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Criteria preprocessing in multi-actor multi-criteria analysis

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Abstract

Multi-actor multi-criteria analysis is a group decision-making framework that allows multiple stakeholder groups to be involved in the decision-making process, facilitating the understanding of the points of consensus and conflict among the stakeholder groups. Carefully selecting suitable criteria is important as they illustrate the possibly divergent priorities of the respective stakeholder group, and overlooking important criteria can lead to erroneous outcomes. Furthermore, the number of criteria needs specific consideration, as a too large number poses problems for human cognition, but a too small number inaccurately represents the stakeholder's interest. In stakeholder groups with many members, such as those representing citizens, defining a criteria set is likely to be even more complicated. Currently, there is no formal guideline to assist facilitators in defining these criteria sets. In this paper, we propose a novel framework for criteria preprocessing with stakeholder involvement that includes a guideline for firstly selecting criteria into a tentative list and secondly selecting the final criteria set. It provides a procedure on how to determine criteria considering the priorities of stakeholder groups with regard to the context. As a final step, we propose a mathematical model for selecting a number of criteria that are both cognitively manageable and representative for the participants' priorities. Based on the principles of the Pareto analysis, as well as the cognitive judgment theory "magic number seven plus or minus two", a recommendation list of the criteria is generated. It prevents key criteria from being omitted while at the same time limiting the overall number of criteria. This framework is applied to a social decision-making case for construction logistics, and the results are compared with the conventional approach of criteria definition.

KEYWORDS
criteria-selection, multi-actor multi-criteria analysis, multi-criteria decision making, Pareto analysis

1 | INTRODUCTION

In operational research, when confronting two or more alternatives, multiple-criteria decision-making (MCDM) or multiple-criteria decision analysis (MCDA) is a commonly used method for evaluation (Zavadskas et al., 2014). In the process of MCDM, stakeholder involvement is increasingly considered important (Corrente, Greco, Kadziński, & Słowiński, 2013). An individual who is involved in the decision-making process that can influence or be influenced by the decision taken is called a stakeholder (Freeman, 2010). In particular applications, involving stakeholder groups is consider beneficial for the quality of the decisions (Beierle & Konisky, 2001). Also the influence of the different interest parties/groups on decision making is increased (Edelenbos & Klijn, 2006), and the decision maker can better understand the points of view of the stakeholder groups (Macharis et al., 2012). Various multi-criteria group decision-making (MCGDM) frameworks with the involvement of stakeholder groups have been developed (Te Boveldt et al., 2021), such as multi-actor multi-criteria

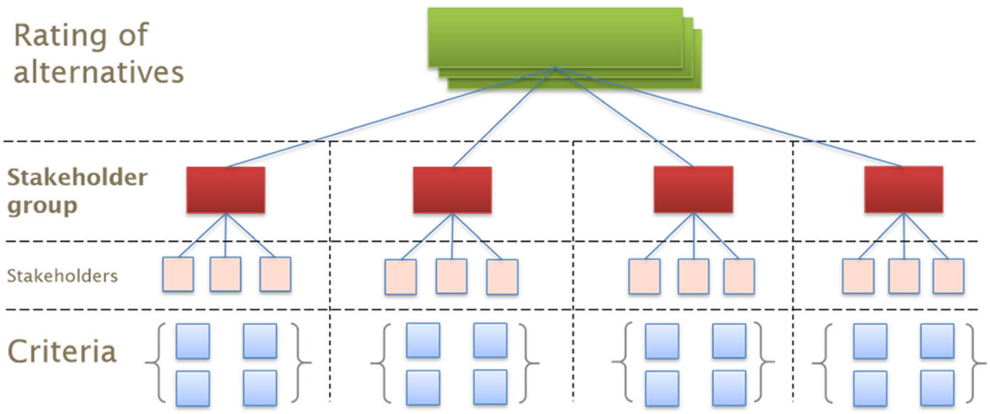

FIGURE 1 MAMCA structure (Huang, Mommens, et al., 2021) (te Boveldt et al., 2020).

analysis (MAMCA) (Macharis et al., 2009). It has been applied in various domains such as mobility and logistics to measure support from key stakeholder groups (Macharis et al., 2018; Macharis & Baudry, 2018). MAMCA can be used for involving stakeholders at an early stage, which can help facilitators identify alternatives and define criteria in their stakeholder groups (Huang et al., 2020).

