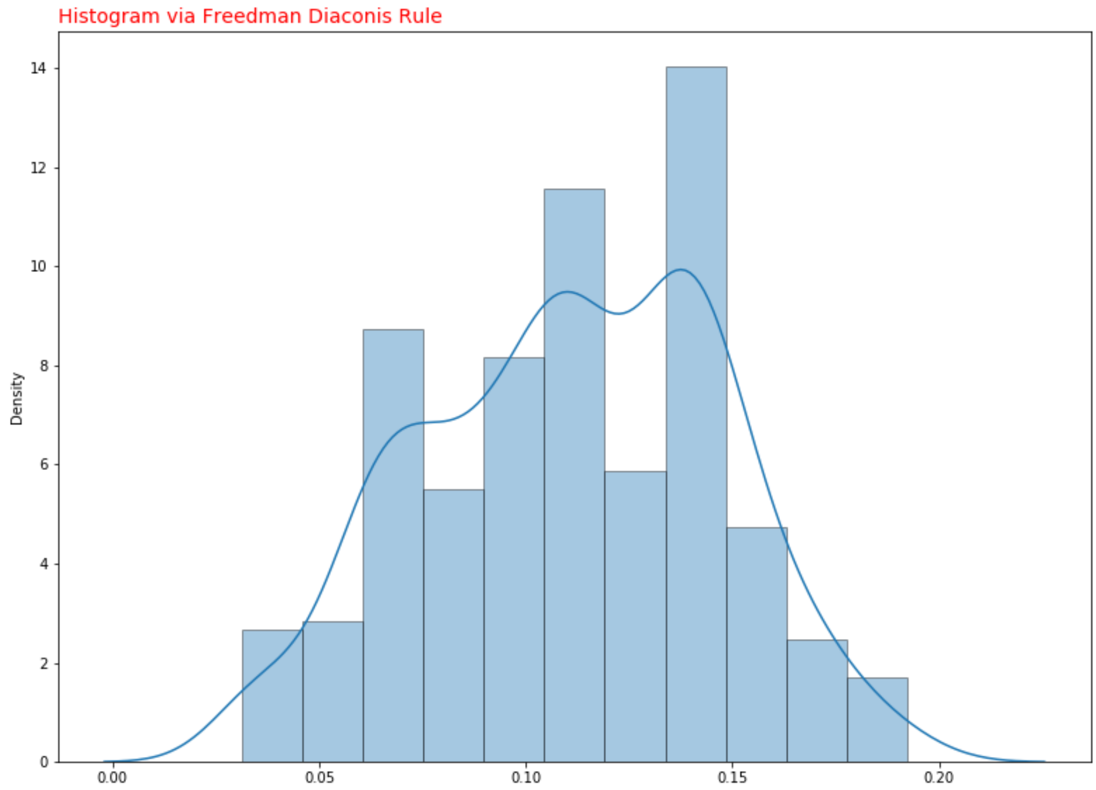

Figure 4.3: The histogram via the Freedman–Diaconis rule

The profile distribution table is shown Table 4.3, along with non-zero rate γ, and the final relevance level score r calculated based on (4.19).

Table 4.3: Profile distribution table and other indicators

ID	γ	1	2	3	4	5	6	7	8	9	10	11	$\bar{v}'$	σ'	r
CECO_1	28%	45%	0%	45%	9%	0%	0%	0%	0%	0%	0%	0%	2.18	1.11	0.29
CECO_2	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00
CECO_3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00
CECO_4	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00
CECO_5	55%	0%	27%	0%	14%	45%	14%	0%	0%	0%	0%	0%	4.18	1.43	1.51
CECO_6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00
CENV_1	75%	0%	0%	0%	0%	0%	21%	3%	31%	24%	17%	3%	8.24	1.43	5.11
CENV_2	63%	0%	0%	12%	0%	8%	4%	16%	52%	4%	0%	4%	7.08	1.90	3.24
CENV_3	65%	0%	4%	4%	0%	8%	8%	17%	42%	4%	13%	0%	7.25	1.94	3.45
CENV_4	48%	0%	0%	16%	11%	21%	5%	21%	21%	5%	0%	0%	5.89	1.89	1.90
CENV_5	58%	13%	0%	13%	4%	13%	35%	13%	0%	0%	9%	0%	5.22	2.38	1.63
CENV_6	83%	0%	9%	39%	0%	18%	33%	0%	0%	0%	0%	0%	4.27	1.48	2.30
CENV_7	83%	0%	0%	18%	24%	15%	30%	6%	0%	6%	0%	0%	5.06	1.58	2.88
CSOC_1	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00
CSOC_2	20%	0%	0%	0%	0%	25%	38%	13%	25%	0%	0%	0%	6.38	1.11	1.05
CSOC_3	78%	0%	0%	19%	0%	6%	0%	6%	45%	19%	0%	3%	7.06	2.26	3.73
CSOC_4	73%	21%	0%	7%	3%	7%	41%	3%	7%	3%	3%	3%	5.21	2.72	1.80
CSOC_5	43%	0%	0%	18%	6%	12%	0%	6%	41%	12%	6%	0%	6.71	2.27	1.89
CSOC_6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.00	0.00	0.00
CSOC_7	50%	0%	25%	5%	30%	0%	0%	15%	20%	5%	0%	0%	4.95	2.44	1.26
CSOC_8	83%	0%	0%	0%	18%	9%	12%	15%	27%	9%	3%	6%	6.94	2.00	4.08

The Pareto analysis is taken based on the final relevance level scores. And the Pareto chart is illustrated in Figure 4.4. It ranks the relevance level scores from largest to smallest and shows the total cumulative percent of criteria's relevance level scores. The bars represent the relevance level scores of the criteria in descending order. The line represents the cumulative percentage of relevance level scores.

After Pareto chart is drawn, we follow the optimization problem (4.20) and set $\alpha = 50\%$. The final recommendation of the criteria is proposed. Table 4.4 shows the recommended criteria.

Table 4.4: Criteria recommendation table for stakeholder group 'citizens'

Ranking	Criteria	Zone
1	Air pollution	Definitive zone
2	Impact on the traffic and accessibility	
3	Business climate during construction works	
4	Noise pollution	
5	Climate change	
6	Landscape quality	Flexible zone
7	Biodiversity	
8	Vibration	
9	Social and economic revitalisation	

Based on the model we built, the criteria with the highest relevance level scores are in the definitive zone. Their score takes more than 50% of the total scores, and there are at least 5 criteria. They meet the minimum requirements of Pareto analysis and

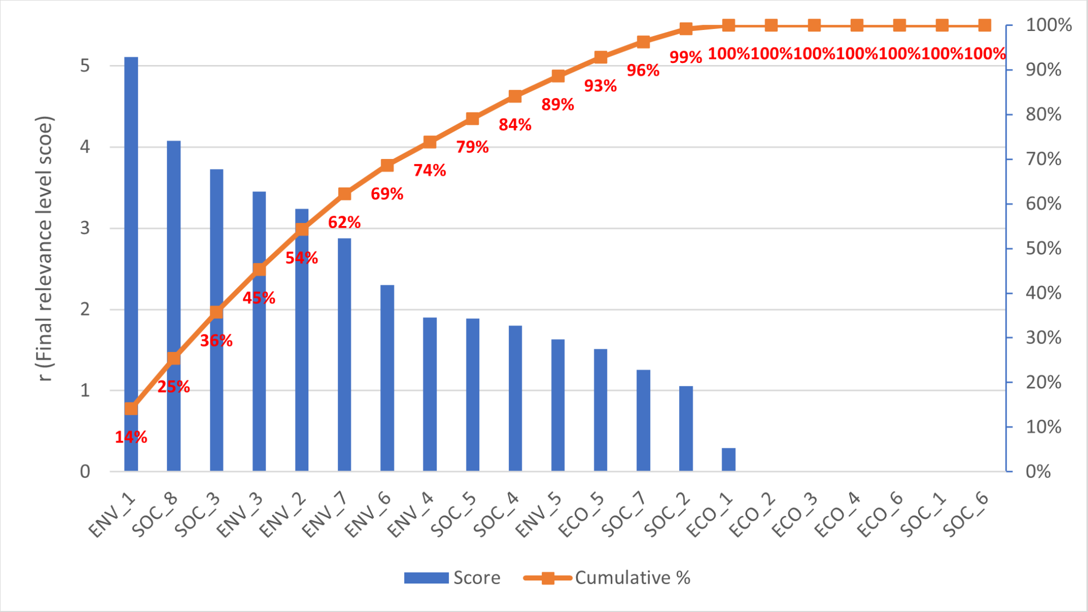

Figure 4.4: Pareto chart based on the final relevance level scores

magic number. And we can also choose the criteria from the flexible zone. They are the criteria with rather high relevance level scores, and the number will not exceed the magic number, i.e., 9. The criteria in the definitive zone are the criteria that must be selected in the final criteria set, as they are the criteria that stakeholders think are the most relevant. The sum of their relevance level scores takes the majority part which takes 54% of the total NS. The criteria in the definitive zone are: CENV_1 “air pollution”, CSOC_8 “impact on the traffic and accessibility”, CSOC_3 “business climate during construction works”, CENV_3 “noise pollution”, and CENV_2 “climate change”. The criteria in the flexible zone are the relative criteria which followed by the most relevant criteria in the definitive zone. The selection of these criteria is up to the facilitators.

4.4.2 Discussion

To compare the criteria selection result between the conventional selection approach and the new criteria selection model, we take the raw data from the new criteria selection. Because, in the new criteria selection model, stakeholders must first select the relevant criteria, which can result in a binary matrix, similar to the conventional approach of selection, and the generated result can be compared to the result of the new criteria selection model. The criteria selection result in the conventional approach is illustrated in Figure 4.5, where the bars represent the number of participants selecting one criterion as relevant.

Assuming 9 criteria are selected in the conventional approach, Table 5 illustrates the criteria set comparison from these two ways. The criteria are listed in ascending order,

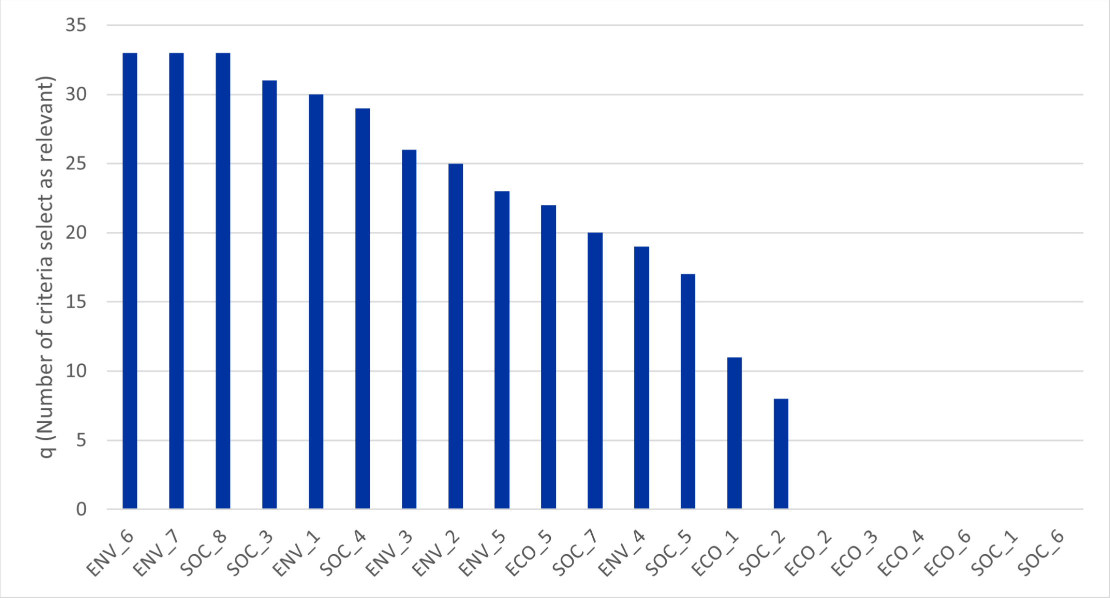

Figure 4.5: Criteria selection in conventional approach

from most to least relevant, with the criteria that are uniquely selected in the methods highlighted in bold.

Table 4.5: Criteria set comparison from two methods of selection

Criteria set proposed in the conventional approach	Criteria set proposed based on the new criteria selection model	
Biodiversity	Definitive zone	Air pollution
Landscape quality		Impact on the traffic and accessibility
Impact on the traffic and accessibility		Business climate during construction works
Business climate during construction works		Noise pollution
Societal attractiveness		Climate change
Air pollution	Flexible zone	Landscape quality
Noise pollution		Biodiversity
Climate change		**Vibration**
Water pollution		**Social and economic revitalisation**

It can be seen that the criteria sets of the conventional approach and the criteria selection model are very similar. In both, “landscape quality”, “impact on the traffic and accessibility”, “business climate during construction works”, “air pollution”, “noise pollution”, and “climate change” are recommended to be selected. This means that these are the criteria that most stakeholders perceive to be relevant to their stakeholder group and are more relevant compared to the other criteria. However, the rankings of the criteria are highly different. For instance, “biodiversity” is the top criterion in the criteria set proposed in the conventional approach, but the criteria selection model has placed it in the Flexible zone. This is because in the conventional approach, the most relevant criterion is the one selected the most by the stakeholders, i.e., the selection is based on a binary decision. However, the new criteria selection model considers not only whether the criteria are relevant or not, but also the extent of the relevance of each criterion. That is, a scale of the criteria's degree of relevance is built in the criteria selection model. Same for "societal attractiveness": out of 40 participants select it as relevant, but rather low scores are given to it, that's why it is selected in the conventional approach but not in the new criteria selection model. The new criteria selection model addresses the three limitations of the traditional method, providing a more rational criteria set for stakeholder groups: it considers the intensity of the relevance on criteria and the heterogeneity of the scores given by participants, and it also reduces unfairness. In addition, the criteria pre-processing with the criteria selection model has additional advantages over the conventional approach:

1. It provides an explicit ranking of the criteria, with virtually no ties. Looking at the top three criteria selected in the conventional approach in Figure 4.5, they are tied up in the first position. This might lead to a dilemma of choice when facilitators need to select criteria but there are tied up criteria. In this case it is difficult for facilitators to select a subset of these tied-up criteria without any other reference. In contrast, the new criteria selection model generates a no tied-up ranking, which could also serve as a mathematical proof for the decision-maker to support his/her decision. The stakeholders can easily identify the most relevant criteria in their priority lists, and the tied ranking happens more often when they identify the less relevant criteria. As we can see in Table 4.5, both approaches are able to easily identify the most relevant criteria. However, for the less relevant criteria, without the distinctive ranking that the criteria selection model has, the ranking in the conventional approach becomes more ambiguous.

2. It is more flexible and robust. The criteria selection model provides a definitive zone of criteria in which the number of criteria is as low as is consistent with making a justifiable decision, while representing the opinions of the majority. It also provides a flexible zone, which can be extended to the upper bound of the magic number seven plus or minus two, i.e., 9, the capacity limit of human cognition.

3. The Pareto chart of the new criteria selection model can better reflect the principle of the Pareto analysis, which means the selected criteria can better represent the priorities of the stakeholder groups. The criteria in the Definitive Zone cover the 'vital few' criteria, which represent the priorities of one stakeholder group, and the 'trivial many' criteria in the Flexible Zone can also be chosen, but with fewer representatives.