In MAMCA, stakeholder groups can have different criteria sets to reflect their respective preferences (Macharis, 2005). 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 (Huang, Mommens, et al., 2021). In Figure 1, the MAMCA structure is illustrated. After defining the criteria, an MCDA process is applied for each participant, as the weight elicitation and alternative evaluation are executed individually (Hadavi et al., 2016). 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 (Macharis & Baudry, 2018). 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 (Lai & Hwang, 1992). Especially for a larger group, the participants' priorities and preferences are likely to be diverse, which makes the determination of criteria more difficult (Barber, 1981). 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 paper proposes a systematic criteria selection framework for MAMCA, which we call criteria preprocessing. 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 (Huang, Mommens, et al., 2021).

In the following section, the MAMCA framework will be introduced. Next, the criteria preprocessing framework is introduced. The steps of preprocessing 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.

2 | MAMCA FRAMEWORK

The MCDM process typically includes the following steps: problem statement, defining alternatives, defining criteria, eliciting criteria weights, appraising alternatives, analyzing scores, and drawing conclusions (Nijkamp et al., 2013). Because of the involvement of the stakeholders, extra steps are needed in MAMCA such as defining the stakeholders. Figure 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, and so forth, 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 (Huang, Mommens, et al., 2021). MAMCA is allowed to use any MCDM method to evaluate alternatives, such as the Analytical Hierarchy Process (AHP) (Golden et al., 1989), ELECTRE (Leyva-Lopez & Fernandez-Gonzalez, 2003), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) (Brans & De Smet, 2016), or Simple Multi-Attribute Rating Technique (SMART) (Edwards, 1977).

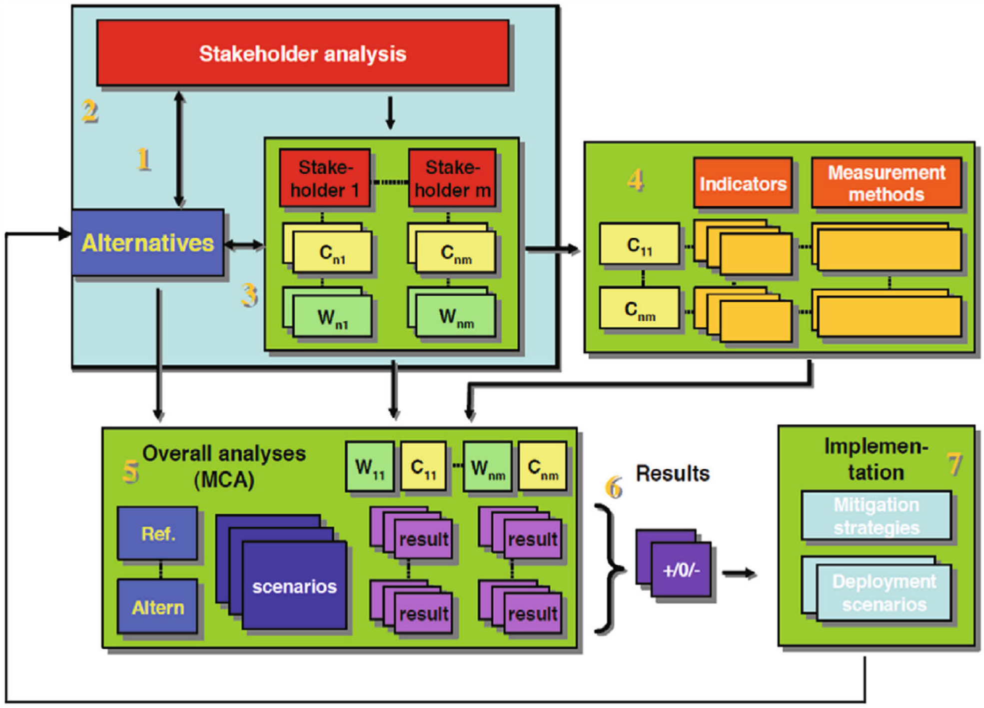

FIGURE 2 MAMCA framework (Macharis et al., 2004).

At the end of the procedure, in step 6, the preference rankings of the different stakeholder groups are visualized in one chart, that is, 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 (Huang, De Smet, et al., 2021). Finally, in step 7, the chosen alternative can be implemented after the decision is made.

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 preprocessing. Earlier applications of MAMCA followed different ways for preprocessing criteria. In their study of stakeholders' preferences for the future of transport in Europe, Keseru et al. (2021) first applied content analysis of the mission statements of interest groups to identify their criteria (Marks & Yardley, 2004). Then an online survey was held among the participants of the stakeholder groups to validate the relevance of the predefined 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. (2016). 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. (2011) first tracked a criteria list for each stakeholder group by literature review. Afterward, the predefined 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. (2015) 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 preprocessing in previous studies are different but similar. Conventionally, facilitators always seek a predefined 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 preprocessing framework.

2.2 | Principles applied in novel criteria preprocessing framework

Before introducing the framework, two important principles of the criteria preprocessing will be introduced. They are used in the framework

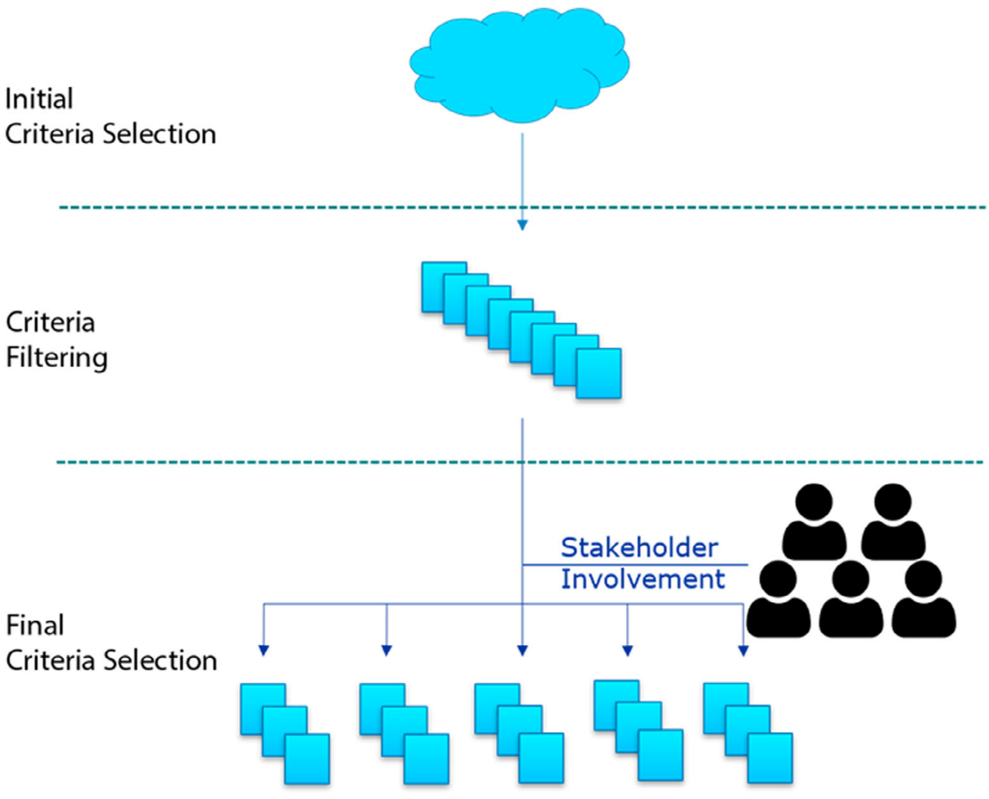

FIGURE 3 Criteria preprocessing framework.

to keep the number of criteria cognitively manageable while not missing important criteria.

2.2.1 | 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 (Miller, 1956). 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 MCDA, 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" (Lai & Hwang, 1992; Saaty & Ozdemir, 2003). The accuracy of the weight allocation decreases when the number of criteria increases (Sun, 2002). Thus, in MAMCA criteria preprocessing, we suggest limiting the number of criteria from 5 to 9.