4. It works better to define the criteria set for a large stakeholder group such as citizens. Participants in one group may have conflicting priorities. It is more common in a large stakeholder group. The conventional approach does not quantify the level of relevance of criteria and does not take into account the variance of participants' scores, which may fail to capture the heterogeneity. The criteria selection

model takes these factors into account when selecting criteria, allowing for more equitable criteria selection in the large stakeholder group. It is also applicable in other MCGDM frameworks for criteria selection if there are a large number of participants in one stakeholder group.

4.5 Limitations and future work

In this study, we presented a pre-processing framework to support facilitators in selecting criteria for stakeholder groups in MAMCA evaluation through soliciting the opinions of participants. There are several limitations that need to be addressed in the future. First, the selected criteria in the case study have not been validated by participants in stakeholder groups. As the research project has ended, criteria validation was deemed practically unfeasible. In the future, it will be useful to create a feedback loop to validate the criteria with participants to ensure that the criteria represent their priorities. The framework could then be used to select criteria alongside all other MAMCA steps to complete the MAMCA evaluation in a real case.

We selected criteria with a flat structure (i.e., without hierarchy) because the criteria are simple, and the stakeholders showed no difficulty understand them. More complex problems, however, will need a hierarchical structure for the criteria. The hierarchy can also ease the process for calculating the weights of criteria. Several methods have been proposed in solving the MCDM problems with a hierarchical criteria tree, for example, the multiple criteria hierarchy process (MHCP) for different MCDM methods [224, 225], AHP [226], hierarchical versions of the INTERCLASS method [227], hierarchical multi-attribute value function [228]. In the future, a pre-processing framework that addresses hierarchical criteria structure problems could be developed.

We mentioned in the presented new criteria selection model that in an extreme case, the participants in the stakeholder group may have widely disparate criteria priorities, making it impossible to select the criteria for the group. As a result, it is suggested that stakeholder groups be divided into subgroups to have more consensual priorities. A method for grouping members of one stakeholder group based on their priorities toward the criteria is needed.

4.6 Conclusion

In Multi-Actor Multi-Criteria Analysis identifying criteria is a fundamental step with different stakeholder groups having different priorities. However, there is no formal guideline to aid facilitators in eliciting, filtering and selecting the criteria for stakeholder groups with stakeholder involvement. In this work, a framework called criteria pre-processing was proposed to identify the criteria sets for stakeholder groups. It can be used for selecting a set of criteria based on opinions from stakeholders. In the same time, it retains the flexibility of the final decision for the facilitators. We develop a criteria selection model to select a reasonable number of criteria that have high relevance within the stakeholder groups. The case study result shows that the criteria selection model from the proposed criteria pre-processing framework offers several advantages over the conventional approach, and addresses the conventional method's limitations: it takes into account the intensity of the relevance level of the criteria, the heterogeneity of the participants' priorities, and makes an effort to ensure participant fairness; in the meantime, it provides an explicit ranking list without ties and leaves the facilitators with the option of selecting. The proposed framework works better in defining criteria for large stakeholder groups and is possible be applied in other MCGDM frameworks. In the future, the framework should be further developed to address hierarchical criteria structure problems.

Chapter 5

Stakeholder Clustering Algorithm

5.1 Introduction

Decision-making is usually a complicated task, as the decision-maker needs to find a compromise solution that considers various factors, such as the economy and environment. Multi-criteria decision-making (MCDM) is a method that helps decision-makers assess several alternatives by evaluating multiple criteria [161]. Nevertheless, it is often difficult for a single decision-maker to consider all relevant factors of a given problem. Therefore, it is often possible to invite multiple evaluators to participate in the decision-making process. This is referred to as the so-called group decision-making (GDM) [229, 230]. By aggregating the evaluation from a group of decision-makers, the collective ranking of alternatives can be obtained [231].

In traditional GDM, evaluation mainly relies on a small number of experts [232]. However, in the decision-making problem in social management [61], environmental management [233], transportation [66], etc., the consequences of the decision-making process can influence or can be influenced by different interest groups, i.e., stakeholders [19]. Stakeholder involvement can help decision-makers find a solution that considers different points of view, so the solution has higher implementation acceptance and a lower failure rate [172]. Thus, inviting stakeholder groups in decision-making is another approach for GDM problems [180].

There are two main general approaches to support the MCGDM problems [57]. Either the stakeholders first reach a consensus on the alternatives, criteria, scores, weights, etc., and then provide a sole ranking of the alternatives similar to a regular MCDM

This chapter is based on Huang, H., De Smet, Y., & Macharis, C.. Clustering members in group decision-making based on criteria ranking. Under review by the European Journal of Operational Research.

[234], or the stakeholders can define their own criteria, evaluate the alternatives to obtain personal rankings, and provide scores for the alternatives that are aggregated at the end [56]. In the first approach, a single group consisting of all stakeholders is formed, and in the second approach, stakeholders are clustered into different groups. In both approaches, participants in one group share the same criteria.

Normally, it is assumed that participants in the same group hold the same interests and preferences [45]. However, stakeholder groups such as ‘citizens’ and ‘residents’ are not always in the case [190] because socioeconomic status, priorities and preferences can be different [235]. On the one hand, it is necessary to involve such stakeholder groups in the decision-making process, especially for issues related to the interests of the public [236]. On the other hand, evaluating alternatives based on the opinions of a large number of stakeholders is a difficult task. First, it is not feasible to invite all participants to an evaluation workshop [100]. Second, the participants might have conflicting interests. As a consequence, a simple aggregation of the evaluation results can no longer represent the preferences of all participants [237]. The first difficulty is often solved by distributing the surveys to the stakeholder groups [238]. One of the approaches to tackle the second difficulty is to cluster the participants into representative subgroups [239, 240].

Clustering methods to partition participants into one stakeholder group have already been studied in the literature. Zahir implements an algorithm to cluster participants with similar preferences [138]. Zhu et al. clustered the participants based on three-dimensional gray relational analysis [241]. Bolloju clusters participants by applying the analytic hierarchy process (AHP) to model participants’ preferences [242]. It can be seen that the current clustering methods are all based on participants’ preferences. That is, the participants are clustered based on the decisions, i.e., the results of the evaluation of alternatives. However, unlike priority identification (i.e., criteria ranking), the evaluation of alternatives is a more objective procedure that often relies on quantitative information [145]. The participants normally know their priorities regarding the criteria, but they may have uncertain knowledge about the alternatives if they are not experts [130].

Therefore, we propose a new alternative procedure for GDM evaluation when we need the opinions of a stakeholder group that consists of a large number of participants, such as citizens, in three steps:

1. The participants complete the survey to rank the criteria from the most important to the least important;
2. The participants are clustered into subgroups based on their priorities regarding criteria, i.e., criteria rankings;
3. Representatives in each subgroup are selected and invited to the decision-making workshop for further evaluation.

There are several ways in the survey to elicit the weights of the criteria converted from the criteria ranking by surrogate weighting methods[243–245], e.g., rank sum weights (RS), rank reciprocal weights (RR) [246], rank-order centroid weights (ROC), and equal weights (EW) [247]. However, in this contribution, we decide to focus on the ordinal information that is provided by the participants. In steps 1 and 2, the objective is to identify the priorities of the stakeholder groups instead of weight elicitation. It is possible that subgroups holding different ranked criteria can be identified, and then the representatives of the subgroups can be invited in the following evaluation process. Hence, ordinal information plays a more important role than cardinal information. In this manner, instead of directly involving the representatives of the stakeholder group, a large number of participants in the group can express their opinions. It guarantees equality among the participants in the group because the voices of participants can be heard as much as possible to avoid missing the essential characteristics of the group. Accordingly, an algorithm that aims to cluster participants based on priorities needs to be developed. Thus, we present a novel algorithm that follows the logic of the k-means approach. We decide to focus on the ordinal information from the participants' rankings. Therefore, a new distance called ranking distance is proposed that is calculated using the weighted Kendall's τ coefficient (which is based on the similarity of the criteria ranking). The algorithm clusters the participants based on their ranking distances. In the following sections, we will first introduce the k-means algorithm and Kendall's τ coefficient; then, we present our algorithm and highlight its distinctive features. Finally, the algorithm is applied in a case study. A quality index is introduced, and the result is compared with the traditional k-means method.

5.2 A brief reminder of the k-means clustering algorithm

The k-means algorithm originated from a vector quantization method in signal processing [248]. Currently, it is popular in the field of data mining as a clustering analysis method [249]. The purpose of k-means clustering is to divide n observations into k clusters so that each point belongs to the unique cluster to which the centroid is closest [250]. Given a set of observations $X = \{x_1, x_2, ..., x_n\}$, each observation is in a d-dimensional space. In the k-means algorithm, one tries to cluster them by minimizing the within-cluster sum of squares (WCSS) [251]. In other words, the goal is to find cluster sets $S = \{S_1, S_2, ..., S_k\}$ that satisfy:

$$\arg\min_{S} \sum_{i=1}^{k} \sum_{\mathbf{x} \in S_i} \|x - \mu_i\|^2, \tag{5.1}$$

where μ_i is the mean evaluation of points in s_i. K-means clustering applies an efficient heuristic algorithm, which can quickly converge to a local optimal solution [252]. The pseudocode of the k-means algorithm is given in Algorithm 1.

Let us note that the initialization of the different centroids can vary and is likely to influence the outputs [253]. A better centroid initialization can speed up convergence

Algorithm 1 The K-means algorithm

```
Input:  Observations $X = \{x_1, x_2, ..., x_n\}$
        Number of clusters $k$
        Initialized centroids $C = \{c_1, c_2, ..., c_k\}$
        Maximum number of iterations $J$
Output: (Local) optimal centroids $C$
        (Local) optimal assignment labels $L = \{l_1, l_2, ..., l_n\}$
        (Local) optimal cluster sets $S = \{S_1, S_2, ..., S_k\}$
changed = TRUE
while changed == TRUE or $j \leq J$ do
    for $id = 1, 2, ..., n$ do
        $l_{id} = \arg\min_{i=1,...,k} \|x_{id} - c_i\|^2$
        $\min Dist_{id} = \min_{i=1,...,k} \|x_{id} - c_i\|^2$
    end for
    for $i = 1, 2, ..., k$ do
        if $l_{id} == i$ then
            Add $x_{id}$ to $S_i$
        end if
    end for
    for $i = 1, 2, ..., k$ do
        $c_i = \frac{1}{|S_i|} \sum_{x_{id} \in S_i} x_{id}$
    end for
    if $\min Dist_{id} == \min_{i=1,...,k} \|x_{id} - c_i\|^2, \forall id = 1, 2, ..., n$ then
        changed = FALSE
    end if
    $j = j + 1$
end while
```

[254]. Steps 3 to 11 in Algorithm 1 are the assignment steps. The algorithm searches for the closest squared Euclidean distances between each observation and the different centroids. The observations are assigned to the groups with the smallest squared Euclidean distances. Steps 12 to 14 are the update steps. For each cluster set obtained in the previous step, the centroid is updated by calculating the mean evaluation of the observations in the cluster. The assignment and update steps will iterate for a given number of loops or until all the observations find the closest distances to the centroids, i.e., the centroids stop updating. Afterward, the k-means algorithm will converge when the assignments for observations no longer change. Since the assignment and update steps will reduce the WCSS value in the objective function (5.1) and there are only a limited number of clustering alternatives, the algorithm must converge to a local optimal solution.

The k-means clustering algorithm has been successfully applied in many fields, such as market segmentation [255], machine vision [256], and geostatistics [257]. It is also possible to be applied in GDM. Consider that there are participants in one stakeholder group $X = \{x_1, x_2, ..., x_n\}$ involved in the decision-making process. They need to evaluate the alternatives based on m criteria; then, the weight allocation from a participant x_i can be described as $W_i = \{w_{i,1}, w_{i,2}, ..., w_{i,m}\}$. This problem can be translated spatially as n observations in an m-dimensional space. Therefore, naturally, the participants with similar weight allocations on criteria are spatially adjacent. That is, they have small squared Euclidean distances. Consequently, by applying the k-means algorithm, the participants with similar weight allocations will be clustered together.

However, the k-means algorithm cannot fulfill the needs of clustering based on criteria priorities. When the weight allocations of participants are similar, i.e., the squared Euclidean distances are close, the ranking of the criteria from participants can be completely different. That is, participants who think different criteria are important can be clustered in the same subgroup by applying the k-means algorithm since the Euclidean distance does not take into account the relative ranking of weight values. In addition, pairs of participants who think that the same criteria are important can be clustered into different groups. For example, if three participants $\{x_1, x_2, x_3\}$ need to weight three criteria $\{c_1, c_2, c_3\}$, the weights of the criteria are given as follows: $x_1 : \{0.25, 0.3, 0.45\}, x_2 : \{0.45, 0.3, 0.25\}, x_3 : \{0.10, 0.20, 0.70\}$. If the k-means algorithm is used to cluster the participants, x_1 and x_2 will be clustered together. Spatially, a centroid can be found such that x_1 and x_2 can have the shortest distances to it. However, x_1 and x_2 hold different priorities on the criteria. On the other hand, x_1 and x_3 have the same priority that c_3 is more important than c_2, which is more important than c_1. It is more logical to cluster x_1 and x_3 into one group.

5.3 Stakeholder clustering based on criteria priorities

Stakeholder clustering is similar to regular clustering. However, it also has two distinctive features:

1. The ranking of the criteria is meaningful. Therefore, the priority of the algorithm is to search the ranking similarities among participants;
2. The centroids in the k-means are used to cluster the surrounding observations. However, they are not meaningful on their own. In contrast, if only the participants are selected as centroids, the centroids have an intuitive meaning: they can be seen as the representatives of the subgroups for data analysis.

Thus, in this chapter, we propose a revised clustering algorithm that is adapted to the context of stakeholder clustering by following the logic of the k-means algorithm:

1. As already addressed, the squared Euclidean distance is not the best choice to investigate the homogeneity and heterogeneity in stakeholder clustering. In this context, to cluster the participants with priorities, the algorithm needs to investigate the ranking of criteria. Based on the weight allocations from the participants, criteria ranking lists can be formed. The heterogeneity of the stakeholder group is mainly determined by the conflicts of the important criteria of participants, i.e., conflicting priorities. Therefore, a new distance needs to be used to calculate the priority differences between participants;
2. The centroids are not randomly selected but are actual observations. In this way, the optimal centroids will be selected as the representatives of the groups. It should be noted that divergence can occur, i.e., the algorithm updates one centroid between two participants endlessly and there will be an unintentional looping [258]. This is because there are limited centroids that can be selected. Additionally, the algorithm can quickly converge to an optimal solution because of the limited options for centroids. However, there is also a high possibility that the solution is a local optimum again because of the limited options for updating centroids. We are aware of this possibility but decide to retain this approach because we want to preserve the actual meaning of the centroids. We decide to repeat the initialization-assignment-update steps multiple times to find a solution with the highest quality of clustering. Therefore, there should be an indicator to evaluate the quality of the clustering.

The evaluation distance and clustering indicator to serve the proposed algorithm are introduced in the following subsections.