2.2.2 | Pareto analysis

The initial statement of Pareto analysis is that approximately 80 percent of wealth was concentrated in approximately 20 percent of a population (Sanders, 1987). According to Pareto's viewpoint, a small percentage of input can generate a large percentage of output (Svensson & Wood, 2006). 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 (Basile, 1996). It is useful for identifying, prioritizing and addressing the factors that have the most impact (Cervone, 2009). 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" (Hartman, 2016). In the MCDA, there are "vital few" criteria that will take up the majority of the weight (Craft & Leake, 2002). By applying Pareto analysis in the MAMCA criteria preprocessing, 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.

3 | A NOVEL CRITERIA PREPROCESSING FRAMEWORK

The criteria preprocessing framework we propose is divided into three steps: initial criteria selection, criteria filtering and final criteria selection. Figure 3 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 focusses on the selecting the criteria. As a result, the criteria are chosen for stakeholder groups based on their relevance levels to the problem.

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?" (Dodgson et al., 2009). 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 (Toth-Szabo et al., 2011; van Rooijen & Nesterova, 2013). To search for synergies in urban and regional mobility measures, Bulckaen et al. analyzed 16 case studies to define the criteria (2015).

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 (Bulckaen et al., 2015; Keseru et al., 2016). 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 and so forth. 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 (Roy, 2013). Also, double counting should be avoided because it will result in a higher weight of the criterion in the subsequent assessment (Tudela et al., 2006). Finally, the criteria must be measurable in order to reflect the stakeholders' priorities (Macharis et al., 2012). A more detailed study on filtering criteria can be found in the literature (Beria et al., 2012; Dodgson et al., 2009; Yurdakul & Ic, 2009). After criteria filtering, the criteria list is ready for the final selection.

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.

3.2.1 | 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 (Pappers et al., 2021; Keseru et al., 2021; Lode, Te Boveldt, Macharis, & Coosemans, 2021), 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 $C := \{c_1, c_2, \ldots, c_n\}$, and there are m participants in one stakeholder group $A := \{a_1, a_2, \ldots, a_m\}$. 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:

$$S_{n\times m} := \begin{bmatrix} s_{1,1} & \cdots & s_{1,m} \\ \vdots & \ddots & \vdots \\ s_{n,1} & \cdots & s_{n,m} \end{bmatrix}, s_{i,j} \in \{0,1\}, \tag{1}$$

where $s_{i,j}$ represents the relevance of criterion i for participant j. We sum each row of matrix (1) to obtain the score vector $Q := \{q_1, q_2, \ldots, q_n\}$, where q_i represents the sum of the binary relevance scores given by participants in one stakeholder group to criterion i:

$$q_i = \sum_{j=1}^{m} s_{i,j}, i \in \{1, \ldots, n\}. \tag{2}$$

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

$$Q' \subset Q, |Q'| = z, \tag{3}$$

where Q' 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

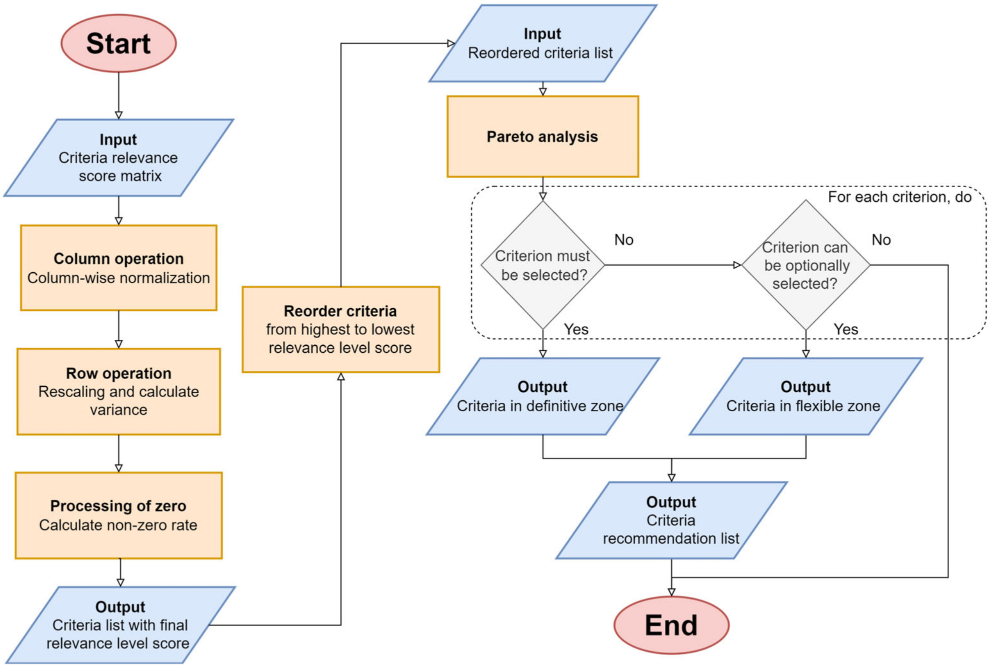

FIGURE 4 Flowchart of the new criteria selection model.

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 stakeholder 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 of 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 have more decision power than those who select fewer criteria as relevant.

3.2.2 | 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).

The new criteria selection model starts with a new raw data collection. Participants are asked to select β criteria they think are relevant, where $\beta \in \{5,6,\ldots,9\}$ to meet the Miler's magic number (Saaty & Ozdemir, 2003). 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:

$$S'_{n\times m} := \begin{bmatrix} s'_{1,1} & \cdots & s'_{1,m} \\ \vdots & \ddots & \vdots \\ s'_{n,1} & \cdots & s'_{n,m} \end{bmatrix}, s_{i,j} \in \{1,\ldots,x\}, |s'_{*,j} \neq 0| = \beta, \exists s'_{*,j} = x, \quad (4)$$

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:

$$\begin{array}{c c} & \begin{array}{ccc} a_1 & a_2 & a_3 \end{array} \\ \begin{array}{c} c_1 \\ c_2 \\ c_3 \end{array} & \begin{bmatrix} 5 & 3 & 3 \\ 5 & 4 & 2 \\ 5 & 5 & 5 \end{bmatrix} \end{array}, \quad (5)$$

where the scores are on a $[1-5]$ scale. We can see that participant a_1 gives all criteria the highest relevance level, that is, 5, while others do not. Therefore, implicitly, a_1 has higher decision power as he has more scores to distribute. Therefore, the first step, *column operation* is processed, that is, to normalize the scores for each participant:

$$s'^{col}_{i,j} = \frac{s_{i,j}}{\sum_{z=1}^{m} s_{z,j}}, \quad (6)$$

s.t.

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

TABLE 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 the column-wise normalized matrix can be seen as each participant distributes 1 to all criteria.

The second step is *row operation*. Let us take a look at (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 (Kunsch, 2018):

where each row of data in Table 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:

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

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

$$\overline{v_i} = \sum_{k=1}^{5} k \times d_{k,i}, \tag{7}$$

$$\sigma_i^2 = \sum_{k=1}^{5} d_{k,i} \cdot (\overline{v_i} - k)^2. \tag{8}$$

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

$$p = \overline{v_i} - \sigma_i. \tag{9}$$

s.t.

$$\begin{bmatrix} 5 & 3 & 3 \\ 5 & 4 & 2 \\ 5 & 5 & 5 \end{bmatrix} \overset{\text{row operation}}{\Rightarrow} \begin{bmatrix} 2.78 \\ 2.55 \\ 5 \end{bmatrix}.$$

The column operation facilitates fairness among participants, and the row operation considers the score variance of participants. However, these two operations cannot be applied simultaneously, because the profile distribution matrix requires the scores to be on the same scale. However, after the column operation, the scales of the participants become different. Thus, a rescaling is needed to put the normalized scores on the same scale. We pick up non-zero scores in the matrix ("0"s will be processed in the next step) after column operation S'^{col}, to flatten and sort it as a vector:

$$o_{\beta \cdot m} = \left[\min_{S'^{col} \setminus 0} s'^{col}, \ldots, \max_{S'^{col} \setminus 0} s'^{col} \right], \tag{10}$$

where $\beta \times m$ is the number of non-zero scores of the $n \times m$ matrix. We choose a suitable interval to put the scores on the same scale based on the vector, taking into account the probability density and distribution, and generate a new profile distribution matrix D' based on it. Now, instead of (9), the relevance level score of each criterion c_i can be computed as:

$$p' = \sum_{k=1}^{x} k \times d'_k - \sqrt{\sum_{k=1}^{x} d'_k \cdot \left(\sum_{k=1}^{x} k \times d'_k - k \right)^2} = \overline{v'} - \sigma'. \tag{11}$$

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, that is, $(n-\beta) \cdot m$, 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:

$$\gamma_i = 1 - \frac{|\{s'_i = 0\}|}{m}, \tag{12}$$

where it indicates the rate of participants selecting c_i as relevant, the higher this indicator is, the more people believe this criterion is relevant. The final relevance level score r is calculated after obtaining the column-wise normalized matrix S'^{col}, the profile distribution matrix D' on the new scale, and the non-zero rate γ:

$$r = \gamma \cdot \left(\overline{v'} - \sigma' \right) = \gamma \cdot p^{'}. \tag{13}$$

By calculating the final relevance level score, a vector of the criteria's relevance level scores is obtained, that is, $R := \{r_1, r_2, \ldots, r_n\}$.

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

$$\min \overline{y} \tag{14}$$

TABLE 2 Criteria list after initial criteria selection and criteria filtering

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 SO_2, NO_2, $PM_{2.5}$ and PM_{10}
	CENV_2	Climate change	Impact of construction works on greenhouse gas emissions CO_2 (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	Labor conditions	Labor 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 and so forth

s.t.

$$\sum_{i=\overline{1}}^{\overline{y}} r_{\overline{i}} \geq \alpha \cdot \sum_{i=\overline{1}}^{\overline{n}} r_{\overline{i}}, \tag{15}$$

where we set $\alpha = 50\%$ to satisfy majority rules (Azrieli & Kim, 2014). This should result in $5 \leq \overline{y} \leq 9$. Otherwise, increase the value of α until $\overline{y} = 5$ is obtained. We say that the criteria in the resulting set $\{c_{\overline{1}}, c_{\overline{2}\ldots}, c_{\overline{y}}\}$ belong to the definitive zone. If $\overline{y}$ obtained in Step 1 is equal to 9, stop. Otherwise, further increase α until $\overline{y} = 9$. We say that these additional criteria, that is, those that are not already in the definitive zone, belong to the flexible zone. There is a possibility that when $\overline{y} > 9$ but $\alpha < 50\%$. This means that the participants in the stakeholder group have widely disparate priorities in terms of