5.3.1 The ranking distance based on the weighted Kendall's τ coefficient

Kendall's τ coefficient is used to measure the correlation between rankings [259]. Another method of measuring rank correlation is Spearman's rank correlation coefficient, but both show almost the same tendency [260]. However, there are variants of τ to deal with the ties [261], for example, $\tau - b$ [262] and $\tau - c$ [263]. Let us consider two participants x_a and x_b; the weight allocations of criteria W_a and W_b can be converted to the criteria rankings vectors R_a and R_b, respectively. For example, a weight allocation of three criteria $\{0.5, 0.3, 0.2\}$ can be converted to the ranking $\{1, 2, 3\}$. The rankings of a and b are pairwise compared as $(r_{a,1}, r_{b,1})$, $(r_{a,2}, r_{b,2})$,$\cdots$,$(r_{a,m}, r_{b,m})$. Any pair $(r_{a,p}, r_{b,p})$ and $(r_{a,q}, r_{b,q})$, where $p < q$, satisfies being concordant if the order $(r_{a,p}, r_{a,q})$ and $(r_{b,p}, r_{b,q})$ agrees. In other words, they are concordant if:

$$(r_{a,p} > r_{a,q} \wedge r_{b,p} > r_{b,q}) \vee (r_{a,p} < r_{a,q} \wedge r_{b,p} < r_{b,q}). \tag{5.2}$$

Otherwise, they are discordant. Then, Kendall's τ coefficient of these two participants' criteria priorities is defined as:

$$\tau = \frac{(\#\text{concordant pairs}) - (\#\text{discordant pairs})}{m(m-1)/2}, \tag{5.3}$$

where $m(m-1)/2 = \binom{m}{2}$ is the binomial coefficient for the number of ways to choose two items from m items. Kendall's τ coefficient has the following characteristics:

- If the ranks are exactly the same (i.e., #discordant pairs $= 0$), then $\tau = 1$.
- If one ranking is the reverse of the other (i.e., #concordant pairs $= 0$), then $\tau = -1$.
- In all other cases, the value of the coefficient is between -1 and 1. An increase in value means an increase in correlation.
- If the ranks are completely independent, then $\tau = 0$.

Let us define two real-valued vectors r_a and r_b that are mapped to the vector with coordinate $\langle p \, , q \rangle$, $p < q$, given by $sgn(r_{a,p} - r_{a,q})$ and $sgn(r_{a,p} - r_{a,q})$. We have:

$$\langle R_a \, , R_b \rangle : \; = \sum_{p<q} \text{sgn}(r_{a,p} - r_{a,q}) \, \text{sgn}(r_{b,p} - r_{b,q}), \tag{5.4}$$

where

$$\text{sgn}(\delta) : \; = \begin{cases} 1, \text{if } \delta > 0; \\ 0, \text{if } \delta = 0; \\ -1, \text{if } \delta < 0. \end{cases} \tag{5.5}$$

Equation (5.4) is an inner product of dimension $m(m-1)/2$. By following the analogous property of the inner property, we can define:

$$||R_a|| : \; = \sqrt{\langle R_a \, , R_a \rangle}, \tag{5.6}$$

Then, we have a Cauchy-Schwartz-like inequality:

$$| \langle R_a \, , R_b \rangle | \leq ||R_a|| \cdot ||R_b||. \tag{5.7}$$

Kendall's τ between R_a and R_b can be defined in a way formally identical to cosine similarity:

$$\tau = \frac{\langle R_a \, , R_b \rangle}{||R_a|| \cdot ||R_b||}. \tag{5.8}$$

Kendall's τ coefficient can successfully reflect the similarity of the two rankings. However, in our case, it is more important to capture the similarity in the higher ranks, i.e., higher priorities. To balance the important and unimportant criteria in the ranking, we decide to use an alternative Kendall's τ that emphasizes the discordance between criteria with high rank, that is, a weighted Kendall's τ [264]. Let us define a nonnegative symmetric weight function $\eta\,(p,q)$ that is based on the ranks of the exchanged elements. Therefore, a weighted Kendall's τ can be defined as:

$$\tau_\eta = \frac{\langle R_a \, , R_b \rangle_\eta}{||R_a||_\eta \cdot ||R_b||_\eta}. \tag{5.9}$$

The properties of τ_η are proven in [265]. In this case, we want to place more emphasis on the criteria having high rankings than those having low rankings. Therefore, the weight function is defined as $\eta_{p,q} = 1/p + 1/q$ for an exchange between criteria with rank p and q. A higher rank discord will result in a higher η, i.e., a sharper change.

Suppose the weighted Kendall's τ is applied in the criteria ranking list of stakeholder group X. By comparing one participant, x_{id}'s criteria ranking $R_{id} = \{r_{id,1}, r_{id,2}, ..., r_{id,m}\}$ with other participants, the pairwise weighted τ coefficient can be calculated: $\{\tau_{\omega,id,1}, \tau_{\omega,id,1}, ..., \tau_{\omega,id,m}\}$. After every two participants are pairwise compared, a Kendall's τ coefficient matrix can be constructed.

$$\mathrm{T}_\omega = \begin{bmatrix} \tau_{\omega,1,1} & \cdots & \tau_{\omega,1,m} \\ \vdots & \ddots & \vdots \\ \tau_{\omega,m,1} & \cdots & \tau_{\omega,m,m} \end{bmatrix}. \tag{5.10}$$

Because the range of weighted τ ranges from -1 to 1, we define a new ranking distance matrix D that is calculated through:

$$D = 1 - \mathrm{T}_\omega = \begin{bmatrix} d_{1,1} & \cdots & d_{1,m} \\ \vdots & \ddots & \vdots \\ d_{m,1} & \cdots & d_{m,m} \end{bmatrix}, \tag{5.11}$$

where d indicates the ranking distance between two participants. When $d = 0$, the rankings of the two participants are exactly the same, while when $d = 2$, the rankings of the two participants are exactly reversed. Moreover, a discordance in the higher rank will result in a more significant distance than a discordance in the lower rank.

5.3.2 The clustering quality measurement based on the silhouette coefficient

There are several indicators to evaluate the quality of a given partition, for example, the Davies-Bouldin index [266], Dunn index [267], and silhouette coefficient [268]. The

Davies-Bouldin index is defined as the average similarity measure of each cluster to its most similar cluster, where similarity is the ratio of intracluster distance to intercluster distance. The Dunn index searches the ratio of the lowest intercluster distance between clusters and the largest intracluster distance among clusters. The silhouette coefficient assesses how similar an observation is to its most similar cluster compared to its own cluster. These indicators are similar but have some differences: The Dunn index is an indicator to seek the worst case in the clustering. In contrast, the Davies-Bouldin index and silhouette index are more comprehensive because they calculate the average clustering performance. The Davies-Bouldin index's calculation is more straightforward than the silhouette coefficient's calculation. However, the distance metric of the Davies-Bouldin index is restricted to Euclidean space [266]. Therefore, the silhouette coefficient is used to evaluate the clustering quality.

To calculate the silhouette score of a stakeholder $x_{id} \in C_i$, we first calculate the average ranking distance u_{id} between one participant and all other participants in the same cluster C_i:

$$u_{id} = \frac{1}{|C_i| - 1} \sum_{a \in C_i, id \neq a} d\left(x_{id}, x_a\right), \tag{5.12}$$

where d is the ranking distance that can be found in Equation (5.8). Then, the average ranking distance between participant x_{id} and the nearest different cluster is calculated:

$$v_{id} = \min_{j \neq i} \frac{1}{|C_j|} \sum_{b \in C_j} d\left(x_{id}, x_b\right). \tag{5.13}$$

The silhouette score of participant x_{id} can be defined as:

$$\zeta_{id} = \frac{v_{id} - u_{id}}{\max\left(u_{id}, v_{id}\right)}. \tag{5.14}$$

In the case of the exploding increase in clusters, when there is only one participant x_{id} in cluster C_i, we have $\zeta_{id} = 0$. Equation (5.11) can also be written as:

$$\zeta_{id} = \begin{cases} 1 - \frac{u_{id}}{v_{id}}, \text{if } v_{id} > u_{id}; \\ 0, \text{if } v_{id} = u_{id}; \\ \frac{v_{id}}{u_{id}} - 1, \text{if } v_{id} < u_{id}, \end{cases} \tag{5.15}$$

where the coefficient ζ ranges from $[-1, 1]$. A smaller u value indicates that it has a close relationship with the cluster to which it belongs, while a larger v reflects a large dissimilarity between x_{id} and other clusters; therefore, to increase ζ, we need to make $u_{id} \ll v_{id}$. The ζ_{id} close to 1 means participant x_{id} is appropriately clustered. On the other hand, if ζ_{id} is close to -1, it means participant x_{id} is more appropriately clustered in the nearest cluster. To evaluate the clustering performance of all participants, where the total number of participants is M, we calculate the global silhouette coefficient as:

$$Z = \frac{1}{M} \sum_{id=1}^{n} \zeta_{id}. \tag{5.16}$$

5.4 A k-means-like algorithm to cluster participants

As already stressed, in the k-means algorithm, the squared Euclidean distance is used to cluster the observations. To cluster the participants based on criteria priorities, a k-means-like algorithm (see Algorithm 2) has been developed based on the ranking distance. The ranking distance matrix among participants is constructed as an algorithm input. There is no need to calculate the distance in the algorithm again. From step 2 to step 3, random participants are selected as initial centroids. Then, the participants are clustered from step 5 to step 16, i.e., assignment steps: The centroid participants are clustered into separate groups. The other participants are clustered by searching the minimum pairwise ranking distance d with the centroids in the distance matrix D. Steps 17 to 22 are the update steps: in each cluster, the intracluster ranking distance matrix D_S is constructed with the pairwise ranking distances among participants that are in the cluster. The participant with the lowest average ranking distance is selected as the new centroid of the cluster. The assignment and update step will iterate until the centroid set no longer changes. That is, the iteration continues until a local optimum converges. It should be noticed that in this iteration the divergence can happen. In the current setup, if the algorithm keeps updating between two participants for 10 times, the algorithm will declare a break statement and the loop will be end. This process iterates J times to obtain J local optimums. These local optimal clustering results are evaluated by calculating the global silhouette coefficient. The clustering with the highest global silhouette coefficient will be selected as the final clustering solution.

5.4.1 Case study

The algorithm is applied in a real-life case study: the sustainable construction logistics scenario (CLS) evaluation in the dense urban Brussels-Capital Region (BCR), Belgium. The construction project is organized as a public-private partnership, and the pilot site is baptized as City Campus. The City Campus will result in a mixed SME park and offers high relevancy for urban construction logistics because of its density, location, construction type, intermodal transport possibilities, and the rich number of participants involved [220]. The neighboring residents are expected to be invited to the evaluation process. However, there are more than 200 households around the construction site. It is not possible to invite all the residents to the evaluation. Therefore, it is necessary to identify the representative residents with different priorities for the evaluation workshop. Therefore, a survey was distributed in the City Campus neighborhood to collect the opinions of the local residents. A criteria set (see Table 5.1) was asked for the residents

Algorithm 2 The stakeholder clustering algorithm

```
Input:  participants $X = \{x_1, x_2, ..., x_n\}$
        Ranking distance matrix $D$
        Number of clusters $k$
        Maximum number of iterations $J$
Output:  (Local) optimal centroids $C = \{c_1, c_2, ..., c_k\}$
         (Local) Optimal assignment labels $L = \{l_1, l_2, ..., l_n\}$
         (Local) optimal cluster sets $S = \{S_1, S_2, ..., S_k\}$
for $j = 1, 2, ..., J$ do
    $A = \text{randint}(n, \text{size} = k) = \{a_1, a_2, ..., a_k\}$
    $C_j = \{c_{j,1}, c_{j,2}, ..., c_{j,k}\} = \{x_{a_1}, x_{a_2}, x_{a_k}\}$
    while $C_j$ updates do
        for $id = 1, 2, ..., n$ do
            if $id \in A$ then
                $l_{j,id} = A.\text{where}(a_i == id)$
            else
                $l_{j,id} = \underset{i=1,...,k}{\arg\min}(d_{id,a_i})$
            end if
        end for
        for $i = 1, 2, ..., k$ do
            if $l_{j,id} == i$ then
                Add $x_{id}$ to $S_{j,i}$
            end if
        end for
        for $i = 1, 2, ..., k$ do
            $D_{S_{j,i}} = \begin{bmatrix} d_{a,a} & \cdots & d_{a,b} \\ \vdots & \ddots & \vdots \\ d_{b,a} & \cdots & d_{b,b} \end{bmatrix}$, where $x_a, x_b \in S_{j,i}$
            $c_{j,i} = \underset{x_{id} \in S_{j,i}}{\arg\min}(\frac{1}{|S_{j,i}|} \sum_{x_a \in S_{j,i}, id \neq a} d_{id,a})$
        end for
    end while
end for
$o = \underset{j}{\arg\max} Z_j$
$C = C_o = \{c_{o,1}, c_{o,2}, ..., c_{o,k}\}$
$L = \{l_{o,1}, l_{o,2}, ..., l_{o,n}\}$
$S = \{S_{o,1}, S_{o,2}, ..., S_{o,k}\}$
```

to evaluate. They were required to evaluate the important levels of criteria on a five-point Likert scale. In the end, a total of 36 residents completed the survey to score the criteria. To compare the clustering result in the k-means algorithm based on criteria weights, the criteria weight allocations are also derived by applying the rank sum (RS) weights method.

Table 5.1: The criteria set for residents to evaluate

Criterion	Name	Definition
Cri_1	Impact on traffic and accessibility	Impact of infrastructure works on the efficiency of a transport system; Accessibility of the region in the vicinity of the construction site by road, public transport, etc.
Cri_2	Noise pollution	Sound level caused by human activities, including transport, during construction projects.
Cri_3	Air pollution	Impact of construction works on local air quality.
Cri_4	Business climate during construction works	Attractiveness of the area in terms of business opportunities.
Cri_5	Landscape quality	Visual nuisances in the surrounding environment.
Cri_6	Attractiveness	Recreational facilities in and around the construction zone.
Cri_7	Climate change	Global impact of construction works on greenhouse gas emissions.
Cri_8	Social and economic revitalization	Impact after finishing the construction site.
Cri_9	Biodiversity	Impact of construction works on an area of nature in the vicinity.

To compare the clustering performances of our proposed algorithm and the k-means algorithm, a simple quality index called the same-priority rate is proposed by finding the homogeneity of the priority in the subgroups:

$$\rho = \frac{\sum_{i=1}^{k} \max\limits_{\alpha} \mu_{i,\alpha}}{M}, \tag{5.17}$$

where $\mu_{i,\alpha}$ is the number of participants in cluster i who think criterion α is the most important one. It can also be extended as the number of participants who think criteria $\{\alpha_1, \alpha_2, ..., \alpha_n\}$ are the top ranking criteria. $\max\limits_{\alpha} \mu_{i,\alpha}$ finds the criterion in each cluster that most participants think are the most important ones. M is the total number of participants. The same-priority rate ρ calculates the percentage of participants holding the same priorities in the subgroup. When $\rho = 1$, the participants are perfectly clustered, as each subgroup holds a consistent priority. A low ρ means that some subgroups have conflicting priorities.

An experiment is performed to evaluate the performance of the algorithm. For $k = \{2,3,4,5,6,7\}$, do:

1. Randomly select 2/3 of the total data, i.e., 24 participants, to the list. The stakeholder weight allocations, a 24×9 matrix, are imported into the k-means algo-

rithm. Then, the ranking distance matrix based on the weighted Kendall's τ coefficient, a 24×24 matrix, is imported into the stakeholder clustering algorithm.