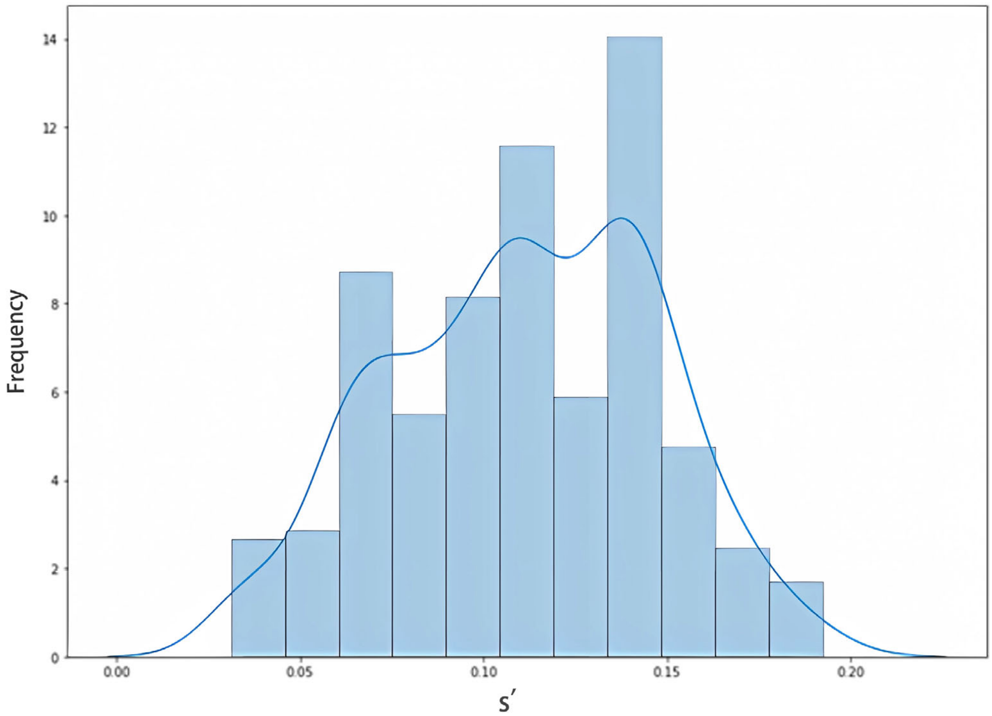

FIGURE 5 Histogram via the Freedman-Diaconis rule.

TABLE 3 Profile distribution table and other indicators

ID	γ	1	2	3	4	5	6	7	8	9	10	11	$\overline{v'}$	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

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 zone. All of 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.

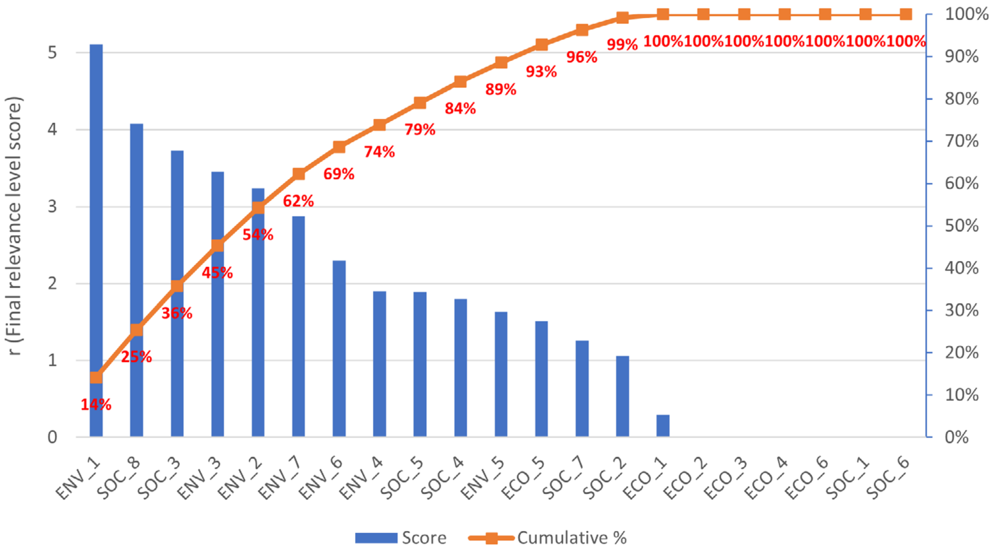

FIGURE 6 Pareto chart based on the final relevance level scores.

3.3 | Case study

The criteria preprocessing 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 will result in a mixed 17.600 m^2 park for agri-food companies and social and student residences, and offers high relevancy for urban construction logistics because of its density, location, construction type, intermodal transport possibilities and the rich number of stakeholders involved (Brusselaers et al., 2021). 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. (Brusselaers et al., 2021).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 (Huang, Mommens, et al., 2021). In light of this study, we analyze data linked to the actor group of Citizens to test the criteria preprocessing framework.

3.4 | Criteria preprocessing

After defining the CLSs and identifying the stakeholder groups, the criteria preprocessing 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 (Macharis et al., 2016) (Van Lier & Macharis, 2016). 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 and so forth. 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 2).