2. The clustering results of the two algorithms are compared based on the same-priority rate ρ.
3. Repeat steps 1 and 2 100 times. Calculate the average same-priority rate ρ of the two algorithm clustering results.

Figure 5.1 illustrates the algorithm comparison results. It shows the box plots of the calculated priority rates under different k values based on the two algorithms. Based on the figure, the proposed stakeholder clustering algorithm has a better performance in clustering participants based on the criteria priority: the average score is higher, while the variance is lower.

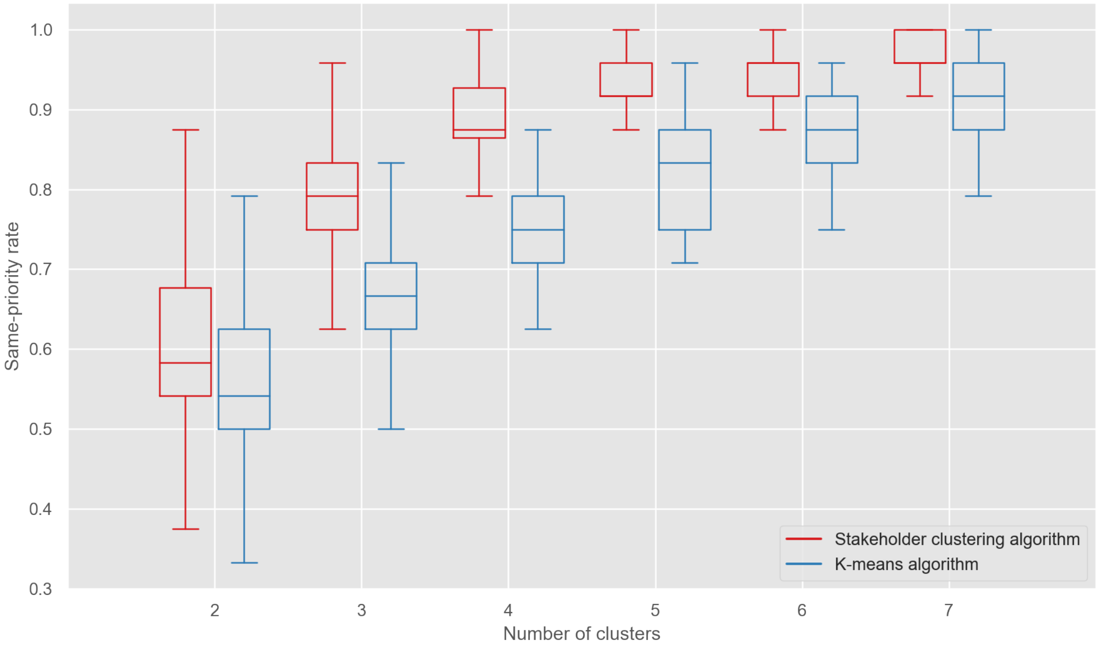

Figure 5.1: Algorithm comparison

The experiment is performed again by altering Equation (5.14) to:

$$\rho = \frac{\sum_{i=1}^{k} \max_{(\alpha_1,\alpha_2)} \mu_{i,(\alpha_1,\alpha_2)}}{M}, \tag{5.18}$$

which aims to seek the criteria set in each cluster that the most participants think are the top two important criteria. Figure 5.2 shows the box plots of the altered priority rates based on the two algorithms. The overall scores are lower than Figure 5.1, as expected, because it seeks the top 2 criteria combination instead of the top 1 criterion.

Nevertheless, the result of the stakeholder clustering algorithm outperforms the result of the k-means. In conclusion, the proposed stakeholder clustering algorithm can better identify the subgroups of participants that hold different priorities.

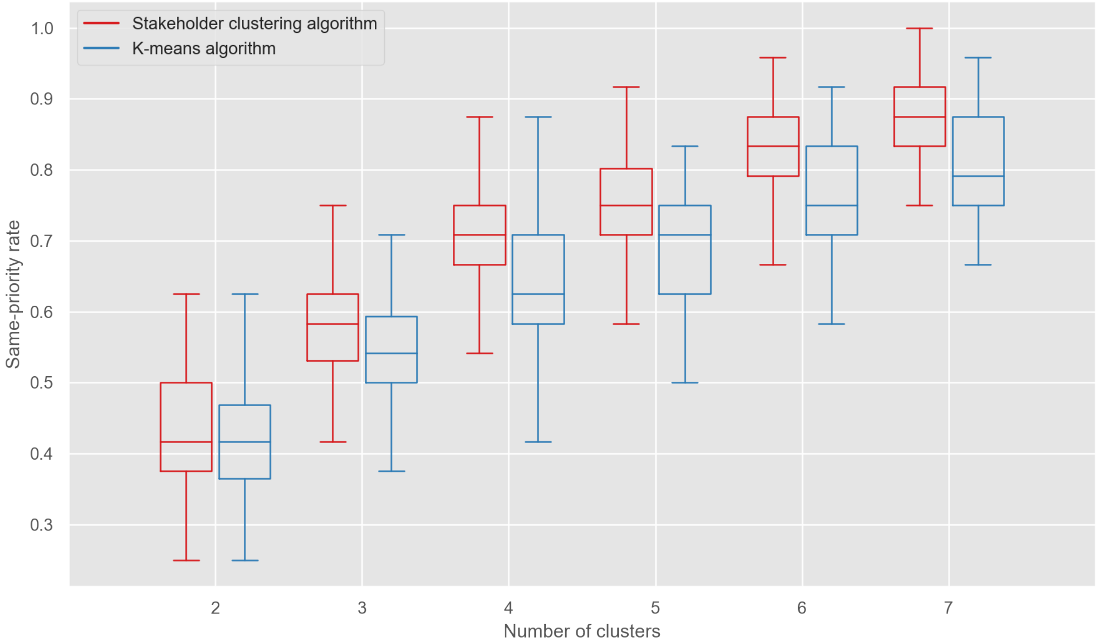

Figure 5.2: Algorithm comparison on top 2 criteria

After validating the performance of the proposed algorithm, the real data are imported into Algorithm 2 to cluster the participants to seek their priories and identify the representatives. To select the best cluster number, the same-priority rate ρ and the global silhouette coefficient Z in different k values are calculated. Figure 5.3 illustrates ρ and Z when $k = \{2,3,4,5,6,7\}$. Based on Figure 5.3, when $k = 4$, the same-priority rate reaches a rather high value, while the silhouette score also reaches a local optimal score. When $k = 5$, ρ increases, but Z decreases. Thus, 4 is selected as the k value. Then, the 36×36 ranking distance matrix based on the participants' criteria ranking is imported into the stakeholder clustering algorithm. The stakeholder clustering algorithm successfully clustered the participants into 4 subgroups. The participants within subgroups hold different priorities. Table 5.2 shows the result of the algorithm. Almost half of the participants think 'Impact on traffic and accessibility' is the most important criterion. The other three subgroups are minority groups. Their most important criteria are different, yet they hold overlapping priorities: 'Climate change' and 'Air pollution'.

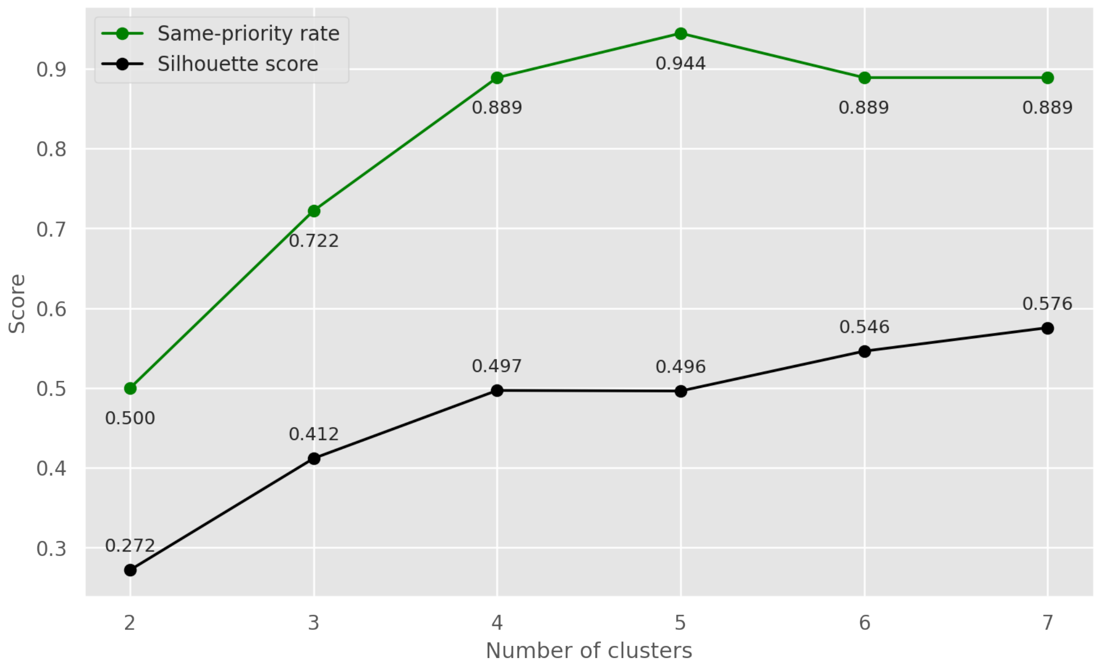

Figure 5.3: Clustering quality in different *k* values

Table 5.2: Clustering result based on the stakeholder clustering algorithm

Cluster	Priority (top ranked criteria)	Number of participants
1	Impact on traffic and accessibility	16
2	Landscape quality, Climate change, Biodiversity	6
3	Air pollution, Climate change	6
4	Noise pollution, Air pollution	8

Based on the clustering result from the algorithm, the centroids of the clusters will be selected as the representatives of the subgroups. Prior to the selection, it is necessary to numerically express the heterogeneity among the centroids (the subgroups). Thus, the pairwise ranking distance matrix among the 4 centroids is calculated and shown in Equation (5.16):

$$\begin{bmatrix} 0 & 0.747 & 0.914 & 1.047 \\ 0.747 & 0 & 0.921 & 0.978 \\ 0.914 & 0.921 & 0 & 0.766 \\ 1.047 & 0.978 & 0.766 & 0 \end{bmatrix}, \tag{5.19}$$

where the distance values are rounded up to 3 decimal places. It shows the diversity of the clustering. They will be invited to the following decision-making workshop. As Cluster 1 is the majority group, to ensure diversity, one more representative can be invited by selecting the participant in the subgroup with the lowest ranking distance d to the centroid. Let us examine the detailed ranking of the 5 representatives selected.

Table 5.3: Representatives criteria ranking

Cluster of the representative	Cri_1	Cri_2	Cri_3	Cri_4	Cri_5	Cri_6	Cri_7	Cri_8	Cri_9
1	1	2	3	8	5	6	7	4	9
1	1	2	3	5	8	6	7	4	9
2	4	5	6	9	1	7	2	8	3
3	6	7	1	3	4	8	2	9	5
4	9	1	2	7	3	4	8	5	6

Table 5.3 indicates the scores given by the five selected representatives. The representatives of the major subgroup in the participants hold the same top ranked criterion ‘impact on traffic and accessibility’, while they evaluate other criteria at the mediocre level. No obvious preference for other criteria can be found at this stage. However, it can be explored afterward in the workshop. For the three participants who represent the other three subgroups, their criteria priorities reflect the priorities of their subgroups.

5.5 Limitations and future work

The stakeholder clustering algorithm provides a new solution in selecting the representatives for the MCGDM process. It can identify the subgroups within the participants based on their priorities. However, there are still several limitations left for the future work:

1. We argue that the ranking of the ordinal information provided by the participants are important to cluster the participants. However, the cardinal information can also be useful. These two types of information can facilitate a better clustering results in different situations. Thus, this algorithm should be further developed by leveraging both ordinal information and cardinal information, i.e., the ranking information and weight allocation values given by participants.

2. In the case study, we propose a simple quality index to help the facilitators to select the number of the subgroups, i.e., to determine the k value. However, the facilitators still need to take effort to observe the clustered results to adjust the k value. A structured way of estimating the k value should be explored, and the clustering result should be validated.

3. We invite one more representative in the majority subgroup that is closest to the centroid. This is because the minority groups consist of a similar number of participants, and the majority group consists of approximately two times the number of participants. However, in the future, a formal way of selecting extra representatives of subgroups should be found to ensure the fairness and the diversity of the

subgroups. This should lead to a decision-making process that ensures that the interests of all participants are not neglected.

5.6 Conclusion

In the MCGDM, when there is a conflict of interest among the participants within one stakeholder group, it is necessary to cluster them into subgroups. The previous literature focused on clustering participants based on the evaluation scores of the alternatives. In this work, we decide to focus on the priorities of the participants. We collect the ordinal information of the criteria based on the criteria importance level scores completed by participants from the survey. A novel clustering algorithm is proposed that clusters the participants based on their priorities, i.e., criteria ranking. Criteria rankings can also be converted from the criteria weight allocations from participants. Then, the ranking distances are calculated by pairwise comparing the rankings based on Kendall's τ coefficient. The ranking distance matrix is imported into the proposed k-means-like algorithm to identify the subgroups. The algorithm successfully clustered the participants into 4 subgroups with different priorities in a real case. The centroids of clusters were selected as the representatives of the subgroups. They will be invited to participate in the following MCGDM process.

Chapter 6

Consensus Reaching Model

6.1 Introduction

Several types of operation research methods have been developed to help decision-makers in the evaluation of transport projects. Among them, Multiple Criteria Decision-Making (MCDM) helps decision-makers to rank or to sort different alternatives based on several conflicting criteria [269]. MCDM has become more and more popular over the recent years as it allows taking into account different kinds of criteria (and not only economical ones), which is important for the sustainability concerns: not only economic variables will be considered during the decision-making process but also the environment protection and social equity [270]. In practical transport cases, more than one individual or group of individuals which can influence the decision are involved. They are called the stakeholders [19]. In considering the perspectives and interests of different stakeholder groups, it is easier to find a sustainable solution which satisfy their needs and concerns. It is therefore crucial to incorporate this distinctive feature and to take into account their different points of view as well as their preferences.

MAMCA, as an extension of traditional MCDM methods, was proposed for transport project evaluations [66], which has been applied in various domains of application, especially in the area of mobility and logistics [68], transport policy measures evaluation [271], transport technologies [156], etc. During the decision-making process, different stakeholder groups are explicitly taken into account. Instead of the single criteria tree, MAMCA allows the different stakeholder groups having their own (and so possibly different) criteria trees. The concept of stakeholder is involved at the early stage of

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This chapter is based on Huang, H., De Smet, Y., Macharis, C., & Doan, N. A. V. (2021). Collaborative decision-making in sustainable mobility: identifying possible consensuses in the multi-actor multi-criteria analysis based on inverse mixed-integer linear optimization. International Journal of Sustainable Development & World Ecology, 28(1), 64-74.

the evaluation, which leads to a better understanding of their respective objectives. As already said, each stakeholder group has the liberty of having their own criteria, but also weights and preference structure. It is only at the end of the analysis that the different points of views are being confronted. However, in some cases, reaching a final consensus among the stakeholder groups has been proven to be a difficult task.

In this chapter, we will investigate how to identify one or a few possible consensuses by assuming that the different stakeholder groups accept limited modifications of their criteria weights. By doing so, we adopt an inverse optimization approach. We determine the minimal weight modification a given stakeholder group has to accept in order to improve the position of a given alternative in his individual ranking. In an ideal case (which is not always realistic), we try to identify the alternative that will request the smallest weight modifications among all the stakeholder groups in order to reach, simultaneously, the first position in all the individual rankings. This approach is inspired by a new weight sensitivity analysis tool developed in the context of the PROMETHEE methods.

This chapter is organized as follows. First, an introduction of Group Decision Making and MAMCA methodologies are presented. Next, a brief reminder of PROMETHEE and the aforementioned weight sensitivity analysis tool is provided. Then, in section 6.4, we illustrate the integration of this approach in the MAMCA methodology. In section 6.5, we apply the proposed model on two real case studies which seeks cost-effective and sustainable mobility solutions. Finally, we conclude and give directions for future research.

6.2 Multi-Actor Multi-Criteria Analysis

In this section, a brief literature review about group-decision support methodologies is presented. This emphases the importance of involving multiple stakeholder groups in the decision-making process. Furthermore, the difference between MAMCA and other Multi-criteria Group Decision Making (MGDM) methods is explained. A detailed introduction about MAMCA methodology is then brought out.

6.2.1 Group-decision support methodology

Fortunately, in many places, people have a democratic right to participate in decision making and their implication is expected to lead to a higher quality of decision making [196]. Classic MCDM methods have been extended to address group decision aspects. Group decision is usually understood as the reduction of different individual preferences of a given set to a single collective preference [272]. For instance, Dyer and Forman [273] investigated the use of AHP in group decision-making. Following the opinion of Saaty, the use of consensus voting is needed to come to a common pairwise comparison matrix for the whole group or to aggregate the individual judgments. Group decision support for PROMETHEE [274] and ELECTRE [57] were also studied. In the context of transportation, Kannan et al. applied Fuzzy-TOPSIS to group decision [275]. Bana e Costa applied MCDM as a methodological framework on the basis of expert judgements to support the search for less conflicting policy options transportation services [276]. Keshkamat et al. proposed a holistic and coherent spatial multi-criteria network analysis approach for the generation of optimal routing alternatives under different policy visions (in a network of existing roads). This enables the comparison of different routing scenarios that represents the interests and perspectives of different stakeholder groups [277]. Mousseau et al. proposed a conceptual and methodological framework which involves massive stakeholder groups for examining ticket pricing reform in public transport [278]. Labbouz et al. proposed a methodology that facilitates a process of concertation involving reasoned public discourse, utilizing multi-criteria decision-making methods to reach a compromise between the technical stakes and local expectations [279].

The concept of sustainability is by nature multi-dimensional, with most of the time conflicting interests among stakeholder groups. The involvement of multiple stakeholder groups in MGDM methods facilitates the decision-making process towards sustainable solutions. However, in all the methods mentioned above, a common hierarchy of criteria for all the decision-makers is considered. From this perspective, the group is assumed to be homogeneous. Though when the public is involved in the decision-making, especially in the context of social decision problems, stakeholder groups are seldom homogeneous and have different and often conflicting points of view. In this context, Macharis proposed the MAMCA methodology which allows the involvement of different stakeholder groups with possible different criteria sets. At this point MAMCA is used to visualize the different stakeholder groups opinions and serves as a discussion tool to find a possible consensus. As far as we know, there is no formal way to identify alternatives that are more likely to become consensus solutions. This issue is investigated in this chapter under the assumption that stakeholder groups accept to slightly modify the weights they associate to their criteria.

6.2.2 MAMCA methodology

MAMCA strengthens the legitimacy and relevance of the decision-making process by engaging the stakeholder groups at the early stage. Multi-stakeholder group involvement helps in structuring the scope of the problems by identifying their conflicting perspectives concerning their own sustainability criteria [68]. MAMCA has often been used in the context of sustainable development. For instance, it successfully supports the assessment of low-carbon transport policy [177], long-term decision making process on mobility, logistics [280] and land-use [281].

The steps of a classic MCDM process include problem statement, alternatives and criteria definition, alternatives screening, scores determination, scores analysis, and conclusions drawing [158]. Unlike classical MCDM methods, the steps of MAMCA are: (1) alternatives definition, (2) stakeholder analysis, (3) criteria and weights definition, (4) criteria indicators and measurement methods definition, (5) overall analysis and ranking, (6) results and (7) implementation [68]. The overall methodology of MAMCA is shown in Figure 1.2.

Similar to the conventional multi-criteria analysis (MCA), in the first step, the potential alternatives to solve the problems are defined. The decision-makers need to identify and classify the alternatives in terms of different scenarios, policy measures and so on. In the second step, the different stakeholder groups are identified. It is a crucial step in MAMCA as for each stakeholder group there is a different criteria tree and an in-depth analysis to understand each stakeholder group's objectives is conducted.

Next, criteria are defined for each group of stakeholders. These criteria can be predefined by the decision-makers/experts with respect to the considered objectives and the purposes of identified stakeholder groups. As already said, it is also possible for the stakeholder groups to define their own criteria and weights. In the fourth step, one or more indicators for each criterion need to be constructed which can be used to measure each alternative, providing the scale for the judgment. The indicators can be quantitative or qualitative.

In step 5, the overall analyses are taken within stakeholder groups. Any MCDM method can be used to assess the alternatives. The Group Decision Support Methods (GDSM) are well suited in this step such as the method used in this chapter: the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) [159, 192].

The results of the analysis are shown in step 6. The ranking of each stakeholder group is visualized. The multi-actor view chart illustrates the performance scores of the alternatives among all stakeholder groups. However, there is not a final ranking of alternatives for all stakeholder groups as they manage different criteria (indeed the sum of performance scores from different stakeholder groups will reduce the individual information). A discussion is needed between the decision-makers and stakeholder groups to reach a consensus on the final solution. However, as the stakeholder groups hold different objectives and preferences, a final consensus is sometimes hard to reach if the individual rankings are widely divergent. As a consequence, a solution is sought to assist the decision-makers to identify one or few candidate solutions to reach a consensus.

6.3 Weight sensitivity analysis based on inversed mixed integer linear programming in PROMETHEE

As already said, the proposed approach is based on a weight sensitivity analysis tool that was recently developed in the context of PROMETHEE methods. We will first start with a brief reminder about the computation of PROMETHEE II rankings. Then, we will illustrate the method based on inverse mixed integer linear optimization.

6.3.1 Short description of PROMETHEE

Let us consider a set of criteria $\mathscr{F} = \{f_1, f_2, \ldots, f_m\}$ which are used to evaluate a finite set of alternatives $\mathscr{A} = \{a_1, a_2, \ldots, a_n\}$. Let us assume, without loss of generality, that all the criteria are considered to be maximized. To compare the preference of two alternatives a_i and a_j on criteria f_k, we define a preference function P_k as follows:

$$P_k\left(a_i, a_j\right) = H_k(d_k(a_i, a_j)), \tag{6.1}$$

where H_k is a positive non-decreasing function and $d_k(a_i, a_j) = \max(f_k(a_i) - f_k(a_j), 0)$. Six standard functions H_k are usually considered in PROMETHEE [159]. Then we have:

$$\begin{cases} P_k(a_i, a_j) = 0, \text{ means no preference of } a_i \text{ over } a_j, \\ P_k(a_i, a_j) \sim 0, \text{ means weak preference of } a_i \text{ over } a_j, \\ P_k(a_i, a_j) \sim 1, \text{ means strong preference of } a_i \text{ over } a_j, \\ P_k(a_i, a_j) = 1, \text{ means strict preference of } a_i \text{ over } a_j. \end{cases} \tag{6.2}$$

After comparing the preferences between the alternatives a_i and a_j for every criterion, the global measure of the preference a_i over a_j can be computed as follows:

$$P\left(a_i, a_j\right) = \sum_{k=1}^{m} w_k \cdot P_k(a_i, a_j), \tag{6.3}$$

where w_k is the weight of the criterion f_k. Weights are assumed to be positive and normalized:

$$\begin{cases} \mathscr{W} = \{w_1, w_2, w_3, \ldots, w_m\}, \\ \sum_{k=1}^{m} w_k = 1. \end{cases} \tag{6.4}$$

The PROMETHEE ranking is based on the positive flow score ϕ^+, negative flow score ϕ^- and net flow score ϕ:

$$\phi^+(a_i) = \frac{1}{n-1} \cdot \sum_{a_j \in \mathscr{A}, j \neq i} P\left(a_i, a_j\right), \tag{6.5}$$

$$\phi^-(a_i) = \frac{1}{n-1} \cdot \sum_{a_j \in \mathscr{A}, j \neq i} P\left(a_j, a_i\right), \tag{6.6}$$

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i). \tag{6.7}$$

In PROMETHEE I, a higher positive flow score and lower negative flow score will result in a better alternative. Let (P^+, I^+) and (P^-, I^-) define the following preorders:

$$\begin{cases} a_iP^+a_j \Longleftrightarrow & \phi^+(a_i) > \phi^+(a_j), \\ a_iI^+a_j \Longleftrightarrow & \phi^+(a_i) = \phi^+(a_j). \end{cases} \tag{6.8}$$

$$\begin{cases} a_iP^-a_j \Longleftrightarrow & \phi^-(a_i) < \phi^-(a_j), \\ a_iI^-a_j \Longleftrightarrow & \phi^-(a_i) = \phi^-(a_j). \end{cases} \tag{6.9}$$

The PROMETHEE I partial ranking is established by considering the intersection of the two preorders:

$$\begin{cases} a_iP_Ia_j \ (a_i \text{ outranks } a_j) \Longleftrightarrow \begin{cases} a_iP^+a_j \text{ and } a_iP^-a_j, \\ a_iP^+a_j \text{ and } a_iI^-a_j, \\ a_iI^+a_j \text{ and } a_iP^-a_j; \end{cases} \\ a_iI_Ia_j \ (a_i \text{ is indifferent to } a_j) \Longleftrightarrow a_iI^+a_j \text{ and } a_iI^-a_j; \\ aRb \ (a_i \text{ and } a_j \text{ are incomparable}) \Longleftrightarrow \begin{cases} a_iP^+a_j \text{ and } a_jP^-a_i, \\ a_jP^+a_i \text{ and } a_iP^-a_j. \end{cases} \end{cases} \tag{6.10}$$

PROMETHEE II complete ranking is based on net flow score ϕ (which does not support incomparability relations):

$$\begin{cases} a_iP_{II}a_j \ (a_i \text{ outranks } a_j) \Longleftrightarrow \phi(a_i) > \phi(a_j), \\ a_iI_{II}a_j \ (a_i \text{ is indifferent to } a_j) \Longleftrightarrow \phi(a_i) = \phi(a_j). \end{cases} \tag{6.11}$$

Finally, the net flow score can be considered as the following function:

$$\phi(a_i) = \frac{1}{n-1} \sum_{k=1}^{m} \sum_{a_j \in \mathscr{A}} [P_k(a_i,a_j) - P_k(a_j,a_i)] \cdot w_k = \sum_{k=1}^{m} \phi_k(a_i) \cdot w_k, \tag{6.12}$$

where ϕ_k is called the k^{th} uni-criterion net flow score:

$$\phi_k(a_i) = \frac{1}{n-1} \sum_{a_j \in \mathscr{A}, i \neq j} [P_k(a_i,a_j) - P_k(a_j,a_i)]. \tag{6.13}$$

At this point, the multi-criteria problem can be viewed as a uni-criterion net flow score matrix, which can be applied in the following analysis based on a MILP model.

6.3.2 An alternative weight sensitivity analysis for PROMETHEE

In MCDM, the definition of weights is not very precise, nor are the values given by a decision-maker [282]. A natural question can be raised: “How a change in the weight values can impact the ranking?”

To solve this question, weight stability intervals (WSI) have been proposed to assess the stability of the ranking. Stability intervals are defined for the weights of the different criteria. They consist of the values that the weight of one criterion can take without altering the initial results (all other weights being proportionally kept constant).

However, when using the WSI, only few alternatives can be ranked first. This method only focuses on one criterion at a time (changes are assumed to be applied uniformly to the other criteria in order to remain normalized). To consider multiple weights of criteria at one time, the problem is formulated as follows: “For a PROMETHEE II application, what would be the minimum modification of the weights such that a given alternative a_i becomes first?” This can thus be considered as an inverse optimization problem on the PROMETHEE II ranking. In this section, we summarize the MILP model introduced in [171]. We will then illustrate its application in the context of MAMCA.

Suppose a MAMCA procedure is applied with the PROMETHEE method. We assume the decision process includes q stakeholder groups $\mathscr{S} = \{s_1, s_2, s_3, \ldots, s_q\}$. Each of them has his own set of weights and is assumed to accept small changes on these values. Let us consider stakeholder group s_p with $p \in \{1, \ldots, q\}$. This stakeholder group considers m_p criteria. The set of initial weights is denoted $\mathscr{W}_p = \left\{w_{1,p}, w_{2,p}, w_{3,p}, \ldots, w_{m_p,p}\right\}$, while the new set of weights is denoted $\mathscr{W'}_p = \left\{w'_{1,p}, w'_{2,p}, w'_{3,p}, \ldots, w'_{m_p,p}\right\}$.

The problem for reaching a consensus can be formulated as follows: “What would be the minimum weight modifications to be applied to all stakeholder groups such that a common alternative becomes first in the ranking of all stakeholder groups simultaneously?”

For a given stakeholder group s_p, the decision variables are the new weights $w'_{k,p}$. The objective is to minimize the sum of distances of these new weights compared to the initial ones:

$$\sum_{k=1}^{m_p} \left| w_{k,p} - w'_{k,p} \right| \tag{6.14}$$

In order to linearize the absolute value, two other sets of variables for each stakeholder group s_p are defined:

- $\mathscr{D}_{1,p} = \left\{d_{1,1,p}, d_{2,1,p}, \ldots, d_{m,1,p}\right\}$
- $\mathscr{D}_{2,p} = \left\{d_{1,2,p}, d_{2,2,p}, \ldots, d_{m_p,2,p}\right\}$

such that, $\forall p \in \{1, \ldots, q\}; \forall k \in \left\{1, 2, \ldots, m_p\right\}$:

$$w_{k,p} - w'_{k,p} = \begin{cases} d_{k,1,p} & \text{if } w_k - w'_k \geq 0 \\ -d_{k,2,p} & \text{otherwise} \end{cases}, \quad d_{k,1,p}, d_{k,2,p} \geq 0 \tag{6.15}$$

$d_{k,1,p}$ (resp. $d_{k,2,p}$) is equal to $w_{k,p} - w'_{k,p}$ (resp. $-(w_{k,p} - w'_{k,p})$) if this difference is positive (resp. negative), and $d_{k,2,p}$ (resp. $d_{k,1,p}$) is equal to 0.

In order to introduce a constraint on the number of allowed modified criteria, the set $\Gamma_p = \{\gamma_{1,p}, \gamma_{2,p}, \ldots, \gamma_{m,p}\}$ is also introduced such that, $\forall p \in \{1,\ldots,q\}; \forall k \in \{1,2,\ldots,m_p\}$:

$$\gamma_{k,p} = \begin{cases} 0 & \text{if } d_{k,1,p} + d_{k,2,p} = 0 \\ 1 & \text{otherwise} \end{cases}, \quad \gamma_{k,p} \in \{0,1\} \tag{6.16}$$

$\gamma_{k,p}$ indicates whether a weight is modified and will serve to count the number of modified weights. In this context, it is important to note that very low value differences (from instance resulting from computation approximations) should not be considered as realistic weight modifications. Therefore, $\gamma_{k,p}$ might be considered to be equal to 1 if the weight difference exceeds a *small* positive threshold, denoted τ, that is set by the Decision Maker.