TABLE 4 Criteria recommendation table for stakeholder group “citizens”

Ranking	Criteria ID	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	

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, that is, $\beta = 9$. 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

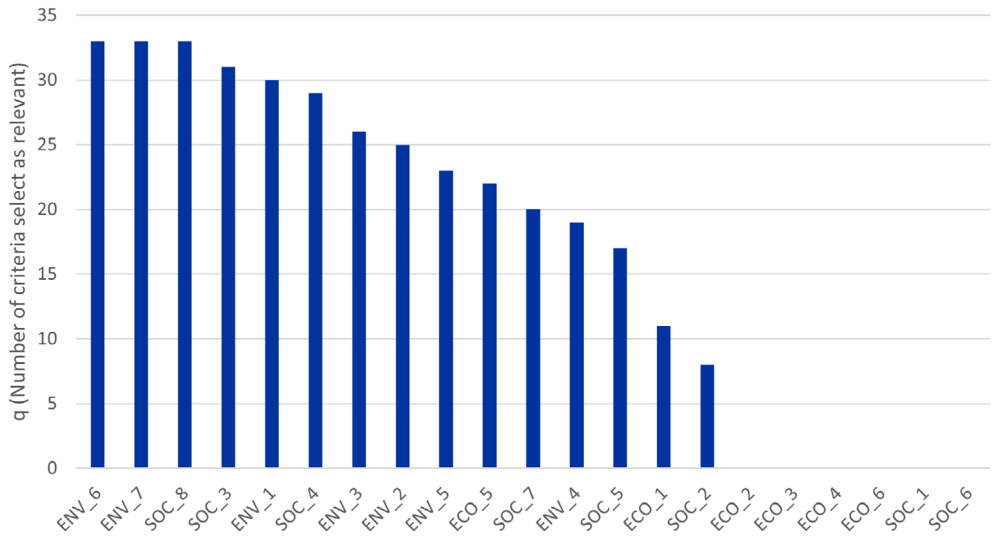

FIGURE 7 Criteria selection in conventional approach.

TABLE 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**

Note: Bold indicates unique criteria proposed in both methods.

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, that is, $S'_{21\times40}, s_{i,j} \in [0..5]$.

3.4.1 | Final criteria selection based on the new selection model

First, the raw score matrix is normalized column-wise, thus $S'^{col}_{21\times40}$ is obtained. The non-zero normalized values in the matrix, totaling 9×40, are placed in the vector $o_{360} = \left[\underset{s'^{col}\backslash 0}{\min}\, s'^{col}, \ldots, \underset{s'^{col}\backslash 0}{\max}\, s'^{col}\right]$ to obtain a new scale that takes the probability density and distribution into account. In this case, we consider rescaling 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 (Howitt & Cramer, 2007). There are several guidelines and rules of thumb for determining the appropriate interval, that is, the number of bins for a given data set, for the histogram (Venables & Ripley, 2002). In this case, we use Freedman–Diaconis rule to obtain a suitable scale (Freedman & Diaconis, 1981). It is a robust estimator that takes data variability and data size into account, which works well when the data size is under 200 (Hyndman, 1995). The interval/bin width of the given vector $o_{\beta\times m}$ is:

$$Interval = 2 \cdot \frac{IQR(o)}{\sqrt[3]{\beta \cdot m}}, \tag{16}$$

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 5.

The profile distribution table is shown Table 3, along with non-zero rate γ, and the final relevance level score r calculated based on (13).

The Pareto analysis is taken based on the final relevance level scores. And the Pareto chart is illustrated in Figure 6. 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 (14) and set $\alpha = 50\%$. The final recommendation of the criteria is proposed. Table 4 shows the recommended criteria.

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 five criteria. They meet the minimum requirements of Pareto analysis and 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, that is, 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 criteria which followed by the most relevant criteria in the definitive zone. The selection of these criteria is up to the facilitators.

4 | 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 7, where the bars represent the number of participants selecting one criterion as relevant.

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

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, that is, 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 preprocessing 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 7, 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 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, that is, 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.

4.1 | Limitations and future work

In this study, we presented a preprocessing framework to support facilitators in selecting criteria for stakeholder groups in MAMCA 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 with 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 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 (Corrente et al., 2012; Corrente, Greco, & Słowiński, 2013), AHP (Saaty & Vargas, 2012), hierarchical versions of the INTERCLASS method (Fernández, 2022), hierarchical multi-attribute value function (Brownlow & Watson, 1987). In the future, a preprocessing 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.

5 | 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 preprocessing 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 preprocessing 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.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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