The constants of the problem are:

- the set of the m_p initial weights of each stakeholder group s_p for the criteria: $\mathscr{W}_p = \{w_{1,p}, w_{2,p}, \ldots, w_{m_p,p}\}$;
- the uni-criterion net flow scores table;
- M, an arbitrary constant so that $M \geq \frac{1}{d_{k,1,p}+d_{k,2,p}}$, $\forall p \in \{1,\ldots,q\}, \forall k \in \{1,2,\ldots,m_p\}$;
- $N_p \in \{2,3,\ldots,m\}$, a constant for the constraint on the number of modified criteria for each stakeholder group s_p.

The MILP model can then be formalized as follows:

$$\min z = \sum_{k=1}^{m_p} \left| w_{k,p} - w'_{k,p} \right| = \sum_{k=1}^{m_p} (d_{k,1,p} + d_{k,2,p}) \tag{6.17}$$

s.t.

$$\sum_{k=1}^{m_p} w'_{k,p} = 1, \forall p = 1,2,\ldots,q \quad \text{(weights constraint)} \tag{6.18}$$

$$w_{k,p} - w'_{k,p} = d_{k,1,p} - d_{k,2,p}, ,\forall p \in \{1,\ldots,q\}, \forall k \in \left\{1,2,\ldots,m_p\right\} \tag{6.19}$$

$$\gamma_{k,p} \geq d_{k,1,p} + d_{k,2,p} - \tau,\ \forall p \in \{1,\ldots,q\},\ \ \forall k \in \left\{1,2,\ldots,m_p\right\} \quad \text{(number of modified criteria)} \tag{6.20}$$

$$\gamma_{k,p} \leq M(d_{k,1,p} + d_{k,2,p}), \forall p \in \{1,\ldots,q\}, \forall k \in \left\{1,2,\ldots,m_p\right\} \tag{6.21}$$

$$\sum_{k=1}^{m_p} \gamma_{k,p} \leq N_p, \forall p \in \{1,\ldots,q\} \quad (N_p \text{ allowed modified criteria}) \tag{6.22}$$

$$\phi'_p(a_i) = \sum_{k=1}^{m} w'_{k,p} \phi_{k,p}(a_i),\ \forall p \in \{1,\ldots,q\} \quad \text{(net flow scores computation)} \tag{6.23}$$

$$\phi'_p(a_i) > \phi'_p\left(a_j\right), \forall j \neq i; \forall p \in \{1,\ldots,q\} \quad \text{(rank change of } a_i\text{)} \tag{6.24}$$

$$w_{k,p}, d_{k,1,p}, d_{k,2,p} \geq 0, ,\ \forall p \in \{1,\ldots,q\}, \forall k \in \left\{1,2,\ldots,m_p\right\} \quad \text{(domain)} \tag{6.25}$$

$$\gamma_{k,p} \in \{0,1\}, \forall p \in \{1,\ldots,q\}, \forall k \in \left\{1,2,\ldots,m_p\right\} \tag{6.26}$$

6.4 Integration of the MILP in MAMCA to reach consensus

In practice, it is most of the time observed that different stakeholder groups have different rankings over the set of alternatives. In order to reach a consensus among them, we can investigate how the rank of a given alternative could be improved on the basis of “acceptable” modifications of criteria weights. In other words, the problem can be formulated as follows: “what would be the minimum weight modifications that should be accepted by the different stakeholder groups such that a common alternative would get a higher position in the different rankings”. Indeed, this would reinforce the possible consensus about this alternative for all stakeholder groups. In an ideal case, we could study the minimum weight modifications that should be imposed to the different stakeholder groups, in order to put a given alternative (simultaneously) at the first position for the individual rankings. Of course, the proposed weight modifications should remain “realistic”. In addition, let us note that such an ideal situation is not always possible.

To perform this analysis, we will solve the MILP for each stakeholder group individually and for all the alternatives. For the sake of simplicity, let us consider the case of alternative a_i and stakeholder group s_p. First, we need to define new binary variables denoted r_j^p as follows:

$$\phi'_p(a_i) - \ \phi'_p\left(a_j\right) \ \leq M.\ r_j^p \tag{6.27}$$

$$\phi'_p\left(a_j\right) - \ \phi'_p(a_i) \ \leq M.\ (1 - r_j^p) \tag{6.28}$$

In other words, r_j^p indicates whether alternative a_i has a higher net flow score, i.e., a better rank than alternative a_j in the modified ranking. We want to find the minimum weight modification that will lead alternative a_i to reach position g in the modified ranking for stakeholder group s_p. First, we will run the MILP for each stakeholder group individually and for all the alternatives. Therefore, constraint (6.24) has to be changed to:

$$\sum_{j=1, j\neq i}^{n} r_j^p = n - g, \forall g = 1, 2, \ldots, n-1 \tag{6.29}$$

Once this has been computed for all stakeholder groups, for all alternatives and for all possible ranking improvements (let us note that some of them might be impossible) one has to identify alternatives that might be considered as good consensus candidates. To do that, we have to consider two conflicting objectives:

- the weight modifications of all stakeholder groups which have to be as limited as possible;
- the ranking positions for all stakeholder groups which have to be as good as possible.

Of course, there are numerous ways to quantify these objectives. To keep it simple, we consider, for each option, the sum of weight modifications for a given total ranking improvement (among all stakeholder groups). Each alternative will thus be evaluated as a set of performances on these two objectives. Our hope is then to identify one or a limited number of alternatives such that their evaluation in this bi-objective space will, together, dominate all the performances of the other alternatives. Finally, let us note that, as a pre-processing step, one can limit the individual criteria weight modifications to limit unacceptable modifications. This has to be discussed with the different stakeholder groups beforehand.

The proposed method will be illustrated on two real case studies in next section.

6.5 Case study

To show the advantage of the MILP model combined with MAMCA, two cases of the CITYLAB project are tested. The objectives of CITYLAB project were to “develop knowledge and solutions that result in the roll-out, up-scaling and further implementation of cost effective strategies, measures and tools for emission free city logistics”. As the rising populations and densities of cities will produce such an increase in freight transportation that the economic and environmental sustainability will no longer be guaranteed. This, in turn, will endanger the future growth potential of European cities [283]. CITYLAB looks for cost-effective and sustainable solutions that can decrease the negative traffic and environmental impacts from goods, waste and service trips in urban areas. The project is applied in different cities with different contexts of transportation. The labs apply public and private measures contributing to increased efficiency and sustainable urban logistics. [1]

For the following two cases, the same alternatives were carried out to evaluate. Table 6.1 lists the evaluated alternatives and the advantages comparing to the base line, business as usual. stakeholder group meetings were held in the CITYLAB cities to test out the CITYLAB solutions. They were asked to allocate weights for different criteria and to evaluate the alternatives based on these criteria. During the evaluation phase, MAMCA was used as the interactive tool to evaluate alternatives and visualize the result.

Table 6.1: Evaluated alternatives

Alternative	Pros
E-freight bikes and micro-hubs	Reduction of emission, decrease of overall operating cost
Online shop and use of spare capacity	Possibility of use spare transport capacity, no additional kilometres
Last-mile carrier and electric vans	Reduction of distance and energy, empty distance reduction
Common logistics in shopping centre	Reduction of dwell times for delivery vehicles, fewer individual transport inside the shopping centre, satisfied store employees, better waste handling
Urban warehouse and electric vans (25%)	Reduction of emission, vehicle kilometre saving
Integrated reverse logistics	Reduction of total vehicle kilometres and emission, financial viability

Five stakeholder group groups were involved in the local stakeholder meeting, each stakeholder group had different criteria for evaluation, which can be found in Table 6.2. Based on Table 6.1 it can be foreseen that different stakeholder groups will be in favor of different alternatives which meet their own interests and priorities, even though the alternatives are all proposed towards sustainability. Then, MILP model can be applied in the decision-making process to help the stakeholder groups to reach the consensus.

6.5.1 Case Oslo

The original first ranked alternatives for the stakeholder groups in case Oslo are listed in Table 6.3. Figure 6.1 illustrates the Multi-Actor view for this case (which is generated by the MAMCA software). It can be noted that different alternatives are ranked first for different stakeholder groups. The alternative “Common logistics in shopping centre” ranks well among all the stakeholder groups except for the group “Receiver”. Meanwhile, alternatives like “E-freight bikes and microhubs” are ranked well in one stakeholder group but badly in another. As a consequence, it is hard to reach consensus based on the conventional Multi-Actor Analysis.

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[1] For more information, please visit: `http://www.citylab-project.eu/`

Table 6.2: Criteria of different stakeholder groups

Stakeholder group	Criteria
Receiver	Positive effect on society, low cost for receiving goods, high quality deliveries, attractive shopping environment
Shipper	Positive effect on society, high quality deliveries, low cost for transport, high quality pick-ups
Shopping centre owner	Financial viability, attractive shopping environment, high quality service
Society	Fluent traffic, attractive shopping environment, air quality, road safety, low exposure to noise
Transport operator	Viable investment, positive effect on society, satisfied employees, profitable operations, high quality service

Table 6.3: Original first ranked alternative and weights for stakeholder groups in case Oslo

Stakeholder group	Original weight allocation	Original first ranked alternative
Shipper	[0.0944, 0.0702, 0.5826, 0.2528]	Integrated reverse logistics
Shopping centre owner	[0.3333, 0.3333, 0.3333]	Common logistics in shopping centre
Receiver	[0.0673, 0.0367, 0.1745, 0.7215]	E-freight bikes and micro-hubs
Society	[0.0919, 0.6209, 0.1809, 0.0238, 0.0825]	Last-mile carrier and electric vans
Transport operator	[0.1738, 0.0691, 0.1496, 0.0338, 0.5737]	Common logistics in shopping centre

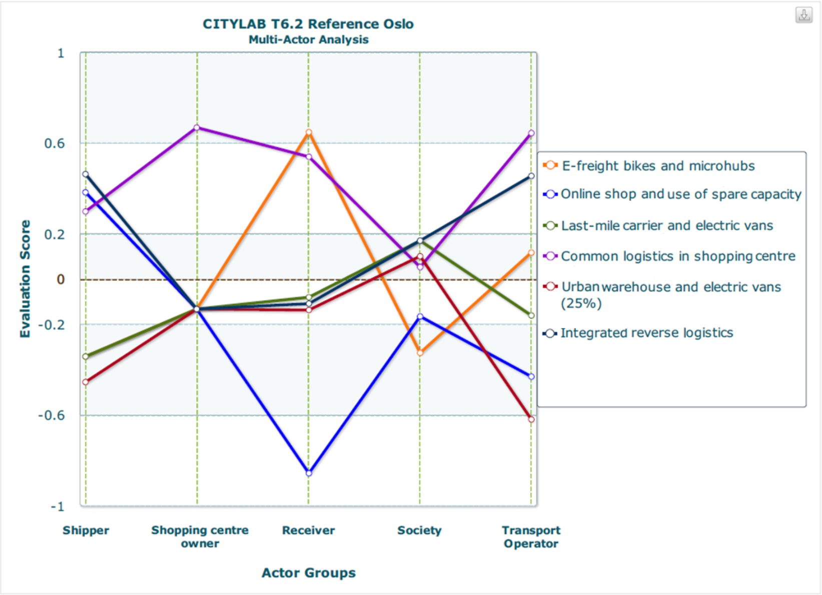

Figure 6.1: Multi-Actor View in case Oslo

Therefore, the MILP model is applied and the weight modifications for alternatives rank at different positions among all stakeholder groups are computed. A new indicator called *rank distance* $o = g - 1$ is calculated (i.e. a rank distance is equal to 0 when the alternative's rank is equal to 1). Then, the sum of the weight modifications from all stakeholder groups of one alternative, denoted Z, along with the corresponding sum of new rank distances O is obtained. Table 6.4 lists the results of alternative "E-freight bikes and micro-hubs" as an example, it indicates every change of rank of the alternative. z_1, z_2, z_3, z_4, z_5 are the weight modifications of 5 stakeholder groups, which lead to the changes of the ranking, i.e the rank distances o_1, o_2, o_3, o_4, o_5. The sum of the weight modifications Z and rank distances O of every change are also listed.

Table 6.4: MILP model result of alternative 'E-freight bikes and micro-hubs'

	z_1	z_2	z_3	z_4	z_5	o_1	o_2	o_3	o_4	o_5	Z	O
1	0	0	0	0	0	0	1	2	3	5	0	11
2	0	0	0	0	0.1	0	1	2	3	4	0.1	10
3	0	0	0.306	0	0.1	0	1	1	3	4	0.406	9
4	0	0	0.306	0	0.315	0	1	1	3	3	0.621	8
5	0	0	0.306	0.354	0	0	1	1	2	3	0.66	7
6	0	0.409	0.306	0	0	0	0	1	1	3	0.715	5
7	0	0.409	0.306	0	0.453	0	0	1	1	2	1.168	4
8	0	0.409	0.602	0	0.453	0	0	0	1	2	1.464	3
9	0	0.409	0.602	0	0.643	0	0	0	1	1	1.654	2
10	0	0.409	0.602	0.902	0	0	0	0	0	1	1.913	1
11	0	0.409	0.602	0.902	1.333	0	0	0	0	0	3.246	0

To find the possible consensual solution of the case, Pareto-efficient solutions are found by treating the results as a set of unsorted data [284]. Figure 6.2 shows the full result of case Oslo. Y-axis represents the rank distances of all the alternatives; And the X-axis represents the weight distances, which are the sum of the modified weights from stakeholder groups of alternatives. The lines with markers illustrate the rank changes of the alternatives with the weight modification. The gray semi-transparent line is the Pareto frontier connected by the Pareto optimal solutions.

It is observed that all alternatives except "Urban warehouse and electric vans (25%)" can rank first among all stakeholder groups in the end but with different weight modifications, i.e. Z. Alternative "Common logistics in shopping centre" and "Integrated reverse logistics" both cover part of the Pareto optimal solutions. While "Integrated reverse logistics" ranks well originally before weight modification, "Common logistics in shopping centre" can rank first with smaller weight modification. Thus, these two alternatives are selected as consensus options. The facilitator is invited to work on these two options to reach a final decision among the different stakeholder groups.

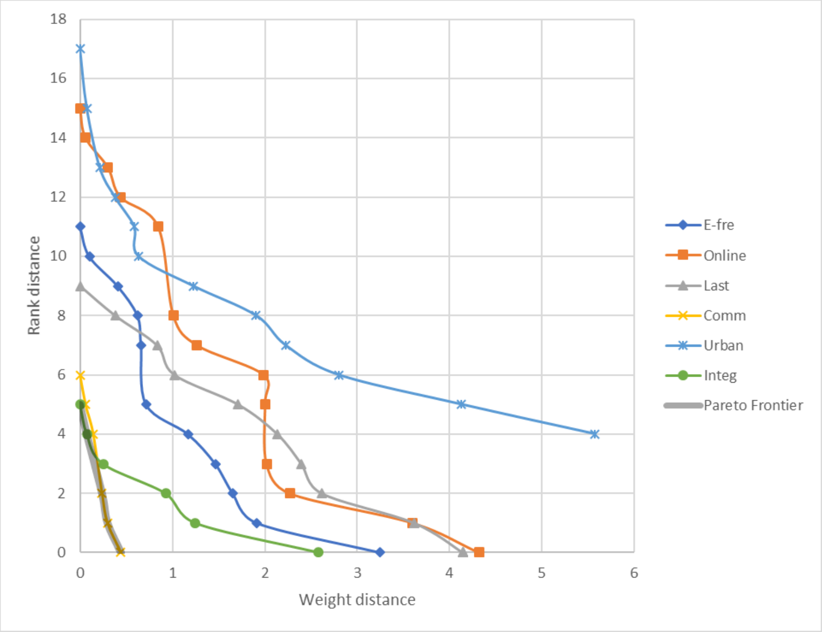

Figure 6.2: MILP result of case Oslo

6.5.2 Case Brussels

During the local stakeholder meeting in Brussels, the representatives of stakeholder group "Shopping centre owner" did not attend, which is why the analysis for this stakeholder group is taken from CITYLAB D5.4. The original first ranked alternatives and weights are listed in Table 6.5.

Table 6.5: Original first ranked alternative and weights for stakeholder groups in case Brussels

Stakeholder group	Original weight allocation	Original first ranked alternative
Receiver	[0.3890, 0.0434, 0.389, 0.1786]	Online shop and use of spare capacity
Shipper	[0.0420, 0.5353, 0.2584, 0.1643]	Online shop and use of spare capacity
Shopping centre owner	[0.4100, 0.4100, 0.1800]	Common logistics in shopping centre
Society	[0.1464, 0.1100, 0.4713, 0.1319, 0.1404]	E-freight bikes and micro-hubs
Transport operator	[0.053, 0.0799, 0.3668, 0.3672, 0.1331]	Online shop and use of spare capacity

The case of Brussels is more complex than that of Oslo. Based on Figure 6.3, it is observed that "Online shop and use of spare capacity" ranked first among three stakeholder groups, though it is ranked in the last two positions among the other two stakeholder groups; unlike the alternative "Common logistics in shopping centre" in the case Oslo which is ranked as a good option in general. Furthermore, other alternatives also obtained good results among different stakeholder groups.

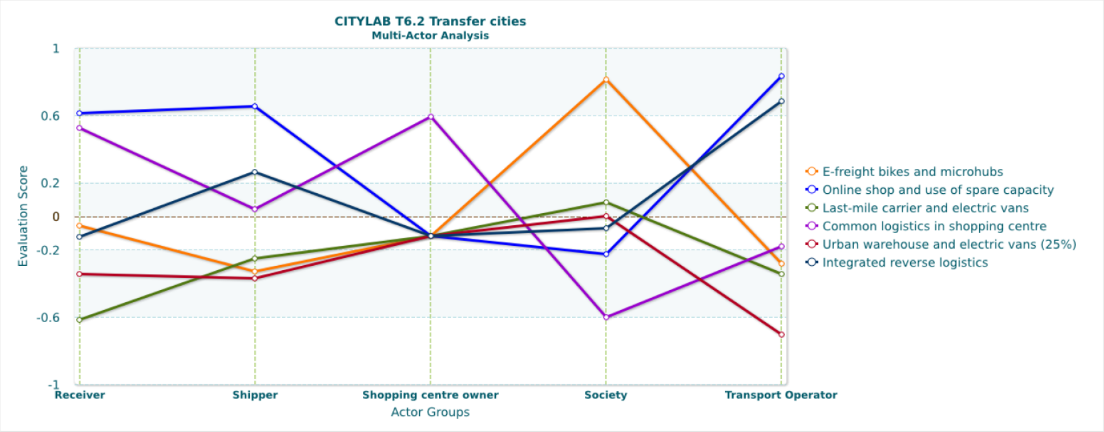

Figure 6.3: Multi-Actor View in case Brussels

Figure 6.4 shows the full MILP result of case Brussels. The alternative "E-freight bikes and micro-hubs" is the only alternative that can rank first among all the stakeholder groups. However, a large weight modification is required. On the other hand, the results of "Online shop and use of spare capacity" are covered by part of the Pareto frontier. This alternative can be viewed as a good consensus solution.

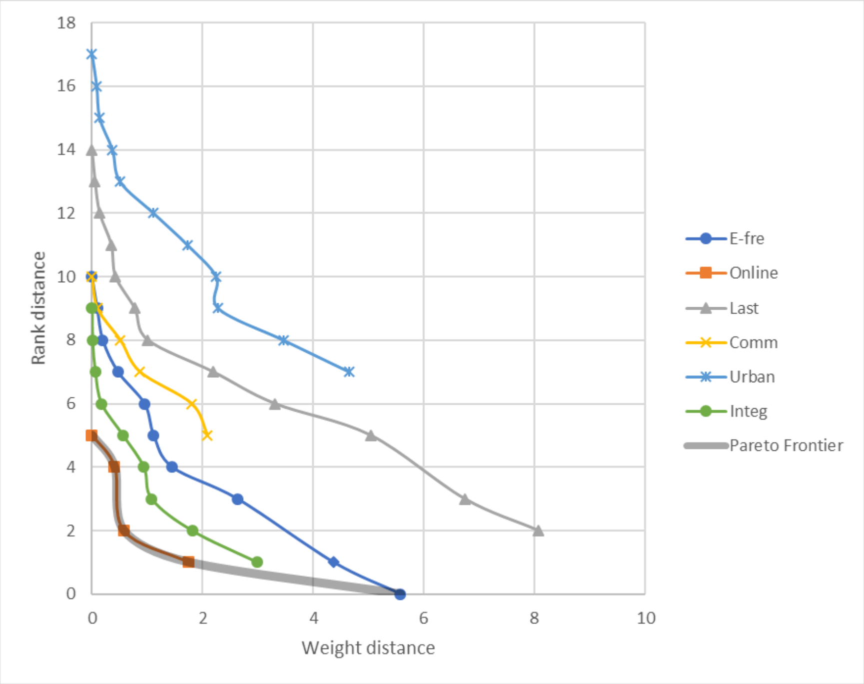

Figure 6.4: MILP result of case Brussels

6.6 Limitations and future work

In the MAMCA methodology, all stakeholder groups are treated equally (i.e. no weights are assigned in order to give priority to some of them). We decided to evaluate the different alternatives by evaluating them according to the sum of weight modifications and the sum of ranking improvements. These indicators were selected because they are easy to understand and so to communicate with the different stakeholder groups. Of course, this implies compensatory effects leading to situations where one or several stakeholder groups should accept more and/or stronger modifications than others. As a consequence, alternative indices could also be investigated. For instance, one could consider indicators that reinforce fairness among the stakeholder groups. This could be done by adding an objective that will limit the weight deviation efforts among all stakeholder groups, or adding constraints to limit the possible weight modifications. For example, a stakeholder group should only be allowed to modify an identical maximum modification value; or the weight of the modification should retain certain information provided by participants, e.g., the importance level of the criteria remains in the same order. From a more general perspective, it could also be interesting to build additional indicators to evaluate the complexity to reach a consensus for a given situation.

This consensus reaching model aims to reach a soft consensus featuring minimum weight modifications [285]. In the case used in this study, the weights of the criteria for the stakeholder groups are elicited through pairwise comparison. However, the weight elicitation methods can be various, especially there are some existing elicitation methods with ambiguous information [286] [287] [288] (A systematic review can be found in [243]). These methods allow the participants to only provide ambiguous information, e.g., the ordinal information, which eases the process of participants but also leaves uncertainty for further analysis. This consensus reaching model can be further developed by leveraging ambiguous preference information in order to promote consensus in group-decision context.

6.7 Conclusion

Finding a sustainable solution normally requires a compromise of the different needs and interests from different stakeholder groups. The MAMCA methodology can include multiple stakeholder groups in the process of evaluation and decision making. However, it is sometimes difficult to reach a consensus among all the stakeholder groups simultaneously for certain projects. By applying the MILP model into the MAMCA methodology, it can be easier for the decision-maker or the analyst to find one or a limited set of possible candidates to reach a consensus solution. By taking the inverse optimization point of view, one can find the smallest modification of weight allocations for one alternative and for all stakeholder groups to converge to a common acceptable solution.

The outcome of MILP model is illustrated in the two MAMCA case studies of CITYLAB. CITYLAB cases reveal the fact that even though the proposed options are all toward sustainable mobility, different stakeholder groups rank the alternatives differently as they hold their own interests and priorities. With the help of the model, we can limit the set of good options to 1 or 2 alternatives. This will help analysts to focus their work on these options but also give (visual) arguments that could be communicated to the stakeholder groups in order to reach a consensus. Finally, by presenting the results as the Pareto optimal solutions of a bi-objective optimization problem, we think we leave room for discussions (instead of imposing a unique candidate for the consensus).

Chapter 7

Conclusion and future work

7.1 General conclusions

For the first sentence of the first chapter, I ask one question: ‘Is there a policy where no one complains?’ And in the conclusion of this dissertation, I respond: ‘There is hardly a policy that everyone is happy with.’ Indeed, the fact is that the public has different issues to focus on, and one policy cannot satisfy everyone. However, the public always tries to express their opinions [289]. When they can’t find a channel, they create one, so that mass demonstrations occur [290]. Therefore, I suggest to create a voice channel for general public to express their preferences in the decision-making process. Because they are the stakeholders of the problem, they influence or are influenced by the decisions that are made. By allowing the public to express opinions in the decision-making process, policymakers can learn what stakeholders really want. I call this mass-participation decision-making. It is a win-win solution where policymakers are more likely to adopt solutions that the public prefer, and the general public can express their needs. Furthermore, it is a process that can contribute to facilitating sustainable development. By involving the views of the public from different backgrounds, a bigger vision can be broadened to seek solutions. Different social, environmental, economic aspects are more likely to be taken into account, even though they may not be in the mainstream. Mass participation facilitates the process to capture these voices. This is **why** mass-participation is needed.

Researchers have found limitations of conventional group decision-making, where one or several representatives of the general public are selected to express their opinions in the decision-making process. It is questionable that these representatives will be able to defend the interests of their group. Thus, they proposed several mass-participation frameworks [101, 119–123, 125, 129–132]. They distribute surveys to collect opinions from the general public, allowing them to express their preferences. But mass can also mean chaos. Surveys provide limited information on the problems, and the assessment of alternatives in decision-making requires expertise. If participants are not familiar with decision-making techniques, they risk making incorrect assessments. They might be unsure of the performance of alternatives based on different criteria, so their choices may not represent their true preferences.

I argue that mass-participation is necessary for social decision-making problem, as it can provide a channel for the general public to express their opinions. However, inappropriate procedures in mass-participation decision-making frameworks can increase costs, operational difficulties, and lead to inaccurate decisions. Therefore, in this dissertation, I raise the following research problem:‘ **How** can mass participation be integrated in MCGDM?’ To address this research problem, I propose a new mass-participation framework and explore the integration of the mass participation concept into the multi-actor multi-criteria analysis (MAMCA). The proposed framework can be seen as a compromise solution that combines the conventional group decision-making frameworks with the previous form of mass participation frameworks. In this novel framework, the facilitators distribute surveys to ask participants’ priorities, but do not ask them to assess alternatives. Based on their priorities, a clustering analysis is performed to cluster subgroups. The representatives are identified and invited to a workshop. In the workshop, they assess the alternatives together with other stakeholder groups under the guidance of facilitators. The facilitators can help representatives to better understand the problem structure, their needs, and what they want. The representatives can further discuss their results. They are able to know what the preferences of others and share empathy, which facilitate a compromise solution. In this way, a voice channel is open, the general public is able to express their opinions. And the representatives selected among them can arguably defend their interests. And the process is easier to manage, the risk of wrong decision decreases.

This dissertation discusses about **how** can mass participation be integrated in MCGDM. In the following subsection, I present the contributions of this dissertation to address the research problem.

7.1.1 Key outputs

The core of the dissertation is the proposal for mass participation in MAMCA. In MAMCA, the current practice of evaluation of one stakeholder group is obtained by inviting one or several representatives to a workshop. However, it is questionable whether the representatives can indeed ‘represent’ the points of view of the entire group. Additionally, the citizen group might have diverse priorities because of different factors such as socioeconomic statuses (SES). Therefore, more voices from the group need to be heard so that the views from minority groups are not missed. However, involving more participants in the decision-making process is not always a good idea because of the extra time costs and possible controversies [291]. In this dissertation, I proposed a novel mass-participation decision-making process to facilitate the search for a compromise solution. It aims to foster legibility and transparency in the decision-making process while reducing the cost and operational difficulties. Thanks to the mass-participation framework, MAMCA can help solve decision-making problems that involve a large number of participants.

The contributions of this dissertation can be categorized into two parts: theoretical contributions and practical contributions. For the theoretical contributions, I propose different methodologies to facilitate the mass-participation decision-making process. For the practical contributions, I developed new MAMCA software that can serve the mass-participation decision-making process.

Theoretical contributions

This dissertation proposes a mass-participation concept for decision-making. In order to provide a more legible and transparent process by involving more participants in the decision-making process. It is aimed to solve problems related to the involvement of mass-participation stakeholder groups. This type of group consists of a number of participants who can statistically represent the group's entire population's interests, priorities, and preferences. The mass-participation framework is integrated into MAMCA, which is a MCGDM framework. The procedure is similar to the conventional MAMCA procedure, but there are some additional steps: I present a formal approach for selecting representatives for the mass-participation stakeholder group. These extra steps are designed to better solicit opinions of participants while not increasing the problem's complexity. I propose to first distribute a survey to participants to identify their criteria priorities. If the participants hold divergent priorities, I developed a clustering algorithm to cluster the participants into subgroups. Following the clustering, several participants can be identified as representatives. They are invited to a MAMCA workshop to elicit weight and evaluate alternative as conventional MAMCA. I argue that those extra steps above can help address the third representation question: 'Can the selected representatives defend the interests of the stakeholder groups?' Furthermore, I argue that the proposed mass-participation framework is a more adequate way for certain problems. In contrast to other mass-participation decision-making frameworks, participants are only asked to rank the criteria, which is a more subjective evaluation in decision-making. The facilitators do not ask them to elicit the weight or assess the performance of alternatives because doing so would require more extensive information about the problems and more knowledge about the decision-making methods. Without guidance, the participants may misrepresent their preferences. Inviting representatives to workshops, rather than conducting the entire decision-making process through surveys, can better guide participants and reduce the risk of misassessment.

In addition, I present a criteria pre-processing framework and consensus-reaching model, which are not only integrated in the mass-participation MAMCA framework but can also be used in conventional MAMCA and other MCGDM frameworks. The criteria pre-processing framework helps the facilitators identify the criteria set for stakeholder groups by taking into account the priorities of the stakeholders. It maintains a reasonable number of criteria for the evaluation, and leaves some flexibility for the facilitator to choose. By inviting participants to select criteria for their own groups, the trust of the participants can be gained and the decision-making process is more transparent [100]. This approach also helps address the second representation problem: 'To what extent do the selected criteria represent the interests of the stakeholder groups?' The consensus-reaching model can help decision-makers find potential compromise solutions. Often, a sensitivity analysis is performed in decision-making to assess the robustness of selected solutions. However, in MCGDM problems, different stakeholder groups may have different preferred solutions. By using an inverse mixed-integer linear optimization on weight sensitivity analysis, this model can assist stakeholder groups in finding compromises. The model also provides visual arguments that could be communicated to stakeholder groups to help reach a consensus.

Practical contributions

The proposed mass participation tool is facilitated by the newly developed MAMCA software. It was developed in a new software stack with more than 20,000 lines of code (see the software development metrics in Table. 7.1). This software follows the evaluation structures of the methodology with a user interface that aims to improve the interaction experience between participants. The proposed participation method guides stakeholders and project facilitators in using the MAMCA software. The multi-actor view, sensitivity analysis and box plots of weight allocations within the stakeholder groups can help stakeholders achieve a better understanding of the influence of their behaviors and preferences. The new data structure makes mass participation possible. To collect the data from the members of the mass participation stakeholder groups, a survey tool is developed and integrated into the new MAMCA software. The survey tool helps facilitators reach the participants of the groups and receive evaluations from them asynchronously. The participants can express their opinions through the survey so that the different points of view in the mass participation stakeholder groups are not neglected. The survey allows exploring the details of stakeholder groups and investigating the homogeneity and heterogeneity of groups. Currently, 889 users have used the new MAMCA software and 569 MAMCA projects have been created. Since the release of the MAMCA survey tool, it has helped several users to manage the survey results, with the largest questionnaire having 130 participants.

Table 7.1: Software development metrics

language	files	code	comment	blank	total
JavaScript	69	23,510	1,972	1,655	27,137
CSS	32	327	77	49	453
JSON	10	122	0	3	125
XML	5	120	2	5	127
HTML	1	22	23	1	46

The new MAMCA software has become an interactive tool to support the evaluation of MAMCA in different areas, such as transportation [212], energy [213, 292], and logistics [220]. The MAMCA software also has educational uses. When students use MAMCA, they can play the role of stakeholders and learn to be cautious about the possible impact of a biased view.

7.2 Limitations and future work

This dissertation proposes a mass-participation decision-making framework and related methodologies, and presents a mass participation tool facilitated by MAMCA software. However, no mass participation decision-making case has been applied to its full extent. In Chapter 5, the studied case meets the requirement of mass participation. However, the subsequent decision-making process has not been fully completed. In the future, this mass-participation decision-making framework is recommended to be tested on a real case. Furthermore, to facilitate the mass-participation decision-making process, in this section, I point out several limitations that are identified when using mass participation tools to support decision-making problems. The limitations are categorized into two parts: methodological limitations and real-life limitations.

7.2.1 Methodological limitations

Limited criteria weight elicitation and alternative performance assessment methods

MAMCA software provides an interactive tool for solving decision-making problems. The flexibility of the tool is reflected in the ability to choose different weight elicitation methods and MCDM methods for performance assessment of the alternatives. However, the number of methods available in the software is limited. In the future, more elicitation and assessment methods could be integrated into the software. Doing so could help the facilitator to select appropriate methods for different situations.

In the software, the AHP weight elicitation method is available. This method utilizes a scale ranging from -9 to 9 for the evaluators to compare the importance levels of the criteria in a pairwise way. This is arguably an easy-to-understand method for evaluators, but the numbers in the scales can have very different meanings for different people, which may lead to the assignment of different numerical probabilities to the same importance level [293]. Furthermore, pairwise comparison requires more comparisons among criteria, which can lead to inconsistency [294]. To cope with different situations, other weighting excitation methods should be integrated into the software, e.g., direct rating (DR), point allocation (PA) [295], SWING [296], and the trade-off method [297].

Of the MCDM methods, only SMART and AHP are integrated into the software. These methods can serve for evaluating alternatives based on qualitative-scale criteria. However, when the alternatives need to be evaluated based on quantitative data, they may provide an inaccurate result. Therefore, other MCDM methods should be integrated into the software to adapt to various contexts, e.g., ELECTRE [298], the best-worst method (BWM) [299], and PROMETHEE [192].

Need for a criteria pre-processing framework for hierarchical criteria structures

In Chapter 4, I propose the criteria pre-processing framework that help facilitators to select criteria for the stakeholder groups by soliciting opinions from the participants. The framework can only be used for a flat criteria structure; a framework to handle hierarchical criteria structures has not been developed. When the problem becomes more complex, however, a hierarchical structure for the criteria is needed. The hierarchical structure can ease the process for calculating the weights of criteria [224, 225]. And the way to select criteria in a hierarchical structure can be various. The current process is done by cutting down the list based on the magic numbers and Pareto analysis. It is also feasible by regrouping the criteria under an ‘umbrella criterion’ in a hierarchical structure. In the future, a pre-processing framework that addresses hierarchical criteria structure problems can be developed.

Need for a new approach to aggregate the scores of members in a stakeholder group

The stakeholder clustering algorithm can cluster mass-participation stakeholder groups into subgroups based on the participants’ priorities. It can identify the representatives of the subgroups who should be invited to the MAMCA evaluation process. The conventional way in which to aggregate the stakeholders’ assessment scores is to simply sum the scores and obtain the arithmetic mean. However, this may not be the best solution for highlighting the preferences of different subgroups and may lead to a ranking in which where individual extremes mutually compensate because of aggregation. It is valuable to investigate the consistency and inconsistency of the assessment scores from the representatives and search for a compromise solution within the mass participation stakeholder group.

Improve the clustering algorithm

In this dissertation, I argue that the priorities of criteria play a more important role in identifying the representatives of stakeholder groups. However, SES is still an important factor with which to partition participants [300]. It is questionable whether selected representatives are the same based solely on their priorities of criteria or their SESs. As a result, a two-layer network can be built to investigate the connection between these. It is possible to improve the clustering algorithm by taking into account the two previously mentioned factors.

A possibility to enrich the data visualization

The visualization of data is an important feature of a decision-making tool, particularly for an MCGDM problem. Because clear and legible data visualization can help participants to better understand the decision-making process and result [301]. A good sensitivity analysis chart, for example, can make it easier for facilitators to assess the robustness of the performance of different alternatives. The multi-actor view is an example of a simple and clear view that can illustrate stakeholder preferences. However, these charts in the MAMCA software can be improved. Other types of data visualization can also be integrated into the software.

Enhance the robustness of decision support and provide a complete validation process

The current mass participation tool provides a more static decision support where the criteria weights, alternatives assessment scores are recorded and analyzed in a non-dynamic manner. However, the decision-making process always comes with different uncertainties [302]. In many practical situations, human judgment is uncertain and may be reluctant or unable to specify exact values regarding criteria weight elicitation and alternative appraisal [303–305]. It is interesting and valuable to further develop the mass-participation decision-making framework in a uncertain context. And robustness analysis should be performed to validate the stability of the results, i.e., the resistance of the changes without altering its initial stable setting [306]. The results of the mass participation tool should also be validated of its robustness in the face of time-varying uncertainties.

On the other hand, in different steps of the framework there can be multiple rounds validation. As mentioned in the previous chapters, the selection of the criteria for different stakeholder groups can be validated by the participants; the clustered results of the mass-participation stakeholder groups also needs to be validated; finally, the selected solutions should be also verified by the stakeholder groups. These multiple rounds of validation can facilitate decision support results that meet the preferences of the participants.

Explore other forms of mass-participation in MAMCA

The mass participation tool makes it possible to involve more participants in the decision-making process. In mass-participation decision-making groups, the priorities and interests of subgroups' representatives can be various. But the priorities and interests of representatives from different stakeholder groups may be similar. It is questionable whether it is still appropriate to identify the stakeholder group first in a mass participation decision problem. It is possible to find another way to identify the groups of participants.

In the future, I argue to propose a novel framework to fit the context of mass-participation decision-making. Unlike normal MAMCA, stakeholder analysis is not performed at the beginning of the process. Instead, a public criteria pool is defined by considering all the possible criteria that the stakeholders might think are relevant. Then, the participants are asked to weigh the importance levels of the criteria, i.e., rank the criteria. Based on the criteria ranking, the participants can be clustered into different groups based on their priorities. Afterwards, participants in groups weight the criteria and assess the alternatives like a conventional MAMCA. Then, the alternative rankings of the groups are revealed, and the final solution is sought.

A further development of the mass participation tool: a multi-information decision-support system in an uncertain world

Current mass participation tool aims to facilitate the decision-making process by soliciting opinions from more participants. While the information from the human judgements plays an important role, the other information should also be take in to account, e.g., the spatial information [307]. These collections of information can influence the performances of the alternatives in decision-making objectively in different areas, for example transportation planning [308, 309], supply chain management [310, 311], etc. The future direction of the mass participation tool could focus on leveraging all the information available in order to have a comprehensive assessment. One possible way is to extend it as a digital twin driven mass-participation decision-support system. With the help of digital twin, the system can understand the different states from the physical entities [312]. It provides various data for the assessment, and also allows for a real-time simulation [313]. The new decision support system should be able to leverage rich data to analyze uncertainty of the alternative performances and participants' preferences, and facilitate a dynamic decision-making process.

7.2.2 Real-life limitations

It is questionable if different voices from participants are truly heard through mass-participation decision-making

When the mass-participation framework is applied in real cases, several problems concerning human and societal aspects still arise:

1. In the construction logistics case (Chapter 5), I collected stakeholder information via a mass participation survey tool. However, the survey could only be completed via a QR code or web link. This caused an unbalanced survey result; most of the respondents had a higher education background because respondents with such a background are more willing to complete the online survey and more eager to express their opinions.

2. The criteria pre-processing framework selects the criteria that most members in one stakeholder group prefer but that may fail to satisfy several members who hold different priorities, i.e., the minority. This can lead to a non-comprehensive evaluation.

3. The stakeholder clustering algorithm can identify the representatives of the stakeholder groups who hold different priorities. However, it does not consider the

numbers of members in the subgroups. If the member numbers in different subgroups vary, this can lead to an implicit bias during the evaluation.

The aforementioned issues indicate that the proposed mass participation framework still needs improvement, as some opinions from the general public may be ignored. I have not established a channel through which all voices from the general public can be heard.

Mass-participation tool is a decision-support tool, but the results needs to go beyond numbers

Decision-support systems (DSSs), as the name suggests, are a class of computerized information systems that support decision-makers in finding solutions to real-life problems [314]. The objective is to solve the problems in a mathematical way [315]. With the rapid developments in artificial intelligence, such systems have been applied to many problems in the fields of clothing manufacturing [316], healthcare [317], property [318], stocks [319] that can be predicted by using computers [320], vehicle routing [321], etc. Computers can quickly provide solutions and make decisions.

However, when solving social decision-making problems, researchers again need to consult humans, because the opinions from the stakeholder groups need to be considered. The sociopolitical aspects of the decision processes should be taken into account as well [45]. In the process of solving such problems, human judgment is needed. For example, to elicit the criteria weights, the evaluators need to subjectively give scores based on their priorities. Evaluating the alternatives may require evaluation from on semantic scales when the criteria have values that are difficult to express in quantitative terms. Finally, when the best alternative is selected in the DSS based on the evaluations, the stakeholder groups may still be unsatisfied with the result. Reaching a consensus among them is also a problem. Thus, it is challenging for mathematical models to support and represent real-life MCGDM problems. It is difficult to capture power differences [44], cognitive biases [322], political dynamics [323], etc., in a mathematical model.

These factors are also challenges for the proposed mass participation tool. As mentioned in Chapter 2, the core of the mass participation tool, MAMCA, gives no weight to the stakeholder groups. It treats all the stakeholder groups equally and provides a multi-aspect result, i.e., the multi-actor view, instead of a final ranking of the alternatives that only indicates the 'best' option. It aims to reflect the preferences of different stakeholder groups. In this dissertation, the proposal of mass participation is to maximize the number of participants involved to create a channel to **truly listen** to the voice from the mass-participation groups. In the development of the mass participation tool, I also consider the aforementioned human factors and societal factors. The preprocessing framework considers the stakeholders' opinions when selecting criteria set for them. The stakeholder clustering algorithm aims to identify the representatives of the stakeholder group who can defend the interests of their members. The consensus-reaching model can find solutions that stakeholder groups may compromise on. I try to use these mathematical models in a better way to support real-life decision-making problems. The consensus model provides a set of solutions on which consensus can be reached among the stakeholder groups from the perspective of mathematics. However, the participants can argue for their interests, and discussions among stakeholder groups are still needed. The presented mass-participation tool aims to better support the decision-making process, but does not provide a final answer. However, the final result may still be the solutions recommended by the tool.

Therefore, in the mass-participation decision-making process, facilitators should be aware of the limitations and challenges of each step and always consider the human and societal aspects. They should encourage participants to express their preferences. Facilitators should always keep in mind that the mass participation tool is a decision-support tool, that its results are not just numbers, and it needs to go beyond numbers.

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Appendix A

List of publications

Publications which are submitted for review, or which are not listed in Scopus (such as poster presentations or publications in journals not listed in Scopus), are listed in grey.

Articles in scientific journals with an international referee system

1. Brusselaers, N., Huang, H., Macharis, C., & Mommens, K. (2023). A GPS-based approach to measure the environmental impact of construction-related HGV traffic on city level. Environmental Impact Assessment Review, 98, 106955.
2. Huang, H., De Smet, Y., Macharis, C., & Doan, N. A. V. (2021). Collaborative decision-making in sustainable mobility: identifying possible consensuses in the multi-actor multi-criteria analysis based on inverse mixed-integer linear optimization. International Journal of Sustainable Development & World Ecology, 28(1), 64-74.
3. Hadavi, S., Rai, H. B., Verlinde, S., Huang, H., Macharis, C., & Guns, T. (2020). Analyzing passenger and freight vehicle movements from automatic-Number plate recognition camera data. European Transport Research Review, 12(1), 1-17.

Interational conference papers

1. Huang, H., Mommens, K., Lebeau, P., & Macharis, C. (2021, May). The Multi-Actor Multi-Criteria Analysis (MAMCA) for Mass-Participation Decision Making. In International Conference on Decision Support System Technology (pp. 3-17). Springer, Cham.
2. Huang, H., Lebeau, P., & Macharis, C. (2020, May). The multi-actor multi-criteria analysis (MAMCA): new software and new visualizations. In International Conference on Decision Support System Technology (pp. 43-56). Springer, Cham.

International conference and symposium abstracts and/or posters

1. Huang, H., Te Boveldt, G., Macharis, C. (2022. July). A criteria pre-processing framework in the multi-actor multi-criteria analysis. In the 32^{nd} European Conference On Operational Research
2. Huang, H., Te Boveldt, G., Macharis, C. (2022. June). Priority-based multi-actor multi-criteria decision making. In 26^{th} International Conference on Multiple Criteria Decision Making.
3. Huang, H., Macharis, C. (2022, April). Involve multiple stakeholder groups to reach a sustainable consensus in mobility projects. In the 93^{rd} meeting of the EURO Working Group on Multiple Criteria Decision Aiding.
4. Huang, H., Macharis, C. (2021, August). Integrating socio-demographic profiles into multi-actor multi-criteria analysis: A case study on university COVID-19 policy evaluation. In 22^{nd} International Federation of Operational Research Societies
5. Huang, H., Macharis, C., De Smet, Y. (2021, July). Data visualization for reaching consensus in the Multi-Actor Multi-Criteria Analysis. In the 31^{st} European Conference On Operational Research
6. Huang, H., Macharis, C., De Smet, Y., & Doan Nguyen, A. V. (2019, June). A Method of Reaching Consensus with the Multi-Actor Multi-Criteria Analysis (MAMCA) methodology. In 25^{th} International Conference on Multiple Criteria Decision Making.